MIND THE GAP: A COMPARISON OF SOCIO-TECHNICAL LIMITATIONS OF NATIONAL HOUSE RATING SYSTEMS IN THE UK AND AUSTRALIA

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ABSTRACT

This paper reviews the national house rating tools in the UK and Australia, evaluates the energy performance of eight different case study houses, and quantifies the magnitude of the performance gap between as-designed energy performance and as-occupied (actual) energy use. To identify contributing factors to the performance gap, post-occupancy evaluations were conducted, and all case study houses were monitored over two years. It was observed that there are performance gaps in all case study houses, however, the gap can be negative (i.e. more actual energy use than simulated) or positive (i.e. less actual energy use than simulated). Results show that the actual heating loads were less than simulated in 5 of the 8 houses (2 UK and 3 AU), and only 1 house (AU) had an actual cooling load more than simulated. The heating discrepancies ranged from 73% to 180% for the UK houses, and 19% to 172% for the AU houses. For the cooling loads, actual energy use in the AU house was up to 4.8 times higher than the simulated.

To understand the underlying causes, several influencing factors (including internal temperature conditions, climate, house form and urban context, construction quality, and processes and assumptions of national house rating tools) were analysed. It was found that a key challenge relates to a limited definition of the energy system (household energy use), focusing on technical issues and largely ignoring or simplifying existing and changing socio-cultural issues. Additionally, the paper argues for the need for extending the system boundary beyond individual buildings to neighbourhood, community and city scales. At both a building scale and community scale, deeper understandings of socio-cultural issues that impact on, and are impacted by, energy metabolism, are required.

Keywords: Performance gap; Nationwide House Energy Rating Scheme (NatHERS); Standard Assessment Procedure (SAP); Household energy use; National energy rating systems

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1 INTRODUCTION

In developed countries, energy consumption of buildings accounts for more than a third of total energy use [1, 2]. The potential of reducing energy use in buildings and hence CO_2 emissions has been widely identified by governments, for example, by the UK Department of Energy and Climate Change [3, 4], and by Australian, State and Territory Governments, as defined by the Nationwide House Energy Rating Scheme (NatHERS) and adopted into building regulations via the National Construction Code (NCC) [5]. To achieve national targets, buildings can be rated for energy performance of the fabric and services at the design stage and may also be rated by comparison of actual annual fuel consumption [6]. National energy codes and standards have created lively debates on their practicality which has resulted in a raised awareness within the building industry and academia about the actions required to tackle climate change at an international level [7-9].

While many studies have explored the potential of new materials and methods [10-12] to design energy efficient buildings, there is extensive evidence worldwide [13-18] suggesting that buildings do not usually meet the energy efficiency targets set at the design stage, although it is inconclusive whether this applies to all building types and all jurisdictions or climate zones. In order to understand and address the performance gap between design targets and the actual performance of buildings, Post Occupancy Evaluations (POE) of buildings are becoming increasing important to measure and compare actual performance with design intents. POE of buildings however are not carried out widely due to the time and cost associated with the exercise.

Simulation tools are used to predict the future performance of buildings when built. Internationally there are numerous assessment tools ranging from advanced dynamic computer simulation programs, capable of representing complex interactions in buildings, to more simplified and stationary calculation methods and tools. While dynamic programs require extensive and detailed value input data, simplified tools may be used with less data and hence with limited scopes and capabilities. Hensen and Lamberts [19] provide a general view of the background and current state of building performance simulation programs. In addition to the physical characteristics of buildings (e.g. their forms and shapes) and thermal properties of their envelopes (e.g. the level of thermal insulation and mass), the life style and behaviour of occupants have profound effects on the overall performance of dwellings [20]. These inputs rely considerably on assumptions, which are often unknown or uncertain at the design stages [21]. In the building rating tools, these assumptions (e.g. standardised occupant behaviour profiles) are pre-defined for regulatory purposes, to enable comparison of buildings within the same context. Inaccurate or unrealistic assumptions may lead to a significant discrepancy between design expectation of energy use and the actual operation and energy use of individual houses and the housing stock in general. It could be argued that this is due in part to the lack of feedback to building designers during the post-occupancy stage, hindering improvements to future designs [14]. The same argument could be applied to regulators: that a lack of feedback about actual operation of housing can hinder improvements in the assumptions applied to the building rating tools.

POE of buildings is also useful to understand users' behavior with regards to regulating the internal environment of the building to enhance their comfort, wellbeing and satisfaction [22, 23]. In buildings where the occupants can play a role in changing the conditions, as suggested by Nicol and Humphreys [24], the users' natural tendencies are expressed in their adaptive approach to thermal comfort. The adaptive approach, as explained by Nicol et al [25], is mainly based on empirical observations in which the adaptive mechanisms operated by individuals, for example opening and closing windows, may be predicted to achieve comfort. The adaptive approach to thermal comfort also suggests that people can tolerate a wider range of environmental conditions, for example temperatures, compared with the case in fully controlled buildings [26].

In the United Kingdom (UK), the Standard Assessment Procedure (SAP) [27] is used as proof of compliance of dwellings with Part L1A of the Building Regulations [28] to evaluate the consumption of fuel and power to determine the performance of dwellings as designed. Similarly, in Australia (AU), NatHERS is used for evaluating the thermal performance of dwellings in the form of a star rating. These star ratings can be used to show a design meets the mandatory energy efficiency requirements for homes and major renovations based on the NCC [29].

This study brings together researchers from the UK and Australia to analyze and compare the methodologies and results of POE projects recently conducted in these two countries. The aim of this study was to evaluate the performance gap of newly constructed light-weight single-family homes in the United Kingdom and Australia. The objectives of the study were to determine whether performance gaps existed and to compare and evaluate influencing factors that could account for differences in consumption as well as differences in performance gaps between households and between the two countries.

2 RESEARCH METHODOLOGY

This research uses a cross-national comparative case study approach. Case studies enable the in-depth and longitudinal examination of housing within a real-world context and the utilisation of multiple sources of data [30]. The cross-national approach enables comparison of data taking into account differences such as governance, climate and culture. UK and Australia were selected for comparison because each has a national house rating system that gives a standardised measure that enables the energy performance of individual dwellings to be compared against national targets and compared with each other in a relatively meaningful and systematic way. These countries also have many similarities in governance, building practices and general cultural practices.

The next section will review and compare SAP and NatHERS building performance tools and detail how these tools evaluate thermal performance of residential buildings. Section 3.2 describes the eight case study houses followed with the data collection methods. Then, the performance tools will apply to these houses to assess their thermal performance. Finally, a comparison will be made between the simulated and measured data to quantify performance gaps and identify contributing factors to these gaps.

2.1 COMPARISON OF BUILDING PERFORMANCE ASSESSMENT TOOLS

In this section SAP and NatHERS building performance assessment tools are reviewed and compared in terms of protocols, climates, thermal energy calculations and internal load assumptions. Some research suggests that the tools themselves could also contribute to performance gaps [31, 32].

2.1.1 PROTOCOLS AND TOOLS

In the UK, SAP provides a home energy rating assessment protocol, using a procedure consistent with BS EN ISO 13790 and calculations are based on the BRE Domestic Energy Model (BREDEM) which is used for research purposes such as stock modelling [33]. The energy performance indicators used by SAP include fabric energy efficiency, energy consumption per unit floor area, energy cost rating, environmental impact rating and dwelling emission rate [34]. Assessors can follow the protocol using the provided calculations, or use approved dynamic simulation software (accredited by BRE). Similarly, Australia's NatHERS establishes the protocols and validates and standardises software (i.e. the tools) utilised for assessing the thermal performance of dwellings (as designed) for the purpose of compliance with the energy efficiency requirements of the NCC. Accredited software (Accurate, BERS Pro and FirstRate5) all use the same underlying thermal simulation engine ("CHENATH") for performing the heat flux calculations [5]. NatHERS supports efforts to 'reduce the energy and greenhouse gas impact of residential buildings' and provides 'a reliable way to estimate and rank the potential thermal performance of residential buildings'[35]. The only energy performance indicator is space heating and cooling load per unit floor area (presented separately and as a total, on an annual basis). Despite angst amongst those in industry regarding the assumptions used by NatHERS, many recognise that the engine and its calculations are highly trusted and that the use of such a scheme allows house designs to be compared fairly. The result is that NatHERS appears to be less concerned about the actual energy performance of individual homes than about the collective energy efficiency of the housing stock in each climate zone (hence the focus on comparison with other houses).

