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An increasing resistance to increasing resistivity

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ABSTRACT
Ever since energy efficiency provisions were introduced into the National Construction Code in 2003, there have been increased requirements for energy-efficient measures with each iteration of the code, particularly around insulation. This is based on the often-repeated objective of reducing Australia's greenhouse gas emissions in the light of climate change. However, there is limited evidence whether the code achieved its stated objectives and whether these will continue to be suited to a changing climate. In fact, there is evidence that the intended and achieved goals are substantially different. This paper is a critical essay, set in the context of the Australian Building Codes Board's scoping study into "Energy efficient measures for 2022 and beyond", and makes the case that current insulation requirements are already excessive against considerations that should be made, as a higher priority, for fire safety, thermal bridging, condensation, heat stress resilience and thermal comfort.

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Energy efficiency; NatHERS; insulation; thermal comfort; climate change; natural ventilation; resilience

1. Introduction

In 2000 the Australian Building Codes Board (ABCB) first announced its intentions to mandate minimum energy efficiency requirements through the National Construction Code (NCC). Energy efficiency provisions were subsequently mandated in 2003 for houses, and similarly for multi-residential buildings in 2005 (ABCB 2016a). At that time, star-rating was still being determined but the requirements then were informally considered equivalent to 4-stars under the Nationwide House Energy Rating Scheme (NatHERS). Stringency for energy efficiency was increased in 2006–5-stars, and again in 2010–6-stars, where it has remained till the present. Minimum standards have been reviewed for a possible increment to 7-stars in the next iteration of the NCC due in 2022 (ABCB 2019a). This proposition reportedly received 'overwhelming support' from the industry (ABCB 2019b). As of this writing, the latest update is that 'the ABCB is currently investigating new residential energy efficiency provisions for the 2022 version of the NCC. The new provisions may be set at net zero.' (ABCB, 24 Jul 2020)

After 12 years of maintaining the status quo on energy efficiency, we find ourselves at the cusp of a decisive move towards greater energy efficiency strictures, and on a scale that could eclipse all prior steps. It is against this background that this paper attempts to elucidate the issues of architectural science that have been obfuscated by rhetoric.

This paper will focus on houses, though not limit itself to that, and do so by referencing primarily to NCC Vol Two. This paper is also longer than usual, in order to provide a sufficiently robust and complete critique.

2. What is the point of energy efficiency?

In the NCC it is stated that 'the Objective is to reduce greenhouse gas emissions' (NCC Vol Two, 2019, O2.6). Now, if greenhouse gas reduction was the goal, one would have thought it would be reasonable that buildings powered by renewables should be exempt from these provisions. Furthermore, on-site renewable production should by the same logic reduce the requirements for energy-efficient design.

However, currently, neither of these considerations offer any leniency in compliance, since the building fabric would, regardless of energy source, still need to comply with P2.6.1 which states:

> A building must have, to the degree necessary, a level of thermal performance to facilitate the efficient use of energy for artificial heating and cooling appropriate to—
>
> (a) the function and use of the building; and
> (b) the internal environment; and
> (c) the geographic location of the building; and
> (d) the effects of nearby permanent features such as topography, structures and buildings; and
> (e) solar radiation being—
>   (i) utilised for heating; and
>   (ii) controlled to minimise energy for cooling; and
> (f) the sealing of the building envelope against air leakage; and
> (g) the utilisation of air movement to assist cooling.

It should be highlighted that it is the *performance requirements* rather than the *objectives* which set forth obligatory criteria upon which compliance is deemed to be achieved (NCC Vol Two 2019, A2.0(2) 'Compliance'). Hence it is incongruous that even though the *objective* can be achieved by any building which is oper-

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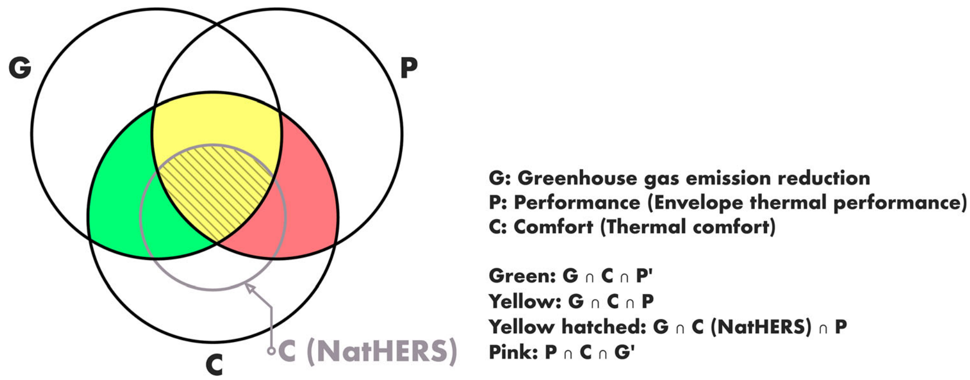

Figure 1. Venn diagram showing how the performance requirements in the NCC (yellow) are narrower in scope than the objectives (green and yellow). Furthermore, in places where NatHERS is the dominant method of approval, the practical reality of design options is even narrower (hatched yellow area). The pink area is where enevelope themal performance and thermal comfort are pursued at the expense of greenhouse gas emissions.

ated entirely on renewable energy (such as an off-grid building), there is no concession for such a possibility. Even if a building emitted zero greenhouse gases from its operational energy, it still had to meet *performance requirements* for envelope thermal performance.

Figure 1 illustrates this distinction: the stated objective of energy efficiency ought to include both the green and yellow regions, but the performance requirement narrows it down to just the yellow region. A design that falls into the green region may feature reduced greenhouse gas emissions but have no envelope thermal performance. To illustrate, one such example could be a 'Queenslander' – an Australian vernacular design for warm climates. Built on raised stumps for air movement and flood avoidance, it features a single-skin facade (i.e. no insulation) often with permanent ventilation openings (i.e. cannot be air-conditioned), with the option for additional air movement by the use of ceiling fans. Though energy-efficient, comfortable and uninsulated (green segment), it will not meet the envelope thermal performance requirements and cannot be approved under the current NCC regime. For another illustration, one could consider any building in Tasmania, where the electricity source is largely hydroelectric. Tasmania's electricity emission factor of 61 g CO2-e/MJ (NCC 2019 Vol One Specification JVb) satisfies the criteria for not exceeding 100 g CO2-e/MJ' (NCC 2019 Vol Two P2.6.2). However, even with such low greenhouse gas emissions, Tasmanian buildings are not exempt from building envelope thermal performance requirements.

