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ARTICLE

Towards global benchmarking for sustainable homes: an international comparison of the energy performance of housing

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Abstract Over the past 15 years, house building standards across the western world have begun to address ecologically sustainable development (ESD) principles. Amongst the range of environmental sustainability issues arising from housing construction and occupation, the energy demand for heating and/or cooling to maintain thermal comfort has the longest history and is most widespread in policy and regulation. Since energy in our homes is mainly fossil-derived, a key issue is global climate change impacts. Since greenhouse gas emissions can be emitted in various locations across the globe with similar results, it follows that a given greenhouse gas emission arising from residential space heating and cooling has approximately equal impact, irrespective of the location of the building. These emissions are therefore an appropriate candidate for benchmarking internationally, yet there have been few attempts to undertake this activity.

This paper reports on a study undertaken in Australia which compares the thermal energy performance of housing in the United States, Canada, UK and Australia. The comparison is based on energy ratings of over 50 house designs from the comparison countries. Each design was assessed as being current and verified as complying with rather than significantly exceeding local regulatory requirements. Issues in design of both the buildings and the modelling tool used are highlighted, and the results are presented. Conclusions are drawn on the reasons for wide variations in thermal energy performance, the implications for benchmarking, and the case for globally consistent housing environmental performance policies and regulation.

Keywords Sustainability · Energy · Benchmarking · Housing

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1 Introduction

Global climate change and the need to reduce greenhouse gas emissions necessitates decisive and timely action to improve the energy efficiency and performance of housing, as these are currently a significant source of greenhouse gas emissions. Since the Bruntland Report in 1987, sustainable development has become enshrined within policy processes at all levels, and global benchmarks are now increasingly needed to enable a meaningful collective response to climate change. The sustainable housing challenge is to reduce resource inputs (such as energy, water and materials) and waste outputs while simultaneously improving liveability of citizens (Newman and Kenworthy 1999). Recent efforts to achieve this date back to the development and application of ecologically sustainable development (ESD) principles, which gained ground during the 1990s, with a range of 'ecohome' demonstration projects (for example, Low et al. 2005).

Mandatory minimum levels of thermal energy performance for new residential buildings have been rapidly developed, although these are generally limited and are locally based. A variety of performance rating tools exist (for example, USGBC 2007; Green Globes 2007; DCLG 2006; HSP 2007) and their scope, scale, weighting approaches, use and prospects have been reviewed elsewhere (for example, Horne et al. 2005; Cole et al. 2005; Gowri 2005). An emerging set of tools aims to model total life cycle environmental sustainability performance (for example, Zhang et al. 2006). Within the wider framework of housing sustainability performance, thermal energy performance is invariably significant, and the relative contribution of this to greenhouse gas emissions warrants a focus around the comparative thermal energy performance of housing internationally.

Notwithstanding the plethora of rating and modelling tools now available, including international collaborative initiatives (IISBE 2007), there have been few documented attempts to compare or benchmark housing thermal energy performance internationally. A recent study achieves a European scale for comparison (Balaras et al. 2007), and there are various regional reviews where housing performance in Europe is reported, but the authors are aware of no studies where northern hemisphere housing thermal energy performance has been compared with requirements in the southern hemisphere.

2 Aims and objectives

This paper reports a study undertaken to compare the modelled thermal energy performance of housing in the USA, Canada, UK and Australia. The main locations used were in the US and Australia, where a wide range of climate zones exist. The study was undertaken in the context of changes to the Building Code of Australia's energy efficiency provisions to mandate minimum performance for all building classes. These changes were implemented in 2006, and included a minimum '5-star' standard for modelled space heating and cooling demand (on a 1–10 star rating scale under BCA Verification Method V2.6.2.1).

The aim of this study was to compare housing thermal energy performance in order to benchmark 'standard' volume built housing internationally, and to test the relative stringency of the 5-star standard. In order to achieve this aim, it was necessary to:

- Establish representative climate zone locations for international comparisons;
- Compare the building code requirements at each location with each Australian location;

- Select and obtain samples of standard house designs (which just meet codes) for each location and model the thermal energy performance of each design using appropriate modelling (rating) software.