2.1.2 CLIMATE FILES

SAP is based on Typical Meteorological Year (TMY) weather files that are a 'composite year' of individually ranked months computed according to the Finkelstein-Schafer statistic from a historical data set [36]. Weather data is available for 21 regions and consists of tables of monthly averages of ambient temperature, wind speed (for calculating infiltration rate), mean global solar irradiance on a horizontal plane, and solar declination (same for all regions). NatHERS uses Reference Meteorological Year (RMY) weather files presented in a fixed record format of the Australian Climatic Data Bank (ABCB) [36]. The RMY files for the 69 climate locations currently available, are derived from Australian Bureau of Meteorology weather data from 1976 – 2004, giving annual long term averages [37]. RMY files for 14 additional climate locations were created in 2011 and new RMY files reflecting recent climate were created in 2016/17 (derived from half-hourly and synoptic data for the period 1990 – 2015) [38], yet these files are not yet approved for use in NatHERS.

2.1.3 THERMAL ENERGY CALCULATIONS

SAP calculates the mean monthly internal temperature separately for the living room and the rest of the dwelling. The 'Space Heating Requirement' is calculated from internal and external temperatures and the heat transfer coefficient, allowing for internal and solar gains (SAP 2012 section 9). It then calculates the fuel / electricity requirements to meet this load, on a monthly basis, taking into account the efficiency of the heating system. It is assumed that the dwelling has heating systems capable of heating the entire dwelling. Assessors are required to enter an infiltration rate, either from a pressurisation test or from SAP worksheet calculations. SAP 2012 can evaluate the likelihood of dwellings experiencing high temperature in hot weather, represented as a single calculation of the predicted average internal temperature each month for the three summer months (June – August) compared to a temperature threshold (Table 1). Cooling loads, however, are not calculated or included in the SAP rating or CO_2 emissions. Dwellings with fixed air-conditioning systems can include cooling loads in the dwelling emissions rate and the cooling pattern is assumed to be 6 hours / day for a specific part of the dwelling (SAP 2012 Appendix P, Tables 10a and 10b)

TABLE 1. Overheating likelihood (from SAP2012, Appendix p)

$T_{threshold}$	Likelihood of high internal temperature during hot weather
< 20.5°C	Not significant
≥20.5°C and < 22.9°C	Slight
≥22.0°C and <23.5°C	Medium
≥23.5°C	High

NatHERS' underlying CHENATH engine couples a frequency response multi-zone thermal model [39] and a multi-zone infiltration and exfiltration air flow model [40]. Internal temperatures (for each zone) are calculated on an hourly basis, to derive the seasonal (heating or cooling) and annual total space heating and cooling loads. NatHERS requires all conditioned spaces to maintain a range of thermal comfort, based on an adaptive comfort model, assuming that occupants can adapt themselves to the outdoor environment and accept a wider range of indoor conditions [37]. The cooling thermostat for each climate zone is calculated using the following equation:

$$T_n = 17.8 + 0.31\,T_m$$

Where T_n is the neutral temperature for January (summer) and T_m is the mean January ambient air temperature for each climate zone. According to NatHERS, all conditioned spaces must not fall outside of thermal comfort range (i.e. 22.5-28.5°C). If T_n is greater than the upper limit of 28.5°C, the cooling thermostat is set to 28.5°C and if T_n is smaller than the low limit of 22.5°C, the cooling thermostat is set to 22.5°C [37]. For the heating thermostat, three different heating setpoints are defined by NatHERS in Australia to account for occupants' expected clothing level, function of the space and time of day. For sleeping spaces, the heating thermostat setting is 18°C (7.00am to 9.00am and 4.00pm to midnight) and 15°C from midnight to 7.00am. For living spaces, the heating thermostat setting is set to 20°C (as shown in Table 2).

In summer it is assumed that indoor adjustable shades (e.g. blinds and curtains) are closed between 18:00 and 07:00 and at other times (to restrict solar heat gain) if each of these three conditions are met: (i) outdoor temperature exceeds the cooling thermostat setting + 2.5°C; (ii) the incident solar irradiance on glazing exceeds 200 W/m^2; and (iii) there is no outdoor blind / shade or it cannot be utilised. Any adjustable outdoor shading that has been drawn into the building geometry is assumed closed when the incident solar irradiance on glazing exceeds 75 W/m^2 and when the outdoor temperature is higher than 26°C or the cooling thermostat setting (if cooling thermostat setting is <26°C.)[37]. The thermal calculations are then adjusted to incorporate a three stage approach to achieving thermal comfort for occupants: natural ventilation (i.e. occupants will operate doors and windows to manage thermal comfort) when the external conditions are better than those inside; cooling via mechanical air movement (e.g. ceiling fans will be used to provide a cooling effect in summer); and adding / extracting energy via heating and cooling appliances [5]. It is questionable whether these assumptions about the operation of the building by occupants are valid, although building automation theoretically would make these actions feasible.

2.1.4 HOUSE ZONING, OCCUPANCY AND INTERNAL LOADS

SAP divides dwellings into two zone models: living area with the 21°C heating set point, and the rest of the dwelling with the lower heating set points (refer to Table 2) [41]. Occupancy assumptions are based on the dwelling's floor area but limited to a small range (1 - 3.5 persons per dwelling). The majority of homes in the UK are between 50-100m^2, and the SAP formulae results in an average dwelling size of 90m^2 having an average occupancy of 2.62 [42, 43]. SAP's heating and cooling regimes are shown in Table 2, with different regimes for weekdays and weekends, and between living and sleeping zones. Some sources of internal heat gains have established equations required by SAP, e.g. metabolic gains (50W per occupant), water heating, pumps and fans internal heat losses (warming associated with incoming cold water and evaporation). Other internal heat gains have baseline SAP equations (based on floor area) and discretionary values (e.g. actual known values) can be entered by the SAP assessor (e.g. lighting, appliances and cooking) [42]. These heat loads are calculated on an annual basis. Some adjustments to occupancy parameters can be applied if a SAP assessment relates to a particular household, such as using actual number of occupants rather than floor area to determine water heating energy, adjusting heating times and temperatures, and verifying calculated energy costs against actual energy bills [44].

NatHERS also has sleeping and living zones (considered conditioned) but assumes at least one unconditioned utility zone (e.g. a bathroom or laundry) in each house. The smallest utility room must be simulated as unconditioned, while other utility rooms should be simulated according to their expected use (e.g. en-suite bathrooms are typically modelled as conditioned). The ‘default’ number of occupants is 2 adults and 2 children, based on a total floor area of 160 m^2 (80 m^2 for living and 80 m^2 for bedroom zones). An algorithm adjusts the number of occupants up or down for different sizes of dwellings; this is summarised below, where NBR is the number of bedrooms, A is the house floor area in m^2. The number of occupants is not rounded off [45].

$$\textit{Number of Occupants} = \max\,(1+ 0.66 \times NBR, A/ 50)$$

Internal latent heat loads and the sensible heat loads of occupants, lighting, appliances and cooking activities, are allocated per zone per hour (based on a 160m^2 dwelling with two adults and two children) [37]. No detail is given as to how (and when) these loads were calculated. Assumptions about thermal set points and occupancy patterns are shown Table 2 with no distinction made between weekdays and weekends. No adjustments to the occupancy parameters are possible (if using the software for regulatory purposes), however the accredited software does allow for a level of customisation (for non-regulatory purposes), known as non-rating mode.

Table 2 . SAP and NatHERS fixed assumptions of occupancy hours, zones and thermal settings

Assumptions	**SAP regulatory settings**		**NatHERS regulatory settings**
Thermostat settings	Heating	≥21°C in living areas ≥18°C in bedrooms	≥ 20°C in living areas 07:00 – 24:00 ≥ 18°C in bedrooms 07:00 – 09:00 and 16:00 – 24:00 ≥ 15°C in bedrooms 00:00 – 07:00
	Cooling	24°C	Ranges from 22.5-28 °C during hours of occupancy depending on climate zone
Heating operation hours	Weekdays in living areas 07:00 – 09:00 and 16:00-23:00 Weekends in living areas 07:00 – 23:00 All days in bedrooms or elsewhere 07:00 – 09:00 and 18:00-23:00[a]		
Cooling operation hours[b]	6 hours/day		

[a] Dwellings with the heating control type 3 (as defined in [46])