We will subsequently see how the yellow area is reduced to the hatched yellow area when NatHERS thermostat settings are used in place of other thermal comfort models. The pink area shows the region of deviation from the objective, which is possible because the performance requirements are not moored to its objectives, discussed later in the paper.

3. 'Necessary thermal performance'

What is the 'level of thermal performance' that is expected to the 'degree necessary' under P2.6.1? In short, houses and residential apartments presently need to meet the NatHERS 6-star requirement. By modelling a house against its climate in the software, the anticipated heating and cooling energy (in MJ/m^2 per annum) is determined and must meet predetermined load limits.

Figure 2 reflects the building approvals against the number of NatHERS certificates issued, revealing that in states such as Victoria and Tasmania (predominantly Climate Zones 6 and 7, i.e. temperate and cool temperate), effectively all houses are approved using NatHERS energy assessments. In the largest audit of its kind as of May 2020, the Victoria state government undertook 2362 energy-efficiency audits of houses in the final stages of construction and found that the distribution between methods of compliance was: 97% by NatHERS accredited software, 2% performance solutions, 1% elemental DtS (deemed to satisfy) provisions (DELWP 2020). The important trend to note is that as energy efficiency requirements have become more onerous, NatHERS software simulation will be the primary, and in some contexts, the exclusive means of compliance.

It is not the intent of this paper to take a broadside against the NatHERS software. The software models energy use based on assumptions on thermal conditions. It is legitimate for any software to make assumptions. The problem with total domination by the NatHERS software is that designers and occupants alike, through prolonged conditioning, tend to relinquish the liberty of experimentation and the rigour of scientific investigation to the efficiency of computer algorithms. 'The subtle biases inspired by computerized decision aids may, moreover, be an inherent part of the human cognitive apparatus for reacting to cues and alarms. By directing the focus of our eyes, the aids distort our vision' (Carr 2015).

On the first assumption that all buildings, regardless of emissions of energy source, must meet minimum envelope thermal performance stipulations, is compounded another assumption that all buildings are to be sealed and conditioned to setpoints defined by NatHERS thermostat settings. Thus, the NatHERS compliance pathway further narrows the available design options to a more stringent thermostat band, previously illustrated in the Venn diagram of Figure 1 as the hatched yellow region. Although NatHERS serves an important function of predicting energy consumption in houses, it cannot be assumed that it is the only, or best, way of producing low energy buildings without considering possibilities outside its algorithm.

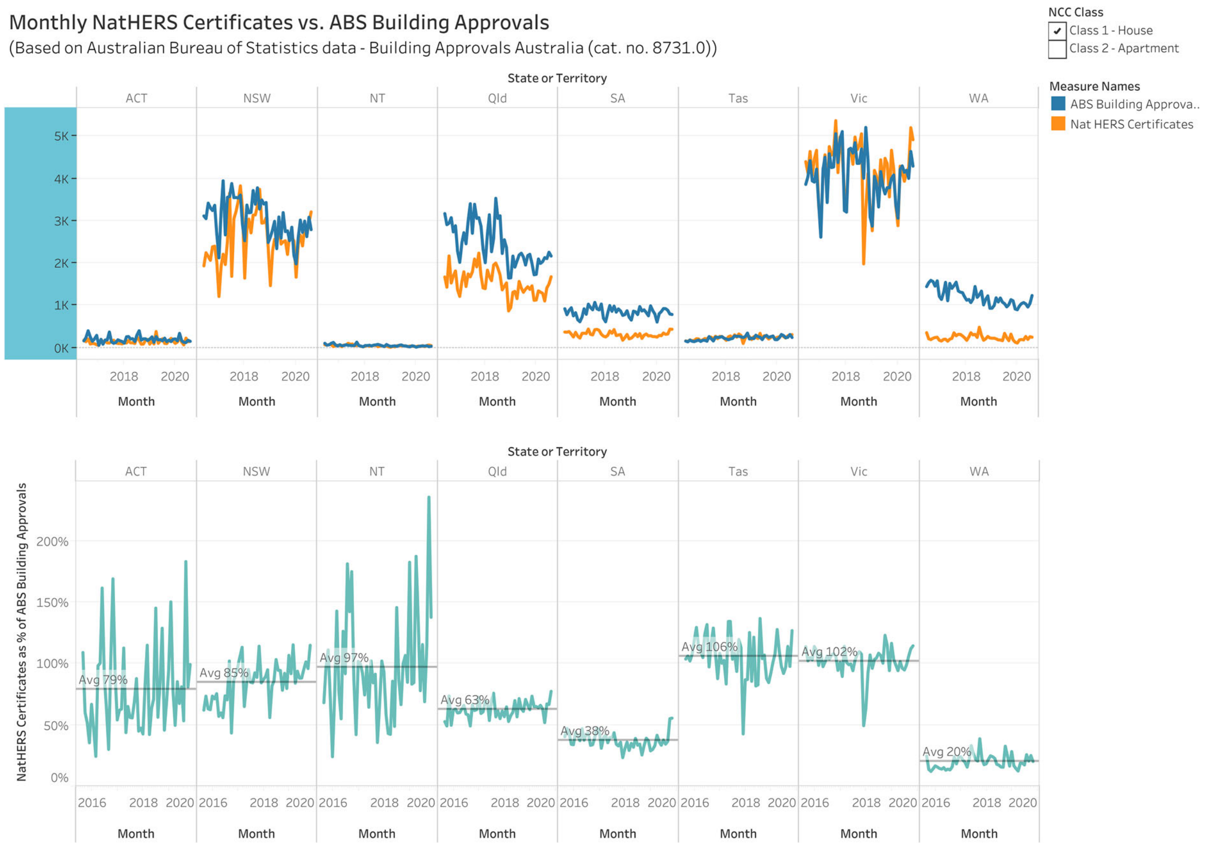

Figure 2. Number of NatHERS certificates in comparison to Australian Bureau of Statistics Building approvals (April 2016 to December 2020) https://ahd.csiro.au/other-data/certificates-vs-building-approvals/

There are four accredited software package that utilises the NatHERS engine: AccuRate, BERS, First Rate and HERO. Although larger thermostat settings are possible in a modified version of AccuRate (Ren and Chen 2018), this is not available when running in 'accredited mode' (previously referred to as regulation mode) under the software accreditation protocol, or SAP (NatHERS 2019). Thus, the thermostat settings used for ensuring compliance are much narrower, and generally more energy demanding, than would otherwise be accommodated with other thermal comfort models.