The methods used to achieve these objectives, and the results obtained, are described in the following Sects. 3–5, respectively. The comparison results are discussed in Sect. 6 and conclusions are drawn in Sect. 7.

3 Climate mapping

As the host country for the study, Australia was taken as the starting point for the climate mapping exercise. There are eight Building Code of Australia (BCA) climate zones, spanning a wide range of temperature, humidity and precipitation regimes with various diurnal and seasonal patterns. These are arranged according to local geographic, topographic, latitudinal and meteorological factors and their specific geographic spread is indicated in Fig. 1. The following list indicates the general climatic characteristics of each zone, and the one representative city from each, chosen as the reference locations for the study:

(1) Tropical: Hot humid summers, warm winters: Darwin
(2) Tropical: Warm humid summers, mild winters: Brisbane
(3) Tropical: Warm humid summers, mild winters: Longreach
(4) Temperate: Hot dry summer, cold winter: Dubbo
(5) Temperate: Warm summer, cool winter: Perth
(6) Cool: Warm summer, cold winter: Melbourne
(7) Cool: Mild summer, cold winter: Hobart
(8) Cool: Mild summer, alpine winter: Thredbo

This meteorological data was then compared with equivalent data relating to overseas locations in the USA, Canada and the UK. The USA provided the largest range of climates which could be broadly compared to the BCA zones (Fig. 2). Specific meteorological data from US cities led to the selection of comparison cities for the study. As indicated in Table 1, each Australian reference city was then mapped across to a corresponding location in the US, the UK and/or Canada, using this meteorological data. In Canada and the UK only the cooler climate zones are represented. Hence, single Canada and UK locations were used as a means to test the robustness of the results, by undertaking a relatively larger sample comparison for one climate zone (7). As shown in Table 1, these were Vancouver and Exeter, respectively.

4 'Deemed to satisfy' comparisons

Deemed to satisfy (DTS) provisions include prescriptive building element performance criteria, and provide an alternative means for energy performance compliance without the need for modelling. DTS requirements vary with climate conditions, since in harsher climates higher performance is essential to help maintain comfort. They also vary between countries across similar climates, due to variations in the stringency of energy efficiency requirements. DTS comparisons were drawn between all localities to indicate any differences in existing housing performance requirements using this compliance option. To