[b] There were no cooling systems in the UK homes in this study

2.1.5 SIMULATION OUTPUT

From a building regulation perspective, SAP generates an energy efficiency index, ranging from 1 to 100, and estimates the annual primary energy (kWh), carbon emissions (CO_2)and cost (£) for space heating, hot water and lighting of the dwelling [34, 47]. Building regulations in England require meeting a Target Emissions Rate (TER) and a Target Fabric Energy Efficiency (TFEE). Wales sets values for a Target Emissions Rate. NatHERS uses the predicted heating and cooling thermal energy (MJ/m^2) to determine an energy star rating (0 to 10 stars), with a 10 star design assumed to need no or little space heating or cooling. An 'area correction factor' is applied to recognize that small dwellings may have a higher surface area to internal volume ratio, and higher window to floor area ratio, than otherwise equivalent larger dwellings. The correction factor acknowledges that while smaller dwellings can have higher MJ/m^2 than their larger counterparts, their overall energy use (for space heating / cooling) will be lower, as heat transfer through the building fabric is proportional to the building surface area [6]. The default 'neutral' building size is 196m^2 (the average size of new dwellings at the time the correction factor was first instigated), and the actual energy rating of a dwelling is adjusted up or down according to its deviation from this 'neutral' size [48]. Thermal energy requirements are communicated through 'star ratings' – a 10 band system where 1 star in any climate equates to a building with virtually no thermal resistance, and a 10 star house equates to a building requiring no or very little space heating or cooling. The relative construction challenges and costs associated with meeting thermal performance requirements in 69 disparate climate zones is addressed by assigning different energy requirements (MJ/m^2) to each star band, for each climate (i.e. the current minimum requirement for 6 stars is nationally consistent, but the MJ/m^2 allowed to achieve 6 stars varies between climate zones). A NatHERS rating also does not include calculations on the energy consumption for lighting and hot water, total primary energy consumption nor energy costs. The main outputs of SAP and NatHERS are summarised in Table 3. Note that this analysis is based on the regulatory mode of the relative schemes.

Table 3. Form and design standard of UK houses

Scheme	Space heating needs	Space cooling needs	Total space conditioning	Lighting energy and cost	Water heating energy and cost	Primary energy	Carbon emissions	Photo-voltaics (PV)
SAP	Y	N[a]	N	Y	Y	Y	Y	Y[b]
NatHERS	Y	Y	Y	N[c]	N[c]	N[c]	N[c]	N[c]

[a] Cooling loads are not included in SAP2012 rating or CO2 emissions. Refer to section 3.1.3.

[b] Emissions saved by energy generation technologies are used to calculate net CO_2emissions attributable to the dwelling. This is indicated by an Environmental Impact Rating (EI) where EI 100 = zero net emissions. It can rise above 100 if the dwelling is a net exporter of energy.

[c] Next generation software AccuRate Sustainability incorporate these performance indicators but it is not yet approved for NatHERS accreditation [49, 50].

In addition to the previously mentioned functions, SAP can also be used to for a number of other functions, such as calculating net energy / cost / emissions (Appendix M), rate existing dwellings using 'reduced data SAP' linked with other data sets (Appendix S) and provide ranked recommendations for building improvement for inclusion in an Energy Performance Certificate (Appendix T). NatHERS, on the other hand, is restricted at the current time to rating new dwellings (or dwelling with significant alterations) 'as designed'.

2.2 CASE STUDY SINGLE FAMILY HOMES

Four homes in the UK (City of Gainsborough) and 4 homes in 4 different regions in Australia (Perth, Broadford, Mount Gambier and Toowoomba) were used for this comparative analysis. These eight specific single-family homes were selected because they were all recently constructed (2012-2015), were light-weight buildings utilising similar construction materials (structural insulated panels) and were each designed to perform higher than current minimum requirements in their respective country. (Note regarding Australian case studies: By 2011, all Australian states and Territories, except the Northern Territory, had adopted a minimum energy performance requirement of 6 stars. While Queensland regulations permit a lower standard of building thermal performance if a house has a grid connected PV system or outdoor living area, no such concessions were considered in this study). Also, all case study houses are in the same broad climate zone (temperate) as per Köppen's climate classifications [51]. Images of the homes are shown in Figure 1 and Figure 2. The form, size and design intent of the homes are summarised in Table 4 and Table 5 while Table 6 and Table 7 summarise the main construction elements of each house. Table 8 shows the long-term summer and winter climatic conditions of each of the locations, based on meteorological data for each location.

Figure 1 . UK houses Gainsborough (a) south elevation, UK_H1 in foreground; b) east elevation

(a) AU_H1, Perth (b) AU_H2, Broadford

(c) AU_H3, Mt Gambier (d) AU_H4, Toowoomba

Figure 2. AU houses in a capital city (a), rural area (b) and regional cities (c, d)

Table 4 . Form and Design Standard of UK Houses

	UK_H1	UK_H2	UK_H3	UK_H4
Environment	Dense urban environment in regional city (pop. 17,000)			
Form	Attached single family homes (rented)			
Storeys	2	2	2	3
Internal floor area	64.68m^2	70.56m^2	64.68m^2	98.28m^2
Internal volume	161.7m^3	176.4m^3	161.7m^3	252.25m^3
Ceiling height	2.4m ground floor, 2.6m other floors			
Glass: floor area ratio	25.8%	18.3%	18.6%	21.1%
Construction year	2012			
Rooftop PV system	3kWp	3kWp	3kWp	3.5kWp
Design standard	Code for Sustainable Homes Level 5 (requires 100% reduction in emissions from regulated energy under SAP)			
All data as per the respective SAP 2009 reports created using SAP Calculator 3.57				

Table 5 . Form and design standard of AU houses

	AU_H1	AU_H2	AU_H3	AU_H4
Environment (Terrain exposure category)	Suburban terrain (capital city, pop. 1.7m)	Exposed open terrain (rural, pop. 4,320)	Suburban terrain (regional town, pop. 26,000)	Suburban terrain (regional city, pop. 110,000)
Form	Detached single family homes (owner occupied)			
Storeys	1	1	1.5	1
Internal floor area	296m^2	232m^2	278m^2	323.2m^2
Internal volume	902.8m^3	846.6m^3	876.4m^3	775.6m^3
Ceiling Height	2.5 - 4.1m	2.7 - 4.2m	2.7 - 4.0m	2.4 - 6.2m
Glass: floor area ratio	16%	35%	11.8%	15%
Construction year	2015	2015	2015	2013
Rooftop PV system	Nil	4.5kW$_p$	3kW$_p$	3kW$_p$
Design standard (NatHERS)[a]	6 Stars T: 70MJ/m^2	6.2 Stars T: 185.8 MJ/m^2	7.1 Stars T: 101.2 MJ/m^2	6.5 Stars T: 69 MJ/m^2
Design standard (NatHERS)[b]	T:66.9MJ/m^2 C:39.5MJ/m^2 H:27.4MJ/m^2	T:185.1MJ/m^2 C:9.5MJ/m^2 H:176 MJ/m^2	T:99.2MJ/m^2 C:13.8MJ/m^2 H:85.4MJ/m^2	T:62.8 MJ/m^2 C:44.6 MJ/m^2 H:18.2 MJ/m^2

[a] = area-adjusted (discussed further in Section 3.5.5).

[b] =area-unadjusted.

T = Total space heating and cooling load; C = summer cooling load; H = winter heating load

Design standard: applies only to assessment of the building envelope (as designed) in relation to space heating and cooling.

Table 6. Specification of main construction elements for 4 UK case study houses

Elements	Summary specific characteristics	*U*-value (W/m^{2}K)
Ground Floor	Proprietary suspended concrete beam and block with 20mm insulation	0.12
External Walls	142mm Structural Insulated Panels (SIPs) finished in Brick or render clad	0.14
Party Walls	Open panel timber frame	

Roof	Single ply roofing membrane fixed to 142mm SIPs and 50mm rigid insulation	0.12
Door	Munster EcoClad timber board effect with triple glazed side screen	1.20[a]
Windows	Munster EcoClad triple glazed windows	1.15[a]

[a] *U*-values as recorded on SAP report; *U*-values reported by manufacturer are slightly different from these figures

Table 7 . Specification of main construction elements for 4 AU case study houses

Dwelling	AU_H1	AU_H2	AU_H3	AU_H4
Ground Floor	Concrete slab on ground (uninsulated)	Concrete slab on ground (uninsulated)	½ Concrete slab on ground (uninsulated); ½ Suspended Timber (insulated *U* 0.2)	Concrete slab on Waffle Pod (EPS insulation)
External Walls	140mm Steel Structural Insulated Panels (140mm) of SL Grade FR Polystyrene (k = 0.038 W/mK) sandwiched between 0.6mm steel skins. Mass 12.5 kg/m^2; R 3.69 at 20^{o}C (*U*-value 0.27 W/m^{2}K), external skin raw or with acrylic render			
Roof	Steel Structural Insulated Panels of SL Grade FR Polystyrene (k = 0.038 W/mK) sandwiched between 0.42 (flat) and 0.6mm (profiled) steel skins. Mass 11.98kg/m^2; R 4.1 at 20^{o}C (*U*-value 0.24 W/m^{2}K)			
Glazing Specifications	*U*-value 6.57 SHGC 0.74	*U*-value 4.8 SHGC 0.59	*U*-value 2.05 SHGC 0.38	*U*-value 6.57 SHGC 0.74