For cool climates, the NatHERS SAP assumes continuous conditioning to these presets: 20°C in living spaces, 18°C in the bedroom when the occupant is assumed awake or 15°C when asleep. What of the possibilities of personal preference for extremities of thermal delight (Heschong 1979)? Or what of the alternating transients for thermal counterpoints and alliesthesia with natural and mixed mode ventilation (de Dear 2014)? Or what of the need for variance in order for one to detect, deliberate and declare a sense of thermal comfort – which by definition is expression of one's state of mind as that of 'satisfaction with the thermal environment' (Law 2013)? In cool climates, the deterministic setpoints do not allow for low-energy adaptive building designs that can be dynamic, interacting, changing, customisable and seasonally adjusted (Nicol, Humphreys, and Roaf 2012).

For warm climates, the NatHERS engine checks if external air temperatures are within the comfortable range of that climate region (one temperature for the whole year) and assumes the occupant will open the windows if the outdoor air is comfortable, or switch on the air-conditioning if it is not. This is more of a geographical adjustment rather than a seasonal adjustment, as it is not a full application of the adaptive thermal comfort model based on a moving average of 7–30 sequential days (ASHRAE 2017). To its credit, the NatHERS engine can expand the comfort range by some 5°C with a maximum 1.5 m/s of wind from combined air movement of natural ventilation and ceiling fan. Natural air movement is considered only for the rooms on the windward side. Furthermore, the engine utilises the effective temperature index (ET∗), so that in very dry climates (as low as 10%RH), an additional 5°C expansion in comfort range is theoretically possible from its 50%RH reference point (Baharun, Ooi, and Chen 2009).

Even with these features, what has been lacking from the engine was the possibility of accepting natural cross ventilation across the whole building (not just the windward side) when considering the internal breeze path. In addition to the cooling effect of a breeze, there are other thermal comfort indices that can account for wind passing over moist skin, such as Standard Effective Temperature, that is, SET∗ (Zhang and Lin 2020). If this had been introduced, the effect of evaporative cooling can be more broadly implemented across climates with moderate humidity.

These other adaptive thermal comfort models expand the periods where buildings can be free-running (operated without using conditioning energy). Thus, without provisions for other thermal comfort models, it should not be assumed that a higher star rating results in saved energy. Quite contrariwise, it was found that a typical house could have improved star rating with additional insulation yet have its annual free-running performance degraded (Kordjamshidi et al. 2007).

The alternative to NatHERS software is a verification method with a non-NatHERS software but using crude deterministic thermal comfort assumptions. This involves modelling to a more demanding and narrower thermostat range of 20–21°C for heating and 25–28°C for cooling at all times (Vol Two V2.6.2.2 'Verification using a reference building'). If one was concerned with greenhouse gas emissions, then the continuous conditioning of air (heating and cooling), with its high global warming potential refrigerants, should hardly be accepted as the only means of achieving thermal comfort.

There are so many other models of thermal comfort that could conserve energy without being fixated about specifying the building fabric's thermal performance in response to stipulated space conditioning thermostat settings. The fact that the makers and users of houses fail to consider these models, demonstrates the insidiousness and prevalence of 'automation bias' already at work. First, we make the algorithm, then the algorithm determines the way buildings are designed and operated. Left unchecked it can, and does, contradict the original intention of reducing emissions. As we will see, this has been possible because of the equivocation in the NCC between its *objectives* and *performance requirements*.

4. So back to the question, what is the point of energy efficiency?

The question that remains unanswered is if, after all these years, we have gotten any closer to achieving the objective of reduced greenhouse gases by mandating energy efficiency of buildings. It cannot be assumed that by improving a building's thermal performance, energy consumption is necessarily reduced and thereby less greenhouse gases emitted. Efficiency could create a situation where the economisation of a resource makes it more readily available, and thus more of it is utilised. The economic forces at play are referred to interchangeably as the 'energy efficiency paradox', 'Jevons theory' or simply as 'rebound'.

This paradox was first captured by William Jevons in his book 'The Coal Question' (Jevons 1865) where he observed that the improved efficiency in the use of coals in a blast furnace for iron production would attract new investment, which would lower the price of iron, thereby stimulating demand, and eventually 'the greater number of furnaces will more than make up for the diminished consumption of each'. Thus, he concluded, 'It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.' (Owen 2010)

Besides coal, the same phenomenon has been observed in vehicles, where a rebound effect of longer trips accompanies better fuel economy (Small and Van Dender 2005) and in supermarket refrigeration – the more affordable refrigeration is, the more refrigerators are likely to be installed (Klemick, Kopits, and Wolverton 2015). Most significantly, in terms of high efficiency LED lighting it is anticipated that 'there is a massive potential for growth in the consumption of light' with market saturation still a long way away (Tsao et al. 2010). In this case, increases in lighting energy efficiency have led to 100% rebound and are 'unlikely to contribute much to climate change mitigation policy' (Saunders and Tsao 2012).

In a report on the evaluation of energy efficiency standards for Australian residential buildings by CSIRO (Ambrose et al. 2013), in all three cities studied (Brisbane, Adelaide and Melbourne), houses with higher ratings consistently had warmer indoor temperatures. The report computed substantial potential savings of some 20% in Brisbane and Adelaide that could have resulted had it not been for this rebound effect. This CSIRO study showed that in reality, without determining the rebound effect against clear emission targets, it was not possible to tell if Australia had not already strayed into the pink zone of Figure 1, where envelope thermal performance and thermal comfort were being pursued at the expense of the objective for greenhouse gas emissions. In places such as Brisbane, the CSIRO study revealed higher NatHERS star-ratings have not ensured a better outcome of reduced energy consumption.