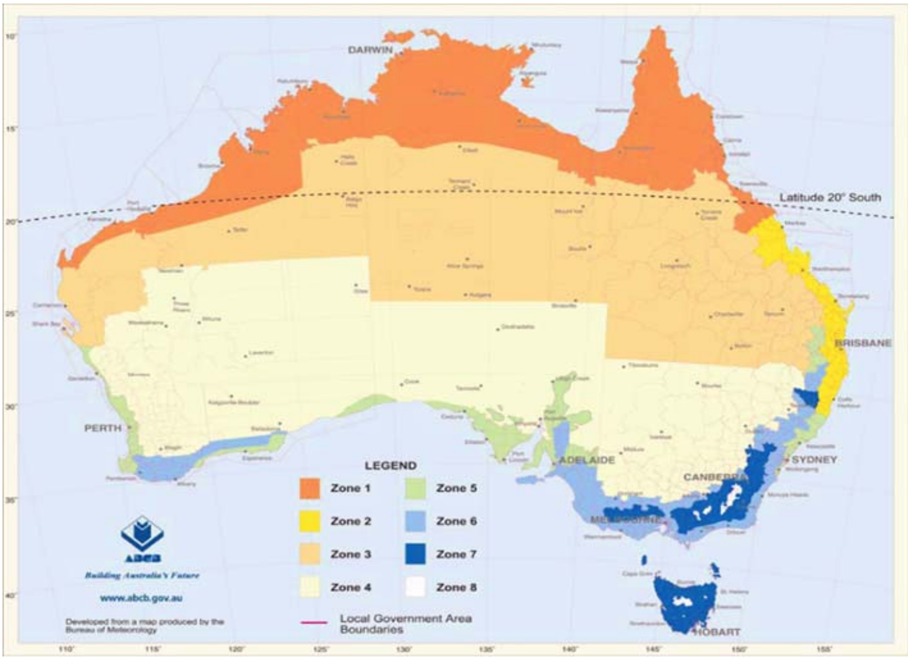

Fig. 1 The eight climatic zones of Australia from the building code of Australia

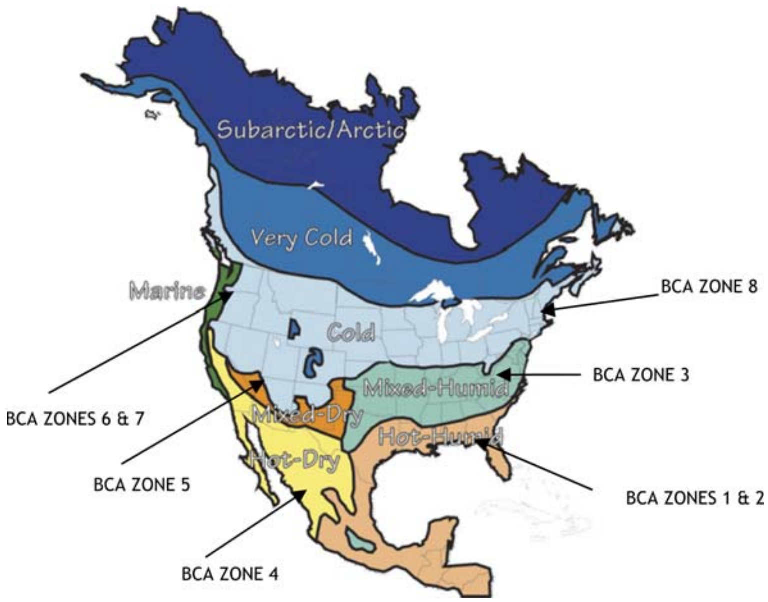

Fig. 2 USA climate zones and nearest equivalent building code of Australia (BCA) Australian Zones

provide a quantitative comparison, performance requirements of building elements in the various codes were converted into similar units, namely common *R*-Values, which measure the resistivity or capacity of a material to resist the transmission of heat.

Table 1 Australian cities, comparison countries and representative locales

Australian BCA zone	Australian city	General descriptor	Comparison country	Representative locale
Zone 1	Darwin	Hot humid	USA	Florida
Zone 2	Brisbane	Hot humid	USA	Texas
Zone 3	Longreach	Mixed-humid	USA	Charlotte, North Carolina
Zone 4	Dubbo	Hot-dry	USA	Phoenix, Arizona
Zone 5	Perth	Mixed dry	USA	Roseville, Bakersfield, CA
Zone 6	Melbourne	Marine	USA	Los Angeles, San Francisco Bay, CA
Zone 7	Hobart	Mild summer, cold winter	Canada UK	Vancouver, BC Exeter, Devon
Zone 8	Thredbo	Cold	USA	Boston, Massachusetts and Pennsylvania

4.1 DTS—USA

The US national model energy code (MEC), established by the Energy Policy Act of 1992, served as a baseline for state energy codes. This was superseded by the International Energy Conservation Code (IECC) in 1998, which has since gone through a number of reiterations (1998, 2000, 2003, 2004, and 2006—the latter being brought in after this study was completed). However, compliance is not mandatory, so some states do not use the code, and there are many local variations. The IECC establishes minimum thermal performance standards for ceilings, walls, floors and windows. It also sets criteria regarding air leakage, ducts and pipes insulation, duct seals, and domestic hot water heating system controls. Minimum building envelope thermal requirements vary according to climate zone; hence, for example, insulation requirements in southern climates are less stringent than in the northern climates. In this study, reference was made to various code requirements in each of the comparison locales listed in Table 1. These included: the Florida building code information systems (FDCA 2007); the model energy code and a recommended programme for North Carolina's state energy code (NCSL 1997; Hadley and Smith 2000); Arizona's state energy code (ADC 2007); California's energy code and energy commission website (CBSC 2005; CEC 2007); and the Massachusetts energy conservation code for new residential low-rise buildings (Massachusetts State 1998)