NOTE: all material specifications (e.g. R, U, SHGC) as provided by the respective manufacturers, recorded on the approved building plans and incorporated into NatHERS simulation

Table 8. Long Term Climate conditions of AU and UK case study houses

Location	AU_H1[a]	AU_H2[b]	AU_H3[c]	AU_H4[d]	UK_H1-4[e]
Latitude	31.92°S	37.2°S	37.75°S	27.54°S	53.4°N
Longitude	115.87°E	145.05°E	140.77°E	151.91°E	0.77°W
Climate description[f]	Hot-summer Mediterranean Csa	Temperate Oceanic Cfb	Warm-summer Mediterranean Csb	Sub-tropical Highland Cwb	Temperate Oceanic Cfb
Summer Conditions (Dec, Jan, Feb in AU; Jun, Jul, Aug in UK)					
$T_{meanmax}$ °C	30.7	23.9	24.5	27.6	20.4
$T_{meanmin}$ °C	17.6	11.8	11	17.2	11.1
RH 9am$_{mean}$ %	51.3	74.7	64.7	71.0	NA
RH 3pm$_{mean}$ %	39.3	49.3	45.3	52.0	NA
Rain $_{mean\ total}$ mm	38.4	142.9	88	307.1	173.7
Winter Conditions (Jun, Jul, Aug in AU; Dec, Jan, Feb in UK)					
$T_{meanmax}$ °C	19	9.8	13.7	17.3	6.8
$T_{meanmin}$ °C	8.2	4.4	5.5	7.2	0.8
RH 9am$_{mean}$ %	77.7	90.3	86.3	71.0	NA
RH 3pm$_{mean}$ %	55.7	78.7	70.7	48.7	NA
Rain $_{mean\ total}$ mm	403.1	190.5	290.3	95.5	138.5
Mean annual temperature(°C)	18.3	12.5	13.9	17.6	9.6

[a] Australian Bureau of Meteorology Station 009021 Perth Airport, WA

[b] Australian Bureau of Meteorology Station 026021 Mount Gambier Aero SA

[c] Australian Bureau of Meteorology Station 088162 Wallan VIC
[d] Australian Bureau of Meteorology Station 041529 Toowoomba Airport QLD
[e] UK Met office Scampton 1981-2010
[f] Köppen Climate Classification [51]
NA = not available

2.3 DATA COLLECTION AND ANALYSIS METHODOLOGY

The simulation of AU and UK houses were conducted by using the relevant nationally accredited software, NatHERS (AccuRate) and SAP, respectively. Both SAP and NatHERS tools uses steady state principles to provide dynamic simulations of heat gains, losses and internal temperatures, assuming 'standard' occupancy and heating/cooling patterns to enable comparison with other dwellings independent of occupancy influenced variables [52]. Neither mechanism, without customisation, purports to give a prediction of the actual heating/cooling energy use of a specific dwelling when occupied by a specific family. The broad similarities of both mechanisms are summarised in Table 9.

Table 9. Similarities between UK and Australian dwelling thermal performance mechanisms

	Broad similarities between SAP and NatHERS
1	Require detailed input of spatial and construction components of the dwelling (as designed)
2	Use weather data files as determined by the respective authority
3	Calculate heat gains and losses through the building envelope
4	Determine annual heating / cooling loads to meet established internal temperature setpoints
5	Have a multi-zonal approach to indoor temperatures (i.e. bedrooms and living rooms)
6	Adjust occupancy numbers based on area of the dwelling
7	Make assumptions about occupancy patterns, latent heat loads and heating/cooling schedules
8	Have been validated [5, 53, 54], but occupancy assumptions have been questioned [52, 55].

Table 10 shows actual and assumed occupancy: SAP calculates occupants based on total floor area as follows [46]:

$$If\ TFA \leq 13.9:\ N = 1$$
$$If\ TFA > 13.9:\ N = 1 + 1.76 \times [1- exp\ (-0.000349\ \times\ (TFA - 13.9)^2)] + 0.0013 \times (TFA - 13.9)$$

where N is the assumed number of occupants and TFA is the total area of dwelling. The NatHERS formulae (mentioned previously), however, includes floor area and number of bedrooms. While the SAP calculation shows good correlation with actual occupant numbers, the NatHERS formulae does not correlate with the actual occupancy of AU_H1, AU_H2 and AU_H4, raising questions about the validity of the algorithm.

Table 10. Comparison of simulated and actual number of occupants

	UK_H1	**UK_H2**	**UK_H3**	**UK_H4**	**AU_H1**	**AU_H2**	**AU_H3**	**AU_H4**
Actual Occupancy	2	3	3	3	4 (2A+2C)	2 (2A)	5 (2A+3C)	2 (2A)
Assumed by model	2.18	2.31	2.14	2.75	5.92	4.64	5.56	6.46

A = Adult 18 or over; C = Child (i.e. under 18)

Each house was evaluated for energy performance at the design stage in accordance to each jurisdiction's regulatory requirements: SAP2009 for the UK houses (https://www.bre.co.uk/sap2009/page.jsp?id=1642) and NatHERS for the AU houses (www.nathers.gov.au). Quantitative measurements and forensic investigations using environmental monitoring and diagnostic testing provided data about the technical performance of the case study houses. Energy use and internal and external temperatures of dwellings were monitored from July 2012 to September 2014 in UK, and from July 2014 to December 2016 in AU. In order to ensure that monitoring devices consistently take accurate measurements, commissioning tests, data cleansing and data reliability processes were implemented on a regular basis to identify and account for missing or erroneous data. Each of the houses was subject to an air leakage test in accordance with the procedures specified by the British Institute of Non-Destructive Testing (BINDT) using an air pressurisation/depressurisation technique (ATTMA TS1) (for UK homes) and ASTM E779 (for Australian homes) incorporating the whole building envelope at an imposed pressure of 50 Pa. Socio-technical methods such as structured interviews, observation, document examination and post-occupancy evaluation provided qualitative data about the houses, their occupants and the national rating systems with which they had to comply. Evaluation of these multiple data sets within the defined climatic and social contexts is a typical real-world approach to building evaluation [56] and enables comparison of building attributes (technical issues) with inhabitant's perceptions (social issues) [57]. Data was evaluated to compare, for each house, measured energy consumption against 'as designed' performance. Data was then normalised to enable comparison between houses and countries. The following section discusses the results of comparisons of predicted versus actual consumption and possible influencing factors: internal temperature conditions and climate, house form and urban context, and construction quality.

3 RESULTS AND DISCUSSION

3.1 PREDICTED AND ACTUAL ENERGY CONSUMPTION AND GENERATION

The annual predicted and measured energy performance for space heating/cooling, hot water and PV generation is compared in Table 11 . For normalisation between all case study houses:

- energy for space heating/cooling is expressed in terms of energy consumption relative to floor area (total floor area for UK houses, conditioned floor area for AU houses);
- water heating is relative to number of occupants; and
- solar generation is gross measured output per kW peak of the installed PV systems.

Note that the AU houses were all electric (i.e. no gas services) and all electrical circuits were monitored, enabling a breakdown of energy consumption per service. The monitoring systems for the AU houses include a Home Energy Management System (HEMS) – AuziMAX by Enopte. The HEMS were customised for the four case study homes to collect data from all electrical circuits in one-minute intervals and store them in a cloud-based platform. Two temperature and humidity sensors (HS109) were installed in the main living room and main bedroom, and connected to the HEMS. For the UK houses, a Wi5 data hub GPRS wireless data logger was installed in House 3 to process data collected from all four houses. All data was continuously collected at 5 min intervals.

External air temperature and relative humidity were measured using an on-site weather station. Gas meters were used to measure the fuel, however, sub meters were not used to differentiate between the energy used for space heating and hot water heating separately. A detailed explanation of the measurement methodology for the UK houses is provided in [58].