What is happening in Australia predictably follows the trend in the UK where energy efficiency was mandated decades ahead of Australia. In the UK we see that:

> … rising incomes and falling real fuel prices leave most households and organisations able to heat their homes and workplaces to any desired temperature all year round without worrying about the cost. As a result many social groups expect to wear the same skimpy clothing indoors in all seasons, with warmer clothing only worn outdoors. Enclosed heated shopping and leisure malls, unknown in the UK until recently, have mushroomed to exploit the new dress habits, and further facilitate and entrench them. Now this has happened, brisk exhortations to turn down the heating and put a woolly on now run up against not only distaste for Puritanism, but also the difficulty many people would have mustering warm clothing suitable for indoor wear, and reluctance to stand out from social norms by looking baggy and frumpy. Starting from where we now are, if we want to evolve less use of energy to change the temperature of buildings, we will need to co-evolve habits and expectations of wearing different clothes in different seasons. (Levett 2009)

Indeed, what we see in the case of energy efficiency provisions of the NCC is a failure to distinguish what precisely is its objective. Such a failure 'causes much confusion and ineffectiveness in energy policy' (Levett 2009).

This is no minor oversight. The hasty implementation and termination of the 2009–2010 HIP (Home Insulation Program, ANAO 2010) followed by the Royal Commission into the deaths of insulation installers found that State and Territories were not familiar with the nature of HIP, thus 'reliance upon the States and Territories, and the lack of communications with them, resulted in there being inadequate regulatory arrangements for installations under the HIP' (Hanger 2014). For the same reason, when the performance requirements of the NCC are not aligned with its objectives, there is no real metric to determine its utility, no clarity for any meaningful scientific scrutiny; and no guidance for building surveyors/certifiers to ascertain what the intent of the construction code is essentially about. As a consequence, the construction code loses any safeguard against bad faith: where manufacturers capture the mandatory provisions for their private interests under the pretext of achieving planetary sustainability.

Improving the energy efficiency of buildings with insulation used to be the low hanging fruit that, by some estimates, would provide the best value approach for mitigating against greenhouse gas emissions (Enkvist et al. 2007). For Australia, this had been an unanswered question. Here, energy efficiency has effectively been disengaged from its objective of emissions reduction, and taken a life of its own. Since the ABCB has made no effort to establish its presupposition that energy efficiency invariably leads to reductions in greenhouse gas emissions, energy efficiency needs to be investigated on its own merit. Even so, the push for higher efficiencies should raise concerns. Prior to the mandating of 6-star, in a regulatory impact statement about the revised energy efficiency requirements from 5-star residential buildings by The Centre for International Economics, the models pointed to a net loss, where there might be \$0.88 benefit for every \$1.00 spent (ABCB 2009).

With no climate benefit, and no economic benefit, has Australia been actually achieving any real energy efficiency?

5. Software modelling

The NatHERS software engine has been widely used and validated against other software tools under a BESTEST protocol (Delsante, 2004). In terms of empirical validation, there have been much fewer studies investigating whether the zone temperatures and energy consumption in houses were similar to what was predicted by the NatHERS software. These are now considered in the context of what caveats should be applied when extending the NatHERS software beyond ratings.

5.1. Temperature modelling

In one of the very few empirical validation experiments, unoccupied test buildings were constructed at the University of Tasmania in 2006, where internal temperatures were compared to NatHERS software predictions (Dewsbury 2011). Dewsbury found that the difference between measured site data and built-in climate files had the greatest impact on the simulation output, with differences on either extreme of up to +12.5°C and −16.8°C. Such a variation in climate inputs would 'significantly effect [*sic*] any envelope simulation and compromise any comparison'. He also found that another definitive contributor to accurate simulations was the use of modelling input calculated based on an as-built fabric, with conductivity values modified from standard data entry. In particular, these modifications were made to account for framing factors that would lower the total *R*-values of the fabric.

In another instance, empirical validation was carried out on three newly built and occupied houses in 2007 ranging from 4- to 5-star (Geard 2011). In terms of the reliability of NatHERS modelling software, AccuRate, some of the pertinent conclusions were as follows:

> The overwhelming dissimilarity of temperature comparison between simulated and measured temperatures in the hallway and the roof space of all houses and in the subfloor of the timber floor houses leads to the conclusion [that] the prediction of the cooling and heating load, and the star rating of this program is seriously compromised. … AccuRate over-predicted temperatures in the subfloor of the timber floor houses. … Achieving the required star rating for timber floor houses might require additional thermal performance measures compared to slab floor houses, resulting in increased and unwarranted construction costs. (Geard 2011)

Geard goes on to observe that when using the U.S. NIST (National Institute of Standards and Technology) passive solar validation test criteria of ±0.5°C (Mahajan 1984), 'all simulation predictions would be deemed as unsatisfactory' (Geard 2011).

It can be argued that differences between site measurements compared to RMY (Reference Meteorological Year) data of NatHERS software is only to be expected and one should not be overly critical about these discrepancies. As a quick way of illustrating the significance of these differences, Bureau of Meteorology (BoM) data for Brisbane (comprising daily minimums and maximums from 2009 to 2019) are graphed alongside that of the inbuilt NatHERS climate zone file in Figure 3. As a summary statistic for each year, the cooling degree days and heating degree days are calculated based on static values using NatHERS thermostat settings of 25.5°C and 20°C, respectively. Even within this short period, it can already be seen that the climate file underestimates cooling degree days, and severely overestimates heating degree days, as seen in Figure 4. The disparity appears to worsen over time and uncovers this problem: that based on NatHERS software simulation, designers guided by energy assessors will produce a house more suited to a cooler climate than what Brisbane is now, with the situation exacerbated in the future.

5.2. Energy modelling

In theory, higher NatHERS star-rated houses should result in both lower winter heating and lower summer cooling energy consumption. The CSIRO evaluation of energy efficiency standard for residential buildings (Ambrose et al. 2013) showed that the reality turned out to be more varied. In the study of houses in three cities, Brisbane had no significant decrease in winter heating, but a significant increase in summer cooling energy consumption. Adelaide showed decreased winter heating, and no relationship with summer heating. Melbourne had decreased winter heating and increased summer cooling.