4.2 DTS—Canada

Buildings in Canada are regulated by a variety of codes, standards, bylaws, regulations and acts which can vary from province to province and from municipality to municipality. Building regulation is the responsibility of provincial governments, who in turn can delegate this power to their municipalities. The federal government, however, can also become involved in building regulations, and minimum residential standards are set for housing constructed under the National Housing Act. The Canada Mortgage and Housing Corporation (CMHC), who administers the Act, uses the standards to help achieve its objective of improved housing.

4.3 DTS—UK

Three methods are available to demonstrate compliance with UK Building Regulations: the Elemental Method, the Target *U*-value Method and the Carbon Index Method. The

Elemental Method in England and Wales utilises look-up tables that specify the acceptable fuel source and efficiency of the heating system, the maximum allowable *U*-values of the building elements, and the requirement that total areas of windows, doors and roof lights must not be greater than 25% of the total floor area (The Stationery Office 2001). The main performance requirements concern insulative properties, and limiting thermal bridging and air leakage of a dwelling. Typical constructions of walls in the UK are either cavity walls with partial fill or full fill insulation or timber frame. To limit the effects of thermal bridging at junctions and around openings and also to limit air leakage, designers and architects are advised to adopt the recommendations given in the robust construction details, which give examples of design details and constructional practices that can deliver the required performances. There are also provisions for heating system specification and efficiency controls, hot water systems and lighting.

4.4 DTS—Australia

Enhanced DTS provisions from 2006 follow the original introduction of energy efficiency measures in 2003. The major areas addressed in the current DTS provisions for housing include increased thermal performance of walls, ceilings, floors, glazing including shading, in order to avoid or reduce the use of mechanical air-conditioning (heating and cooling). The provisions also include sealing of buildings to reduce energy loss through air leakage, natural ventilation and internal air movement, where appropriate, to avoid or reduce the use of mechanical air-conditioning.

5 Thermal energy performance modelling

A total of 51 house designs were obtained from major house builders in the USA, Canada and the UK. The sample size and range of key variables (size, dwelling type, climate setting, and construction type) were selected in order to ensure a broad range of conditions across the volume house builder market they represented. The sample was not designed to be representative of the proportions of dwelling types and size either in the overseas locations used or the comparative locations in Australia, since an indication of the range of ratings for ‘standard’ volume-built homes was the primary aim of the study. However, an attempt was made to select a split of housing types broadly representative of expected future residential building types in Australia. A total of 20 detached dwellings were selected, with 17 semi-detached and 14 apartments, reflecting a percentage split of approximately 40, 33 and 27%. Existing stock is more dominantly detached, but given that all metropolitan areas in Australia are currently pursuing compact city/new urbanism influenced planning policies, the future new build mix is likely to be broadly represented by the sample designs chosen for the study. Construction type was dominantly lightweight timber frame with brick veneer and concrete slab on ground for the detached and semi-detached properties, with a small minority of double brick configurations, again broadly reflecting current Australian configurations.

Checks were made to verify that the designs did not significantly exceed the local code requirements. Each design was rated using the national rating software developed for use with the BCA ‘5-star’ provisions and known as AccuRate (Accredited Regulatory Version dated June 2005, provided by the Australian Greenhouse Office). Since designs were obtained from the northern hemisphere and being rated in software calibrated for southern hemisphere conditions, the orientation of each design was inverted.