Table 11. Comparison of simulated and measured annual energy consumption of case study houses

		UK_H1	**UK_H2**	**UK_H3**	**UK_H4**	**AU_H1**	**AU_H2**	**AU_H3**	**AU_H4**
Heating (kWh/m^2/yr)	Simulated	27.71[a]	32.78[a]	30.39[a]	28.87[a]	7.61[b]	48.89[b]	23.72[b]	5.06[b]
	Actual	49.98[a]	23.88[a]	22.88[a]	35.78[a]	No	2.63[d] (11.52)	11.64[d] (52.38)	0
Cooling load (kWh/m^2/yr)	Simulated	No[a]	No[a]	No[a]	No[a]	10.97[b]	2.64[b]	3.83[b]	12.39[b]
	Actual	No	No	No	No	No	3.84[d] (17.13)	No	0
Water heating (kWh/pp/yr)	Simulated	1121.8	770.1	738	854	NA	NA	NA	NA
	Actual	976	2439	1131	1028.6	NA	1396	1106	421
PV generation (kWh/yr)	Simulated	862	862	862	862	No PV	1370[c]	1411[c]	1666[c]
PV generation (kWh/kW$_p$/yr)	Actual	940	927.5	953.5	860.6	No PV	908	1466	1066

NA = Not Available

[a] SAP calculates cooling loads but only heating loads are used in the rating. As none of the UK homes had space cooling appliances, the very small simulated cooling load was ignored. These loads are presented as electrical loads, taking into consideration the type and efficiency of the space heating equipment to be installed.

[b] Although NATHERS calculates both heating and cooling loads (Total in MJ/m^2), which is then area adjusted used for regulatory purposes (*refer to section 2.1.5*), the values quoted here show area-unadjusted thermal energy in kWh/m^2.

[c] NatHERS does not simulate PV generation. AU figures provided here are expected PV output based on solar radiation and assumed installation practices (e.g. orientation, tilt etc)

[d] These figures are measured electrical energy, whereas NatHERS simulations are thermal energy. The figures in brackets convert the measured electrical energy into equivalent thermal energy, taking into account the COP / EER of the heating / cooling appliances.

The simulated heating loads (presented as electrical loads) for the UK houses are similar. UK_H1 and UK_H4 though being end terraced, have lower simulated heating demands per square meter of their total floor area as compared with the mid terraced ones (i.e. UK_H2 and UK_H3), believed to be due to combined effects of different characteristics of the houses. For example, there are differences in the ratios of total external envelope area (external walls, doors and windows, roof and ground floor) to total floor areas. The corresponding ratios are 2.39, 2.95, 3.07 and 2.22 for houses 1, 2, 3 and 4 respectively. Another factor contributing to the variations in calculated heating loads is the differences in the solar gain potentials. In the month of January for example, the estimated solar gains are of the order of 147.48W, 77.89W, 72.59W and 103.65W in UK houses 1, 2, 3 and 4 respectively.

The simulated heating and cooling loads of the AU houses (presented as thermal loads) differ as expected, given the different climate zones. AU_H2 and AU_H3 are in heating dominated climates (look at the difference between heating and cooling load), while AU_H1 and AU_H4 have a cooling demand that is slightly higher than the heating demand. Refer to section 3.2 for further comparison of the impact of climate.

Figure 3 shows the simulated and actual electrical heating and cooling loads of the eight houses. The simulated thermal loads of the AU houses have been converted to electrical loads using an assumed COP of 3.5 for heating and EER of 3.3 for cooling. These are considered typical conversion efficiencies for reverse-cycle air conditioners in Australia and were used by Goldsworthy for simulation of Australian heating and cooling loads [59]. Comparison of all eight houses show five of the houses (UK_H2, UK_H3, AU_H1, AU_H2, AU_H4) used less space heating energy than simulated. The actual heating loads of UK_H1 and UK_H4 were 180% and 124% of the simulated demands respectively, while UK_H2 and UK_H3 used 73% and 75% respectively of simulated demands. AU_H1 and AU_H4 used no mechanical space heating. AU_H2 and AU_H3 measured heating electrical energy use were 19% and 172% of their respective simulated heating demands. The discrepancy for AU_H2 is attributed to this house's context (rural environment where wood heaters are permitted) and heating technology (a high efficiency wood heater using timber sourced on site is used by the occupants in preference to the reverse-cycle air conditioner). Neither the heating technology nor the energy source (onsite renewable biomass) are options for the simulation software or for urban environments. There is a large discrepancy between the simulated and actual heating load of AU_H3, despite the COP of the installed heat pump being considerably better than the assumed COP used in converting thermal load to electrical load (i.e. COP 4.5 actual compared to COP3.5 assumed). The performance discrepancy is partly due to this family's indoor temperature preferences compared to simulation tool assumptions (refer to Figure 6 and Figure 7 and Table 2). The occupants sought to mitigate the carbon emissions impacts of their thermal comfort preferences by scheduling the heating system to only operate during solar hours (hence potentially maximising renewable energy utilisation for space heating).

Only one house (AU_H2) used space cooling, even though all AU houses had a simulated (though small) thermal cooling load. AU_H1 did not have any fixed heating/cooling appliances installed and AU_H4 had not utilised the reverse cycle air-conditioner that was installed. The measured cooling load of AU_H2 was 480% of the simulated load (though both the simulated load and actual load are quite small). Despite this, the total measured space heating and cooling load for this house was only 55% of the total simulated load. With the exception of AU_H3, the Australian homes had significantly less measured space heating and cooling loads than the simulated ones. A potential reason is that these occupants tolerated a wider range of temperatures than those assumed by the adaptive comfort model (refer to Fig 6). Some other contributing factors are the tendency of Australians to heat or cool specific rooms for short periods of time, rather than all conditioned spaces all the time [59], and the 'under occupation' of Australian homes (e.g. more bedrooms than occupants). AU_H3, in contrast to other AU houses, had a thermal load more than double the simulated load. Some potential reasons for this high actual load are: the number of occupants (no unoccupied bedrooms in AH_H3), a centralised heating system (hydronic floor heating from a heat pump system) and a narrow indoor temperature band (refer to Figure 6 and Figure 7).

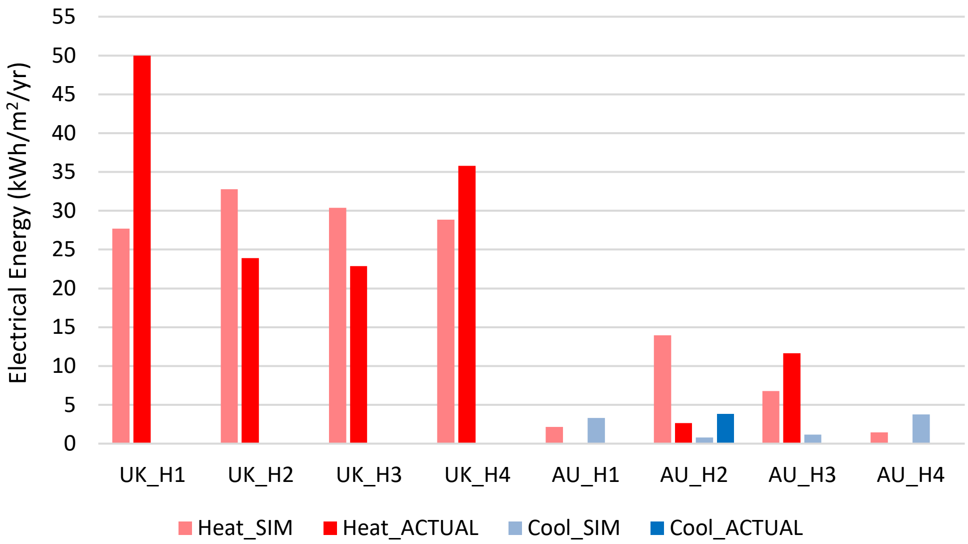

Figure 3. Comparison of simulated and actual space heating and cooling (electrical) energy

The estimated hot water demands for the UK houses are also shown in Table 11, revealing that UK_H2 consumed significantly more hot water than the three neighbouring properties. The actual hot water energy consumption in the AU houses also varied widely, for example, AU_H2 consumed 1396 (kWh/pp/yr), which is 3.3 times more than AU_H4. The climate could be a contributing factor to this discrepancy (refer to Table 8) between two houses with the same occupancy (2 adults). AU_H2 is in the coldest of the four Australian climates, has the highest number of heating degree days (HDD) and conceivably would have a lower cold water inlet temperature compared to other locations. This was seen for 12 monitored water heater systems scattered across Adelaide, by Whaley et al. (2014) [60], where the average monthly cold water inlet temperature varied by as much as 7°C for each month, when compared to those assumed by Australian Standards used to predict heated water system energy consumption. Interestingly SAP takes into consideration, from a national perspective, variations in cold water temperatures (SAP 2012 Table R1) and assumes a 'standard' 125 l/pp/day.

NatHERS does not consider water heating, although water efficiency and the efficiency of water heating are included in other sections of Australia's NCC. Occupant water usage patterns are also implicated, for example, AU_H2 – a 2 person household – uses more hot water than AU_H3 – a 5 person household. Possible explanations for the wide variation in hot water consumption figures across all eight houses include: occupants' personal bathing habits (e.g. frequency of washing; preference for showers or baths; duration of shower); clothes washing frequency and habits (e.g. nappies or heavily soiled work clothes that might require higher water temperatures); plumbing fixtures (e.g. flow rate of showers) and the energy efficiency of the type of hot water service (e.g. solar, gas, electric resistive element, heat pump).