A study in South Australia did show NatHERS star-rating had a correlation between simulated with actual energy use (O'Leary et al. 2016). However, with a variance value (r^2) ranging from 0.32 (heating) to 0.55 (cooling), the correlation is reasonable, though not particularly strong.

5.3. Limitations to modelling

Despite the cautionary caveats and clear limitations, software modelling is not only continuously promoted, but even used as justification for changes to the code. For instance, the committee working on draft reforms to NCC Section J claimed that their energy modelling showed 'buildings could see a 30 per cent increase in energy efficiency' between the 2016 and 2019 versions of the NCC (Aliento 2018).

NatHERS software, like any other software, has its limitations. It was intended as a rating tool but has increasingly been used to claim improvements to energy efficiency. One should not assume its inerrancy, or worse still, use it to 'prove' that buildings will be improved by increasing their star rating. First, the industry needs to get the practise of energy assessment and construction of buildings to match the simulation. Then, only after a correlation has been established, can we try to use the software to improve the way buildings are designed and built. Without

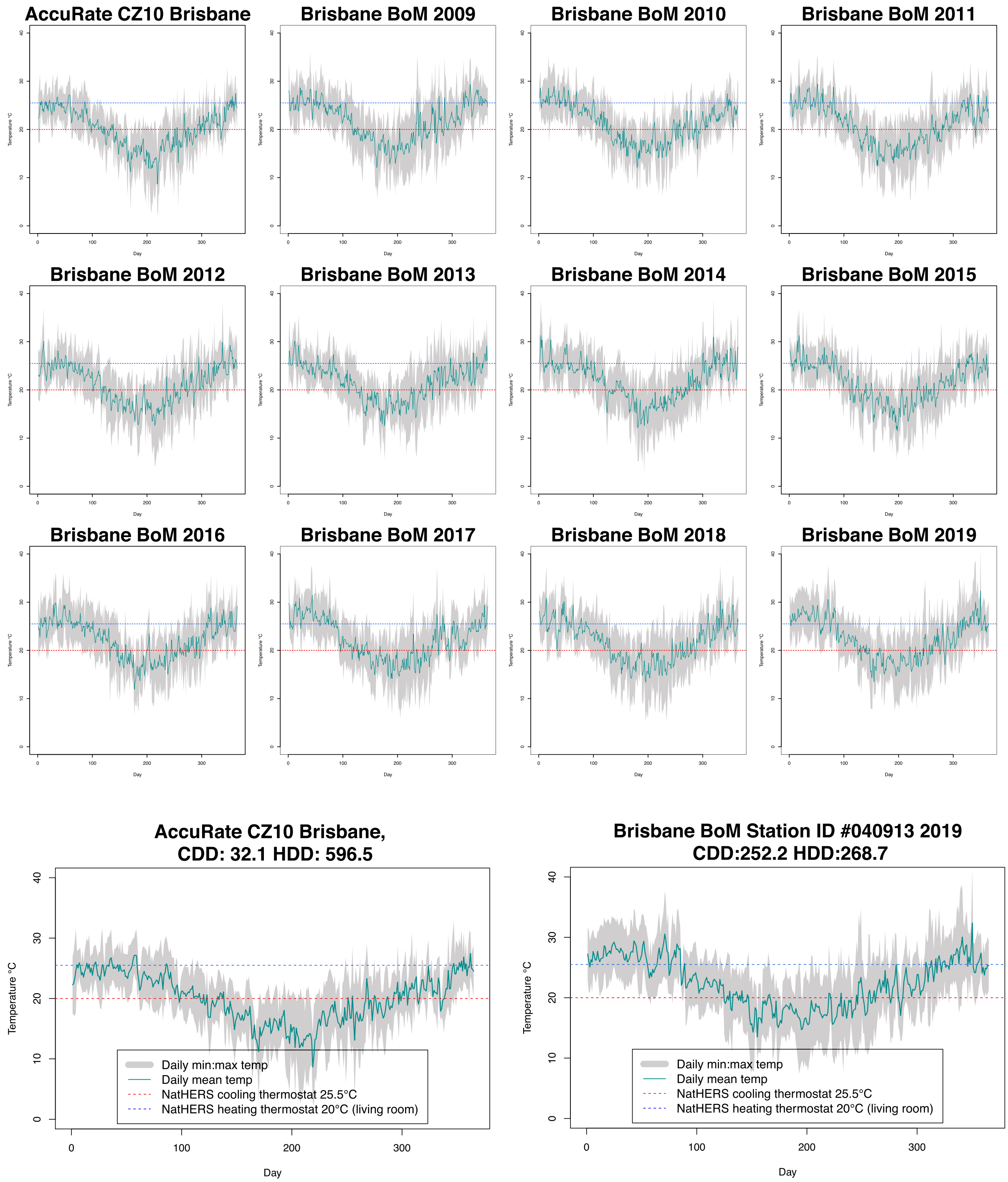

Figure 3. Top: Daily min, max and mean temperatures from built-in climate zone file and from BoM measured data (2009–2019). Bottom: Enlarged for clarity, same data for built-in climate zone file (left) and BoM records in 2019 (right).

energy utilisation feedback from the operation of buildings, the software is still taking a stab in the dark about a house's actual performance.

Building scientists have an adage: what you cannot measure you cannot monitor, and what you cannot monitor you cannot manage. To date, there is no substantial data to show existing houses consume as much heating and cooling energy as meets the 6-star heating and cooling caps they were meant to. Even a correlation between higher star-ratings and reduced actual energy consumptions ranges tenuously. There is a clarion need to measure the space conditioning energy by submetering that component. Only with utilisation feedback is there evidence of a successful implementation of energy efficiency criteria. Thereafter, and then only, will increment to energy efficiency be meaningful. Without data, the industry can make itself appear busy without accomplishing anything.