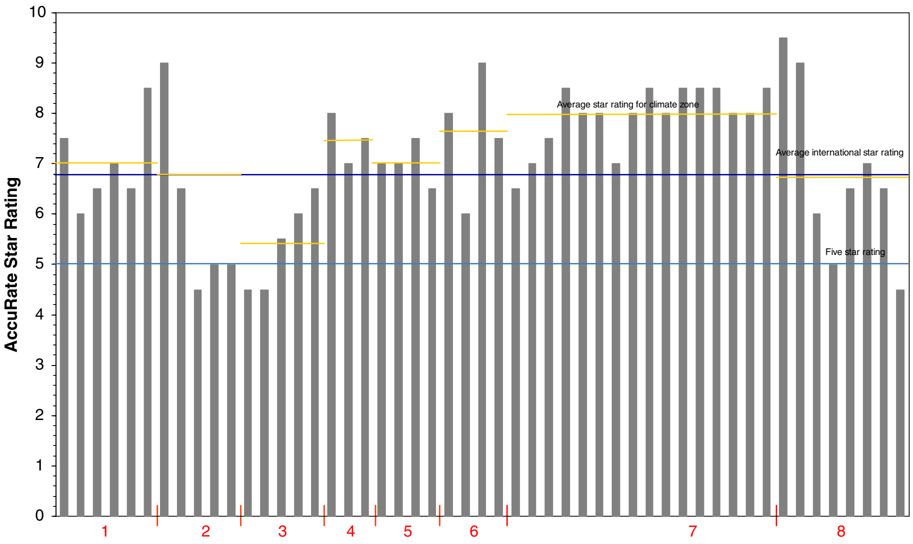

Fig. 3 AccuRate results

AccuRate is a thermal energy demand modelling software tool capable of accommodating up to 50 different thermal zones per dwelling, and includes the detailed modelling of sub-floor spaces and roof spaces, as well as modelling of attached dwellings (e.g. apartments). User-definable and modifiable factors include various natural ventilation and sky lighting scenarios, the effect of ceiling fans and window and window covering specifications. The rating achieved (0–10 stars) is based on the space heating and cooling demand in MJ/m^2 calculated from the sum of the annual heating and cooling requirements for the home divided by the conditioned floor area, and then adjusted for dwelling size. This adjustment is designed to negate the beneficial effect that the initial measure bestows on larger dwellings, arising from their smaller ratio of total surface area to floor area. A fuller discussion of the algorithms and assumptions of AccuRate is outside the scope of this paper, but is available elsewhere (for example, Delsante 2007). The software was used in rating mode, which provides some standard settings for heating and cooling requirements, as well as window covering settings.

The results are summarised in Fig. 3 and aggregated by climate zone in Table 2. They show a mean AccuRate star rating score of 6.8 across the 51 designs. This indicates that housing in the USA, Canada and UK is significantly out-performing the Australian 5-star national requirements. Only four house designs out of 51 drop below the proposed 5-star standard, and all climate zone comparison mean averages are well above it. In the majority of climate zones, the comparison country house designs perform at 7 stars or above. Within each climate zone, there are variations, although all mean climate zone comparison performance levels are above 5 stars and there is no significant pattern of performance according to warmer or cooler climates, or dry or humid climates. Generally, apartments and townhouses perform better than detached houses and the higher performing climate zones reflect comparison localities with more stringent local building codes. The only significant exceptions to this expected result occurred where selected apartments were on (originally) north facing sides of the building, and so would be expected to receive low levels of solar assistance with winter heating.

Table 2 Summary of AccuRate results by BCA climate zone

Australian equivalent climate zone	Comparison location	Total number of plans rated	AccuRate stars range	AccuRate stars median	AccuRate stars Mean
Zone 1 Darwin	Florida	6	6–8.5	6.5–7	7
Zone 2 Brisbane	Texas	5	4.5–9	5	6
Zone 3 Longreach	N. Carolina	5	4.5–6.5	5.5	5.4
Zone 4 Dubbo	Arizona	4	6.5–7.5	7	7
Zone 5 Perth	California (Bakersfield)	3	7–8	7.5	7.5
Zone 6 Melbourne	California (SF Bay)	4	6–9	7.5–8	7.6
Zone 7 Hobart	UK: Canada	16	6.5–8.5	8	7.2
Zone 8 Thredbo	Pennsylvania: Mass.	8	4.5–9.5	6.5	6.8
All Zones	–	51	4.5–9.5	7.5	6.8

6 Discussion

Referring to Table 2, there are clear performance variations between the comparison climate zones. For example, the least number of best performing designs on aggregate were found in North Carolina (equivalent to zone 3), with a mean equivalent of 5.4 stars. Each zone comparison is now examined to establish the potential explanations and implications.