The simulated and actual electricity generated by the rooftop photovoltaic systems is also shown in Table 11. For the UK houses, actual electricity generated by PV panels varies from 860.6 ($kWh/kW_p/yr$) for UK_H4 to 953.5 ($kWh/kW_p/yr$) for UK_H3, respectively. Appendix M in SAP gives the expected output of PVs in the range of 720 – 940 $kWh/kW_p/yr$. This would indicate that these PV systems have been installed with due consideration to their orientation, tilt and possible shadowing, applicable for their climate. The approximately 10% difference in performance between the 3.5 kW$_p$ system of UK_H4 and the other systems could be attributed to a difference in the matching of the inverter to PV configuration.

Although NatHERS does not include PV generation in its simulations, Table 11 still compares the annual expected output for the AU houses. The same metric of kWh/kWp/yr is presented, and it shows that of the three AU houses fitted with a solar PV system, two appear to be underperforming, whilst the other (AU_H3) has generated slightly more solar energy than expected. The differences in normalised output of the PV systems could be attributed to several factors including: rooftop shading, the differences in irradiance levels, the inverter rating compared to PV system size, the types of inverters used (central vs. micro), cable lengths and inverter technologies. A previous study by Whaley et al. (2014) [61] showed that households with monitored solar PV systems can underperform due to shading, installation issues such as incorrect connections, blown fuses and offline systems (residents unaware of inverters that have tripped). Whaley et al. (2018) [62] also showed that almost every household with access to monitored data from their solar PV system (e.g. a smartphone app or web portal data) was unable to interact with the information to sufficiently determine if their PV system was operating at the correct level. Many householders were alerted to system issues only once bills arrived that were higher than expected, as their solar credits had vanished. This took about 12 months to notice and resulted in a large amount of missed solar energy generation. These findings are significant in light of policies promoting net zero energy buildings.

The following section examines climatic conditions and measured indoor temperatures to determine to what extent these factors may influence actual space heating and cooling loads.

3.2 INFLUENCE OF CLIMATE CONTEXT AND INTERNAL TEMPERATURE CONDITIONS

The climatic contexts of the 2 sets of houses were shown previously in Table 8 , comparing the three summer months and winter months respectively (note the different calendar months). Two standout differences are that each of the four Australian climates has a much greater temperature range in both summer and winter than the UK climate, and that the annual average ambient temperature of the Australian climates is 50 - 100% greater than that of the UK climate. Rainfall is also significantly different, with clear delineation between summer and winter rainfall (as indicated by climate classifications). The respective climates can also be compared by heating and cooling degree days (HDD and CDD) (Table 12). All five climates are heating dominated, but the Australian climates have significantly fewer heating degree days and varying ratios of HDD:CDD (3:1 AU_H1; 30:1 AU_H2; 35:1 AU_H3; 4:1 AU_H4). The UK and Australia also have differences in their approach to base temperatures (on which HDD and CDD are determined). The UK has one common base temperature (15.5°C), whereas Australia has multiple base temperatures: Australia's Bureau of Meteorology supplies data for HDD12, HDD18, CDD18 and CDD24 [63] while air-conditioning energy efficiency reports use HDD15 and CDD21. Please note that data provided in Table 12 are for comparison purposes only and the actual cooling and heating degree days might vary over the course of experiment.

Table 12. Comparison of heating degree and cooling degree days

	Annual HDD15°C[c]	Annual HDD18°C[b]	Annual CDD24°C[b]
AU_H1 (Perth)	420	911	282
AU_H2 (Ballarat)	1532	2366	77
AU_H3 (Mt Gambier)	1223	2081	65

AU_H4 (Oakey)	585	1018	253
UK[a]	2463 (HDD15.5°C)	-	213 (CDD15.5°C)

[a] UK uses 15.5°C as the base temperature for both heating and cooling. Data from www.vesma.com/ddd/std-year.htm

[b] Australia uses a range of base temperatures. HDD18 and CDD24 are the closest match to NatHERS protocols. Data from [63].

[c] Data provided for comparison purposes.

Figure 4 normalises the simulated and actual space heating demand for each house against HDD (HDD15.5 for the UK and HDD15 for AU). The normalised simulated heating load immediately highlights great disparity across the AU houses, reflecting NatHERS differentiation between climates and its attempt to not disadvantage the construction costs of houses in more severe climates compared to more moderate climates.

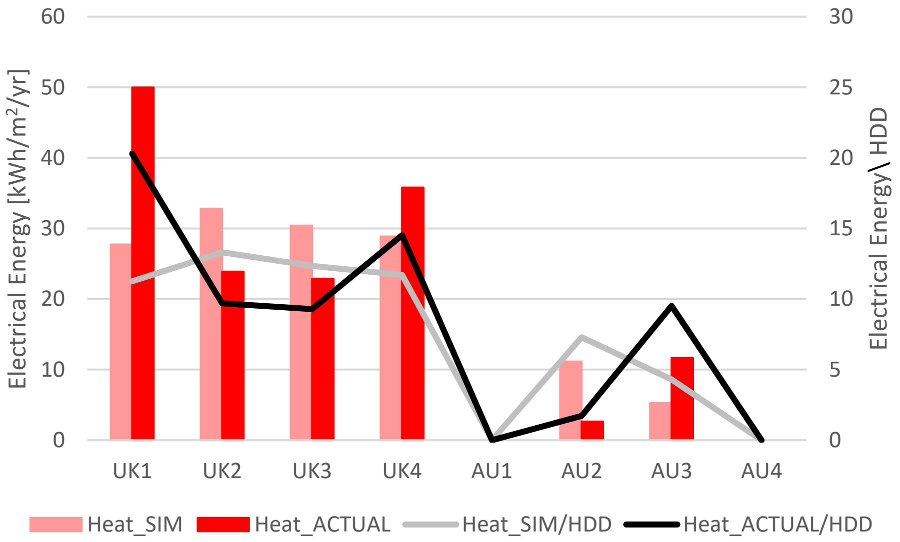

Figure 4. Heating load normalised to HDD

A comparison of space heating and cooling demand (simulated or actual) is somewhat meaningless without knowing the internal conditions of the respective houses. Figure 5 shows the actual and predicted monthly average external temperatures and the Mean Internal Temperatures (MIT) in the living rooms of the UK houses. As can be seen, the internal air temperatures predicted by SAP are close to each other in different houses without sharp lows and peaks. This is due to normalised patterns such as occupancy patterns used in the calculation method. As shown, the mean internal temperatures are higher during June to September with the peaks in July, which are consistent with the SAP calculations, showing that no heating is required during this period. There are also two significant drops in the MIT profiles for UK_H1 and UK_H3, which are related to the fact that House 1 during January and February 2013 and House 3 during December 2013, January and February 2014 were partially vacant, and therefore the heating systems were switched off (or not utilised). In addition, the external air temperature used in SAP is smoother than the measured temperatures. The reason is that SAP uses typical meteorological year (TMY) weather data which represents typical rather than extreme (worst-case) conditions.

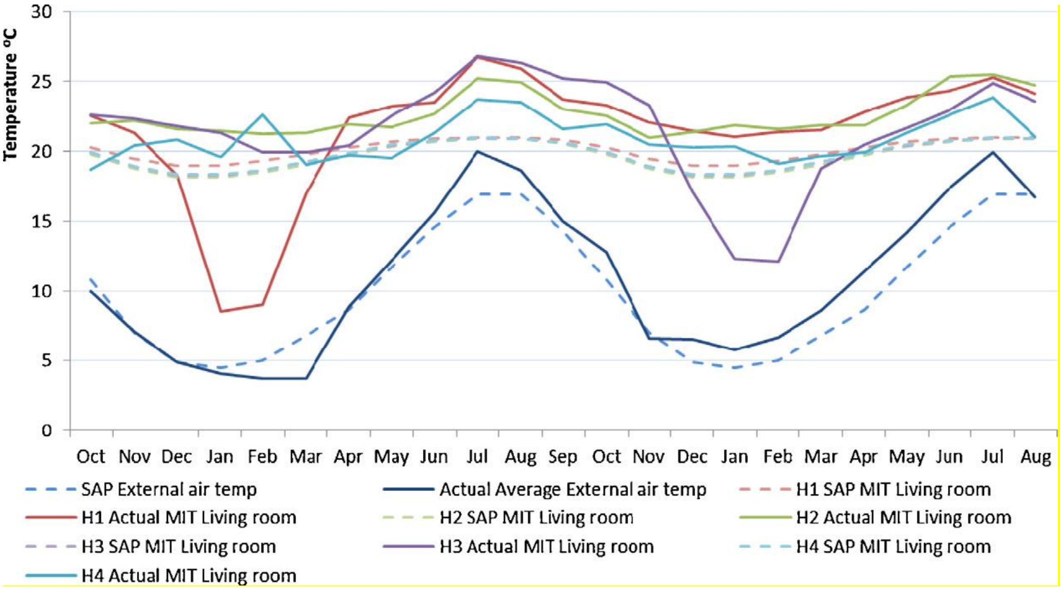

Figure 5. Comparison of Actual T_{IN}, predicted T_{IN} and T_{EXT} in UK_H1-4 [31]