Why should the public be tentative about increasing energy efficiency? Amongst many other reasons, this paper will focus on just two: (1) a building's energy efficiency features are not assessed in the same way they are being built and (2) if energy

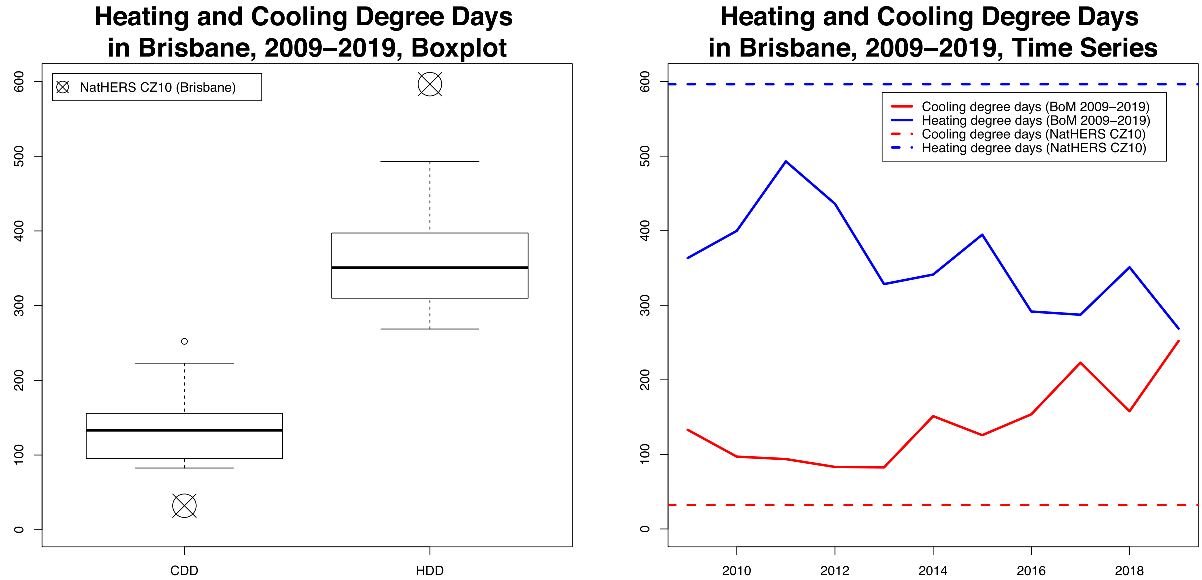

Figure 4. Heating and cooling degree days of BoM acquired data presented as boxplot (left) and time series (right) against built in climate file for same Brisbane. Note how the inbuilt climate file underestimates cooling degree days, and seriously overestimates heating degree days.

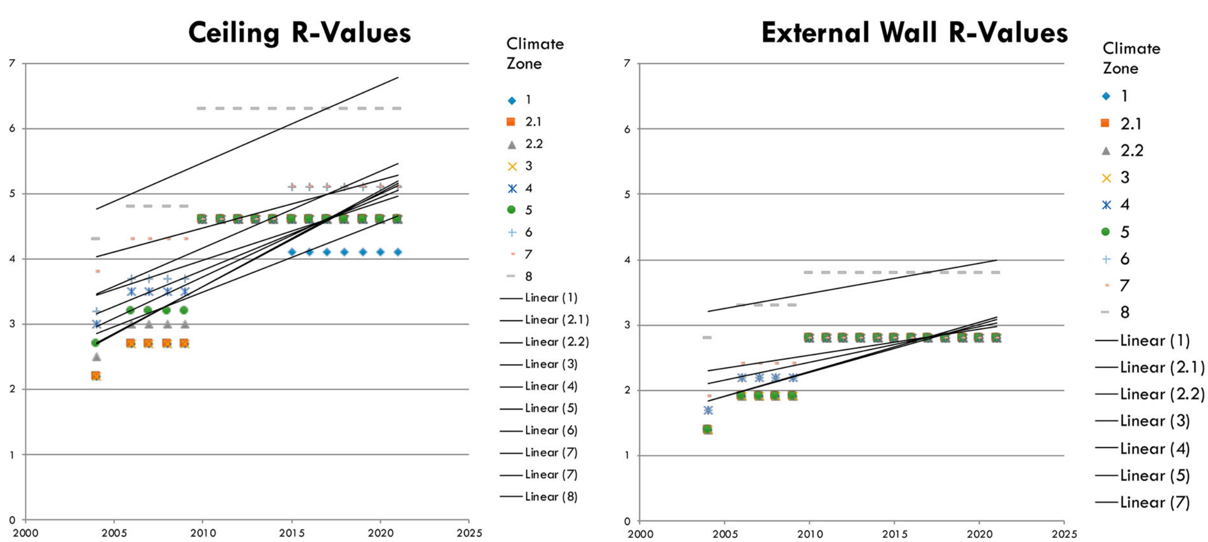

Figure 5. NCC DtS R-Values of ceiling and external walls, by climate zone. 2.1 and 2.2 refer to climate zone 2 above and below 300 m altitude, respectively.

efficiency is not about mitigating disastrous anthropogenic climate change, then there are many other issues of a higher priority compared to improving a building's thermal performance.

6. Getting insulation right: by definition, by design and by execution

Figure 5 shows the DtS requirements for ceiling and external wall insulation for various climate types, illustrating marked changes when provisions were increased to the next star band. It is practically certain that if 7-stars were mandated, more insulation would be required.

In NCC Vol Two, the definitions for *Total R-Value* and *Total System U-Value* omit consideration for thermal bridging. This is an unrealistic omission, especially if the code aspires to higher energy efficiency at its next update. Thermal bridges – such as framing factor, or steel structure, or missing insulation – completely undermine the thermal performance of the building fabric. To explain the ramifications of omitting thermal bridging, four types of wall construction are illustrated in Figure 6. In each case, the wall insulation has an R-Value of 2.0 m^2 K/W. Based on the NCC Vol Two definitions, in every one of these cases, the insulated wall frame will be deemed to have a Total R-Value of 2.0 (with additional amounts for the plaster, cavity and cladding). However, when adopting a method that considers thermal bridging, such as *Total R-Value* calculation method in AS4859.1 (Standards Australia 2018), a very different picture arises as can be seen.