6.1 Climate zone 1

The climate of Orlando, Florida is compared with that of Darwin in BCA zone 1. The results of the six Florida designs vary between an equivalent 6 and 8.5 stars using the Australian Accurate software. Two townhouses provide the highest thermal energy performance; otherwise, the results are consistent. Unsurprisingly for this climate zone, cooling demand is the dominant factor, and improvements in ventilation would make a large difference to the cooling load. Window openings are smaller than in Australian comparisons. Also, Florida appears to vary from typical US house designs in that the designs all have ground floors of heavyweight materials. The building code performance requirements of main fabric materials are generally equal or lower in Darwin than Orlando, further illustrating the difference in the comparative stringency of thermal energy performance.

6.2 Climate zone 2

The AccuRate results for the five designs from Austin, Texas vary between an equivalent 4.5 and 9 stars, the townhouse providing the best performance. In general, it would appear that Texas houses have large void spaces between the upper and lower floor, which reduces their energy performance considerably. As a result, the modelling of the designs from Texas reveal that it is one of the worst performing states, with three out of five houses equivalent to or below the Australian standard. High insulation and glazing is generally used in Texas, although the DTS comparisons show that building code performance requirements of main fabric materials are generally of the same order in Brisbane as in Austin, and this explains the modest gap in the comparative stringency of housing thermal energy performance.

6.3 Climate zone 3

The comparison locale for Longreach in Australia is Charlotte, North Carolina. Results of the modelling reveal that the five designs vary between 4.5 and 6.5 stars equivalent, providing the lowest mean star average of all the zones in the study. The house designs available for current construction in North Carolina show a broad and consistent similarity of style and build type. They are relatively very large houses, with generally more thermal mass in them than those in other states. As in the case of Florida, passive cooling would be greatly improved by better cross-flow ventilation. Some of these houses didn't have double glazing, and this, combined with the poor window shading, resulted in poor cooling performance. With regard to the comparison of DTS requirements, the building code performance requirements of roofing are lower in Longreach than Charlotte. However, glazing performance requirements are higher. Overall, there are broad similarities therefore in overall stringency of housing thermal energy performance.

6.4 Climate zone 4

The AccuRate results for Phoenix, Arizona show that all four designs that were rated outperform the Australian 5-star standard, with an equivalent 6.5–7.5 stars. Both the single and double storey version of the houses rated are relatively very large, in excess of 250 m^2. The house designs generally did not have high specification glazing (double glazing but not low-emissivity, low-E), although this did not seem to greatly affect their performance. The climate in this zone is relatively mild, so building envelope performance is not as critical as in zones 1 and 8. Nevertheless, substantial cooling requirements dominate the energy demand picture.

With regard to the comparison of DTS requirements, the building code performance requirements of main fabric materials are generally similar overall in both Phoenix and Dubbo. However, the house designs rated perform well above the 5-star standard. There are two possible explanations for this. The enhanced Australian DTS provisions do not necessarily prescribe 5-star performance, and may therefore be relatively more stringent when applied to this climate zone than others. Alternatively, although the plans have been checked for over-compliance, the major house builder who supplied the plans may use designs in Phoenix which marginally exceed the code requirements, since there are a number of code variations across Arizona and the surrounding region. Indeed, Arizona is a home rule state, and no mandatory state level energy inspection procedures exist for building construction. Despite a state-wide effort to develop consistent standards and guidelines, cities and jurisdictions still have varying code requirements.