Figure 6 shows the measured average external temperature (as recorded at the nearest Bureau of Meteorology station) and average internal temperature (as measured in the living room) for the AU houses. While it is well known that there can be large discrepancies between climatic conditions recorded at meteorological stations compared with the microclimate of a specific building, simulation software uses weather station data to predict the internal temperatures of houses in order to calculate thermal loads. For this reason, weather station data, rather than site date, is used in this graph. The internal temperatures discussed below could be considered in the context of the thermostat settings assumed by the respective building codes (Table 2). Despite some missing data, Figure 6 shows that AU_H1 and AU_H4, with no space heating or cooling appliances, have a broader indoor temperature range than the other two AU houses. Occupants of all four houses report satisfaction with their indoor thermal environment. There was no correlation between indoor mean temperature and demographics, as AU_H2 and AU_H4 have the same occupancy profile and similar age demographic, as do AU_H1 and AU_H3. Comparison between Figure 5 and Figure 6 show that three houses: UK_H1, UK_H3 and AU_H1 (for AU_H1 only data in December are available) had summer mean internal temperatures >25°C, however, overall mean internal temperatures were in the range of 18-26°C (excluding a data anomaly for AU_H4 in February).

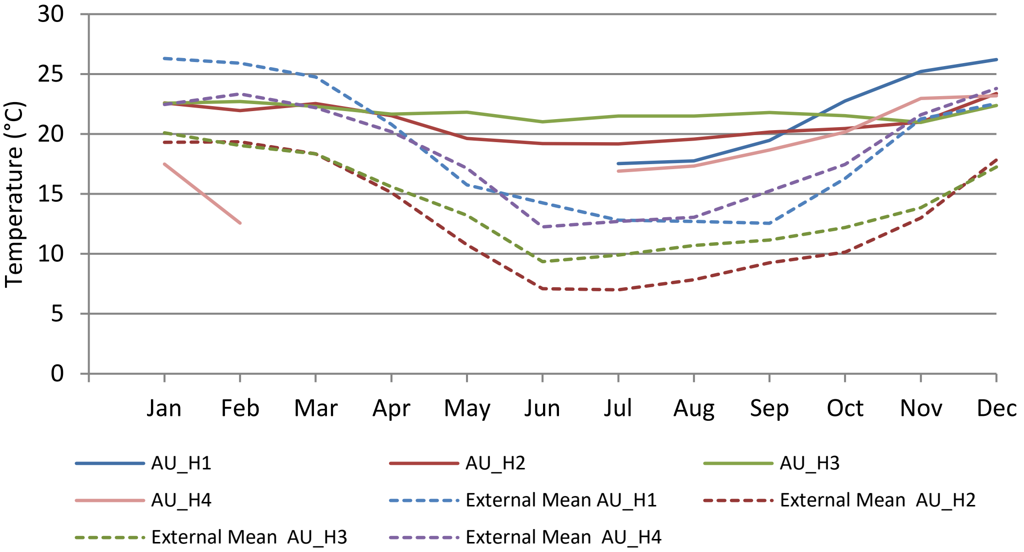

Figure 6. Comparison of actual T_{IN} (Living Room) and T_{EXT} in AU_H1-4

Figure 7 gives an example of the correlation between mean internal and external temperature and actual space heating and cooling load for AU_H3. The measured outdoor mean temperature for winter (June – Aug) was 9.98°C, compared to the long term winter mean of 9.6°C. Peak heating energy use was in August, accounting for 25% of annual heating demand. The heating system (hydronic floor heating) was utilised to varying degrees from May through to September inclusive (5 months). This heating regime differs from the UK houses which were expected to require heating for 8 months of the year. No heating (or cooling) was used October – April inclusive. Summer comfort levels were achieved with no mechanical assistance, with 100% of summer hours within the temperature zone expected by the adaptive comfort model in NatHERS. Note the small variation in internal temperatures, a reflection of occupants' preferences, as discussed previously. The 'baseline' energy consumption from the heat pump is due to the nature of heat pumps, requiring some continuous energy for lubrication purposes.

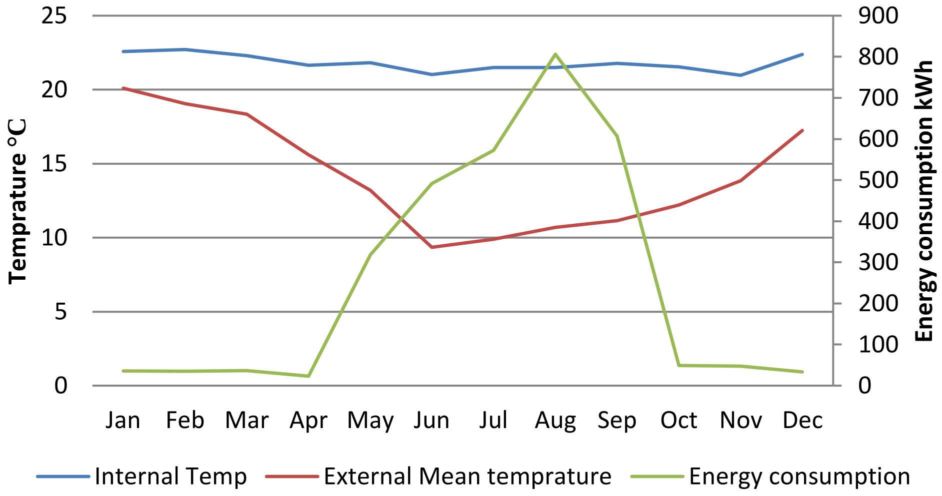

Figure 7. Comparison of T_{IN}, T_{OUT} and heating load in AU_H3

NatHERS simulations for each of the Australian houses predicted that some cooling energy would be required (to varying degrees), however, Table 11 shows that three of the houses did not use any cooling energy. AU_4, for example, had a very high level of 'natural comfort' in summer without mechanical cooling: 100% of the time for the main bedroom and 98% of summer for the living room. This is despite this climate having the second highest CDD24 (refer to Table 12). The summer internal temperatures (living room and main bedroom) in AU_1 (with the highest CDD24) were within NatHERS adaptive comfort design parameters (18-28°C) for 77% and 68% of the time respectively, yet the occupants reported that their house was very comfortable and did not require air-conditioning. This indicates that a portion of the measured performance gap (lower than predicted) is attributable to occupant preferences for temperatures outside of those considered by the rating regimes. This is consistent with the adaptive comfort approach as discussed previously and with the multiple ways in which people perceive thermal comfort and can take action to achieve it [25, 26, 64].

3.3 COMPARISON OF HOUSE FORMS AND URBAN ENVIRONMENT

The form, size and design intent of the UK and AU case study homes are shown in Table 4 and Table 5 and Figure 1 and Figure 2. Australian homes are much larger in floor area (3-4 times) and volume (4-5 times) than those in the UK. The ceiling heights of these modern Australian homes are also greater than their UK counterparts, reflecting modern Australian housing regulatory and market trends for higher ceilings as a means of enabling greater daylight penetration and for summer heat management (e.g. safe operation of ceiling fans and allowing stratification of hot air above the occupied zone). UK_H1 and UK_H4, being on either end of the row house structure, would have a higher exposure to the external environment than their neighbours, although this has not affected their simulated heating demands due to differences in the ratios of total external envelope area to total floor area (refer to 3.1).

Building specifications that impact on the envelope thermal efficiency also vary between the houses. Although all homes were constructed utilising SIPs panels, the wall and roof *U*-values of the product used in the Australian homes were approximately twice those of the product used in the UK homes (refer to Table 6 and Table 7). The window *U*-values showed the greatest performance difference, however, with the Australian glazing 2 – 6 times the *U*-values of the UK glazing. On the other hand, however, NatHERS does take into account another attribute of glazing – the solar heat gain coefficient (SHGC) - in recognition of the importance of this indicator in limiting incoming solar radiation in summer. The ratio of window to floor area also varied (18-26% in UK houses and 12 – 35% in AU houses). Australia doesn't set any limits to window area, but England and Wales set an upper limit of 25%. No correlation was found between measured space heating and cooling energy and the window to floor area ratio in the Australian houses, indicating that the impact of other factors is likely more dominant than window to floor ratio. For example, AU_H3, with the lowest ratio (11.8%) was the only AU house that had a measured space heating and cooling consumption higher than simulated. AU_H2 with the highest ratio (35%), had a measured thermal load approximately half that of the simulated load. Both houses had double glazing, although the technical specifications for glazing for AU-H3 were much higher (Table 7).