The presence of a steel thermal bridge, commonly introduced as structural steel framing around large-span windows, renders it meaningless to have any insulation batts installed within the frame. The appropriate construction method would have been a rigid insulation installed on the outside of the frame (i.e. overclad). However, important nuances like these are not commonly understood by building designers and energy assessors because the definition in the NCC accommodates

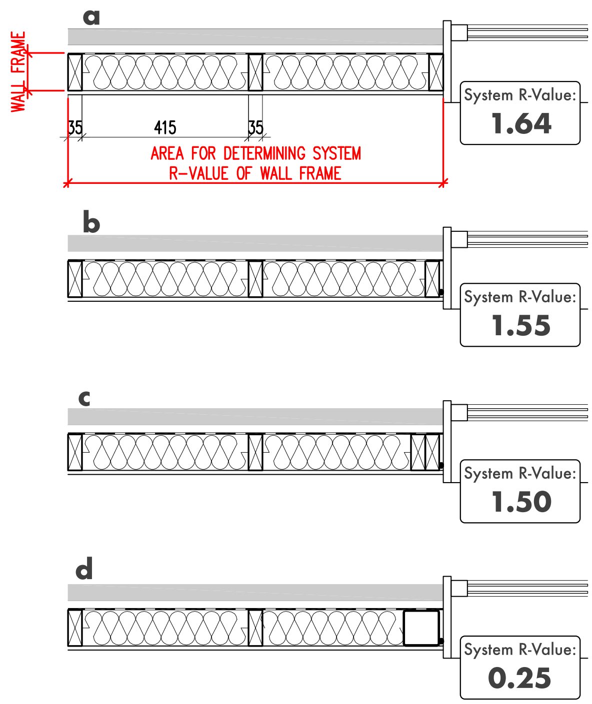

Figure 6. R-Values of the insulated wall frame (i.e. excluding air cavity and cladding) determined using method described in AS4859 (2018). (a) Softwood framing (90x35mm), double top plate, bottom plate and one noggin per panel. (b) Similar to (a), with 10mm construction tolerance still air gap between window reveal and frame by backer rod. (c) Similar to (b), with addition of jack stud besides the jamb stud, as commonly constructed. (d) Replace jack & jamb stud with 89mm steel SHS (3mm wall thickness), common with large span windows.

unintelligent oversimplifications stemming from NCC Volume Two's definition of *Total R-Value*.

Figure 7, from AS3999 (Standards Australia 2015), shows how different insulation thicknesses are meant to be installed in the tight spaces around the roof perimeter. This standard is not referenced in the NCC and is thus non-mandatory. As a result, Figure 8 illustrates the common practice and misunderstanding with ceiling insulation. When insulation is installed after the roof has been completed (done in this sequence to keep insulation dry), installers cannot tell at which point the ceiling overlaps the wall. Instead, they push the insulation as far as they can. Increasing the thickness of ceiling insulation creates a wider thermal bridge around the perimeter that would more than negate the increased insulation thickness. Energy assessors, under pressure to meet star-ratings, do not properly consider the geometry of insulation in the places they are meant to be installed into. Thus, a building with R7 ceiling insulation, in a software model, always trumps the same building with R4. The truth of the matter is that in this instance, more is less.

The NCC requires that a roof (as distinct from a ceiling) be insulated, and in an instance where the ceiling is flat, 'have greater than or equal to 50% of the added insulation laid on the ceiling'. (NCC Vol Two 3.12.1.2 'Roofs'). In a situation where wet area exhausts are discharged into the roof, such a roof is to be ventilated (NCC Vol Two 3.8.7.4 'Ventilation of roof spaces'). Figure 9 illustrates instances where this can be applied (or misapplied) to mean that the roof should be the primary location of

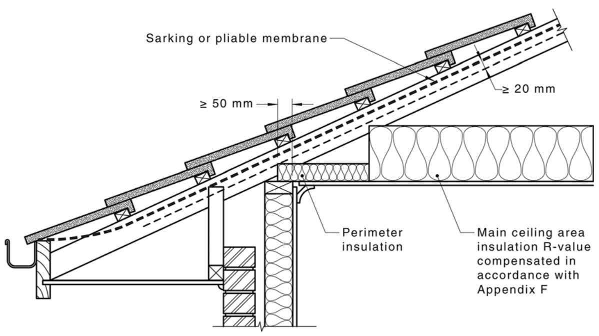

Figure 7. Required clearance of insulation under roof sarking (AS3999, 2015, 46).

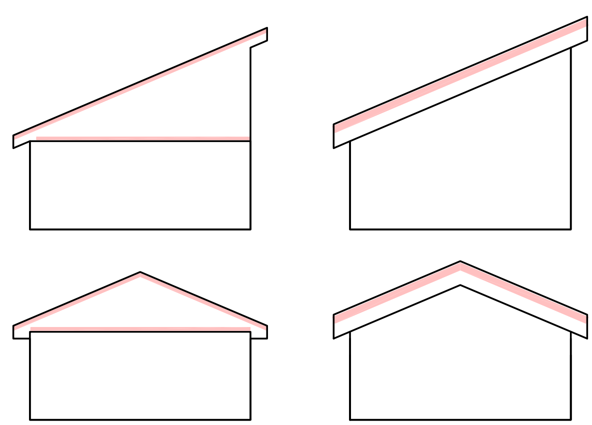

Figure 9. Placement and thickness of insulation when located in different roof types. (Left) Skillion and gable roof with flat ceiling, half the insulation in roof and half on ceiling. (Right) Skillion and gable roof with raked and cathedral ceilings respectively, all insulation in roof, none in ceiling.

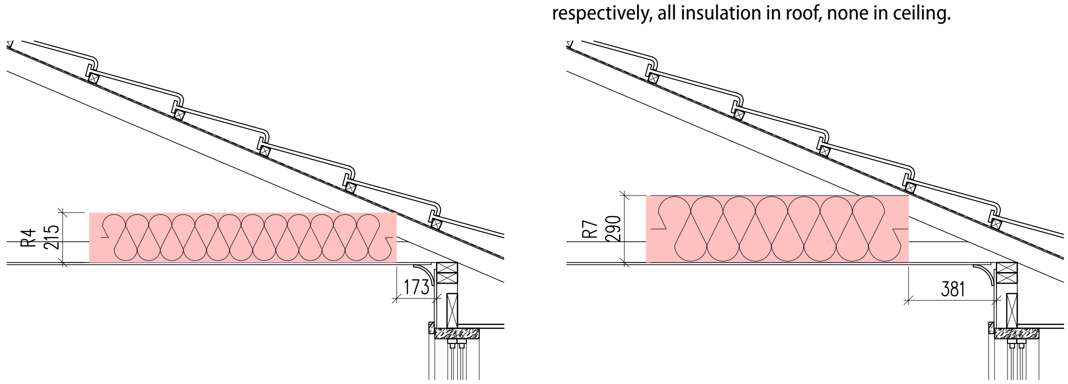

Figure 8. Impact of insulation thickness on the thermal bridging near the roof eaves.