6.5 Climate zone 5

Bakersfield, California, is the comparison locale with Perth in Australia in the study. The AccuRate results of the Bakersfield designs vary between an equivalent 7 and 8 stars. Whilst displaying similarities with the other US states, the Bakersfield designs have a higher specification than most, being closest to those from San Francisco Bay (climate zone 6), also in California. As a result of these higher performance standards, the AccuRate outcomes are consistently very high. With regard to the comparison of DTS requirements, the building code performance requirements of main fabric materials are substantially and consistently lower in Perth than in Bakersfield, further illustrating the marked difference in the comparative stringency of housing thermal energy performance.

6.6 Climate zone 6

Melbourne is compared with San Francisco Bay, California, where the four designs modelled all perform markedly better than the Australian 5-star standard, within the range 6–9 stars. All of the dwellings represented here are either townhouses or apartments, since this is the dominant design type in the San Francisco Bay area. Generally, in this study, apartments and townhouses perform better than detached houses, so this may have been a factor in the high performance of the designs rated. However, in addition, the designs consistently contain high insulation R5.5 ceilings, R2.5 walls, double glazed low-E glass in vinyl frames with small windows (although no shading to the windows). Hence, the high specification is clearly a factor in the high performance, and this is reflected in the DTS comparisons. California has much higher standards for thermal performance under its DTS requirements than Australia. The building code performance requirements of main fabric materials are therefore substantially and consistently lower in Melbourne than in San Francisco Bay.

6.7 Climate zone 7

Hobart is compared with two overseas locations: Vancouver BC, Canada, and Exeter, UK. The nine designs of the former vary between an equivalent 6.5 and 8.5 stars, and the seven latter designs show an equivalent range of 8–8.5 stars. The DTS requirements comparison revealed that the building code performance requirements of main fabric materials are substantially and consistently lower in Hobart than Vancouver and Exeter. Moreover, the Vancouver house plans used indicate relatively higher levels of roof insulation and mandatory double glazing, while the Exeter house plans showed relatively high levels of insulative performance in window frames and all major envelope elements—walls, roof and floors. Taking the plans and the DTS requirements together, it is clear that stringent code requirements have led to significantly higher performance for the Canadian and UK designs.

6.8 Climate zone 8

Six house designs from Boston, Massachusetts and two from Pennsylvania were used to compare performance with Thredbo in Australia. The designs from Pennsylvania are two apartments, which rated equivalent 9 and 9.5 stars, while the results for Massachusetts are more mixed, showing an equivalent range of 4.5–7 stars. While ceiling and floor insulation requirements are higher in Boston than Thredbo, walls and glazing performance requirements are similar or lower, which contributes to the explanation of the mixed results.

7 Conclusions

Three main conclusions can be drawn from the results outlined above. Firstly, Australian homes built to 2006 energy efficiency requirements generally achieve significantly lower thermal energy performance when compared to the international sample of modelled comparison dwellings used in the study. Within each climate zone, there are variations, and, generally, apartments and townhouses perform better than detached houses.

The typical format of lightweight construction on slab seen in current new housing in Australia is also seen in the USA. However, in order to meet generally more stringent building code requirements for building fabric (especially roofs and windows) US house designs generally incorporate more insulation and lower window areas per unit floor area. The house designs obtained from the UK and Canada indicate that in these countries, substantial houses are built to relatively higher thermal energy performance standards.

Secondly, those locations with more stringent DTS building codes and performance requirements result in the highest performing designs. For example, in California, current standards are comparatively advanced, and the two locations which provide comparisons with Australian climate zones 5 and 6, namely San Francisco Bay and Bakersfield, clearly show higher performance. This indicates that energy (and greenhouse gas) savings can be achieved by increasing building code stringency.

Thirdly, within the context of policy and regulatory development and the consequent drive to more sustainable housing, there is a *prima facia* case for establishing international consensus over housing sustainability performance and its assessment. However, there is currently a lack of international benchmarking of housing sustainability performance, and an appropriate starting point for this exercise is to benchmark modelled thermal energy performance. The study outlined above demonstrates that thermal energy performance can be benchmarked internationally. In the process, the study produces new comparative information, which can be used to inform policy and regulation in the comparison locations.

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