An additional difference between the built form in the UK and AU was in the ground floor: two of the AU houses had uninsulated cement slabs. While this is common construction practice in Australia and is arguably acceptable in warm climate zones, one could question the adequacy of this practice in colder climate zones (e.g. for AU_H2), especially if the goal is for high energy efficiency and thermal comfort. A further point of difference between these UK and AU houses is their physical context, as briefly described in Table 4 and Table 5 AU_H2 is the 'odd one out', being constructed on an exposed hilltop in a rural setting. The other AU houses are in typical Australian suburban settings, perhaps best described as medium density, while the UK houses could be considered to be in a dense urban environment. The urban context of houses could be an additional influencing factor on thermal performance, as density can restrict air flow and solar radiation, and can also increase urban albedo. None of these factors are included in SAP assessments. NatHERS does take into account the 'terrain exposure', as it impacts on air flow and wind speed. Assessors are also meant to input data relating to overshadowing (i.e. nearby obstacles, such as fences, that could impact on solar access). Neither national protocol accounts for urban albedo or reduced air movement related to urban density.

3.4 CONSTRUCTION QUALITY

The case study homes were compared for construction quality – in particular air and thermal leakage – as these are known to impact on actual space heating and cooling consumption. The results shown in Table 13 are for the air leakage tests (i.e. pressurisation / depressurisation tests) carried out before any of the houses was handed over to the respective client. The UK homes were all below the design value of 3 $m^3/h\ m^2$ and well below the England/Wales default air permeability rate of 5 $m^3/h\ m^2$ as specified in SAP. Two of the Australian homes would also meet the UK design value, while the remaining two would meet the England/Wales default rate. It is worth noting that while Australia's NCC has set conditions for restricting air infiltration from external windows and doors, no air tightness requirements have been specified for a dwelling [65]. Testing by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) suggests that new homes are quite leaky, with an average of 15 air changes per house (ACH_{50})[45]. Consideration is currently being given for the 2019 NCC to mandate a maximum of 10ACH. It is also worth noting that the infiltration rates used by NatHERS accredited software AccuRate are based on hourly wind speeds (from the climate files), building height (to modify the wind speed) and terrain category (exposed, open, suburban and urban) – which incorporates the stack infiltration factor and wind infiltration factor. A detailed explanation can be found in [66]. This is different to SAP which uses monthly mean wind speed and did not account for the effects of elevation until recently. Another difference is that SAP assumes a certain number of extract fans based on total floor area (2 for up to $70m^2$; 3 for 70 - $100m^2$ and 4 for $>100m^2$) whereas NatHERS requires assessors to enter the actual number of extraction fans (e.g. one in each wet area and one above the kitchen stove). Australian assessors also need to stipulate whether extraction ducts are permanently open or are closable.

Table 13. Air tightness test results (permeability) for all case study houses

Permeability at 50 Pa	UK_H1	UK_H2	UK_H3	UK_H4	AU_H1	AU_H2	AU_H3	AU_H5
$m^3/h\ m^2$	2.97	2.99	2.96	2.92	4.06	2.65	2.38	4.79

A thermographic survey was also conducted in accordance with the simplified testing requirements of BS EN 13187:1998 (for the UK homes) and ASTM E1186-03 (for AU homes). The key findings for each set of homes are shown in Table 14. Both sets of houses displayed evidence of possible thermal bridges at floor/wall junctions and openings and the Australian houses showed thermal bridges at the wall/roof junctions. Thermal breaks were also observed in three of the Australian houses (1, 2 and 4) – predominantly as air leaks from the window or door frames. The thermal bridging in the Australian homes can be explained by the construction method of these steel skinned SIPS, as explained in detail in [67]. From a regulatory perspective, SAP includes a protocol and calculation methodologies for determining linear thermal transmittances, with a default value of Ψ = 0.05 W/m^{2}K. NatHERS does not provide any information about calculating thermal transmittance, nor does accredited software reveal what default levels are assumed.

Table 14. Key findings of thermographic surveys

	Common thermal issues
UK houses	Possible thermal bridges: rendered sections of walling between SIPs at floor junction; Ground floor / external wall junction; openings
AU houses	Thermal bridges: wall-roof junction; wall-floor junction; window and door frames (non-thermally broken aluminium) Thermal Breaks: openings (i.e. air leaks from window and door frames)

4 CONCLUSION

This study evaluated the performance of eight newly constructed single-family homes in the United Kingdom and Australia. The objectives of the study were to determine whether performance gaps existed and to compare and evaluate influencing factors that could account for differences in consumption as well as differences in performance gaps between households and between the two countries. Accordingly, the performance gaps between 'as designed' and 'as operated' for eight houses were measured. Results showed that the performance gap exist in all case study houses, however, the performance gap can be negative (houses use more energy than simulated) or positive (houses use less energy than simulated). Results for the heating loads showed positive performance gaps in 5 of the 8 houses (2 UK and 3 AU), and the heating discrepancies ranged from 73% to 180% for the UK houses, and 19% to 172% for the AU houses. For the cooling loads, only one house (AU) had a negative performance gap in which the actual cooling load was 4.8 times higher than the simulated. It was also observed that despite the fact that cooling load was predicted for all AU houses, not all houses had actual cooling loads, and the post occupancy evaluation showed that occupants are satisfied with their indoor thermal environment, indicating that the performance gap is partly related to the fact that occupants can tolerate a wider range of indoor conditions than those considered by the NatHERS tool.

A comparison of the rating tools showed that both national rating systems are very engineering and technology focused in both inputs and outputs. While same construction and energy efficiency characteristics have been used in the UK houses (and fairly similar construction in the AU houses), significant actual energy differences were observed between dwellings. This highlights the impact of occupants' behaviour, and their lifestyle on the dwellings' energy consumption. If rating certificates are to be used as an indicator for national moves towards more energy efficient housing, these results suggest that more attention should be given to POE in buildings to better quantify the socio-cultural indicators, and hence the assumptions written into the rating tools. If POE takes places widely, data can be employed to reduce the uncertainties associated with occupants' behaviour in the inputs of building simulation tools. The information can be also used as a learning loop to provide designers and regulators with valuable feedback on lessons learnt to guide them to the better design of future buildings, and the better design of rating tools and regulations.

This comparative study has shown a range of factors that may contribute to actual energy consumption and hence the effectiveness and usefulness of SAP and NatHERS. Issues covered in this comparison include: (i) socio-demographic characteristics (family typologies, demographics, home and zone occupancy patterns); (ii) approaches to thermal comfort (e.g. static or adaptive; whole house or zonal conditioning; continuous or periodic conditioning; with or without occupant action to modify environment); (iii) building form / housing typology (e.g. area, volume, glazing area; detached or semi-attached); and (iv) construction industry (e.g. construction method and quality). The continued use of historical climate files and 'average conditions' is also problematic, given that occupants experience actual weather, with all of its extremes and dynamic changes, and that the buildings are influencing occupant comfort in the present and into the future (not in the past). A recent report also highlighted the problem of building regulations around the world using historic weather files [68]. Moreover, collections of buildings impact on the climatic conditions (e.g. urban heat island effect and changes to wind speed and ventilation) and on occupant options for managing their indoor environment (e.g. pollution, noise, security etc). Neither SAP nor NatHERS take these issues into account.

There is no doubt that national rating protocols such as SAP and NatHERS serve a useful purpose, however this study demonstrates that substantial performance gaps exist between the actual and simulated energy demands and therefore suggests that their usefulness could be further enhanced by revisiting both technical and socio-cultural-technical assumptions on which the protocols are based, to ensure they are evidence based and relevant to the contexts to which they are applied. The findings support Shove's premise [69] that we need to understand, and re-think, the way we define energy efficiency, establish energy efficiency objectives, and establish its temporal and spatial boundaries.

Lastly, there was no evidence from either SAP or NatHERS that the data collected by these processes for individual dwellings was being utilised more broadly, such as contributing to the development of tools, processes or frameworks for understanding broader urban metabolism or planning precinct or city scale infrastructure. It would appear that these national 'datasets' have, to date, been severely underestimated and hence underutilised.

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