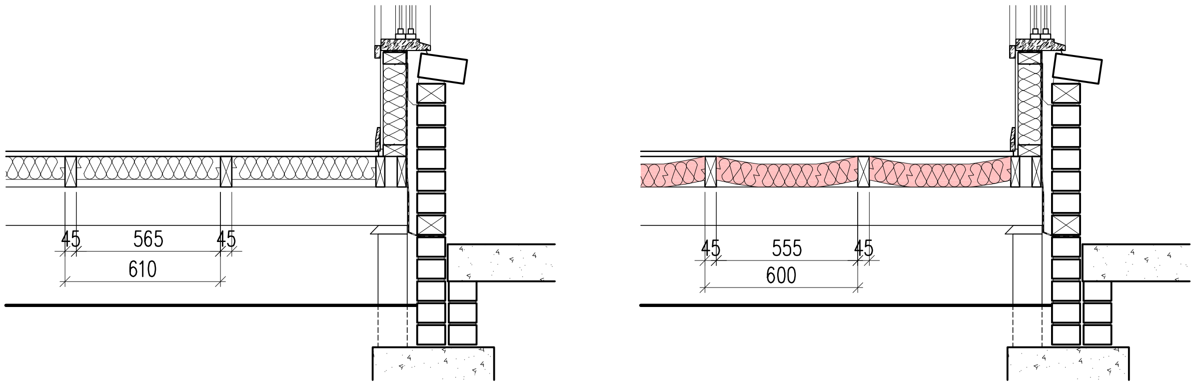

Figure 10. Effect of ill-fitting floor insulation.

insulation installation, such that with a flat ceiling only half the insulation separates the ceiling from the naturally ventilated roof space containing air close to outdoor temperature. Worse still, with a raked or cathedral ceiling it is permissible under the NCC to have all insulation at the roof (such as with the use of a foil blanket), and *no* insulation between the ceiling and ventilated roof space.

Figure 10 illustrates another problem when there is a mismatch between the batt widths and the spacing between floor joists. Underfloor batt insulation is manufactured in widths of 415 mm or 565 mm to match joists of 35 mm widths at either 450 mm or 600 mm intervals. However, the residential timber framing standard AS1684.4 (Standards Australia 2010) has framing tables that permit joists of widths of 35 mm, 45 mm and 50 mm. For these other cases, the floor batts will be ill-fitting and have compromised performance. These considerations are often unappreciated, given that there is no responsible party for ensuring that structure is coordinated with insulation from design to assessment, to certification, to construction.

For a building to be actually energy efficient requires coordination between multiple parties. However, by compartmentalising the roles of building designer, energy assessor, building surveyor and builder, no one party is ultimately responsible for the thermal performance of a building. Moreover, as far as actual heating and cooling energy remains unquantified, there is neither transparency nor accountability. The degree of delegation and specialisation has resulted in insulation being one of the most poorly executed energy-efficiency measures.

This can be further illustrated in the instance of insulation continuity. Figure 11 demonstrates the method of bulk insulation installation as is specified under the voluntary standard AS3999 (Standards Australia 2015). The need for continuity of ceiling insulation across ceilings of different levels is clearly exemplified. Attention is drawn to common omissions, for example, to 'insulate vertical wall section … to the same value as ceilings'. This is a starting point but remains an incomplete detail and specification. This instruction needs to be further captured in the drawings by the building designer with due consideration for the vertical wall framing, as ceiling batts differ from wall batts in available R-Values and are not interchangeable since wall batts require stiffeners to maintain rigidity. Figure 12 shows an instance where the wall in a ceiling space has been left uninsulated. For ceilings with high R-Values (for instance R-4), a combination of stiffened wall batts (R-2) and rigid insulation (R-2) will be needed instead of running ceiling insulation at this wall section. The additional work to do things correctly often leads to insulation being omitted. Many in the industry do not appreciate the fact that as far as insulation continuity is not meticulously considered, any increase to insulation values is futile.

There has been advice, since some three decades ago, that 'for Australia's temperate coastal regions, insulation with a thermal resistance of 1.5–2.0 m⊃2·K/W would be generally adequate for ceilings' (CSIRO Notes of the Science of Building, Aug 1991; in Wren Industries 2007). This has been corroborated by Logan (2018) identifying that when simulating the energy consumption of a building in Perth (Climate zone 5) the 'sweet spot … that provides the highest benefit for the least cost' is around R-2 to R-2.5. Rather than plunging headlong into increased star-ratings, the public would be better served by ensuring that buildings were actually designed and built correctly, achieving measurable energy efficiency using far less insulation than currently mandated. In other words, getting 6-stars done correctly before attempting 7-stars.

7. Insulation is more than a single R-value

It needs to be understood that R-values are not a static value. Where there is air movement around bulk insulation, the 'wind-washing' effect reduces its actual resistivity (Straube 2007). However, when using the NCC definitions of R-Value, different insulation types such as foil sarking in the roof and bulk insulation in the ceiling appear to be interchangeable. This is not the case, especially in warm climates dominated by radiant heat. In a study sponsored by the South Australian government it was found:

> Perhaps one of the most consistent items of discussion was around the lack of applicability of the BCA to workable and comfortable tropical buildings. The important role of the local strategy of reflection of heat through radiant insulation, backed up by air movement to provide evaporative heat loss, is at odds with the focus on sealed and bulk insulated buildings in the code driven designs … A building with two layers of reflective sarking in a ventilated roof cavity - and no bulk insulation above the ceiling - does not rate highly in many assessment tools or schemes but works well in the tropics. (Pitt & Sherry & Swinburne University of Technology 2014)

Insulation sold in Australia is tested to AS4859.1 (Standards Australia 2018) where thermal resistivity, or R-Value, of a sample is determined around an average reference temperature of 23°C.

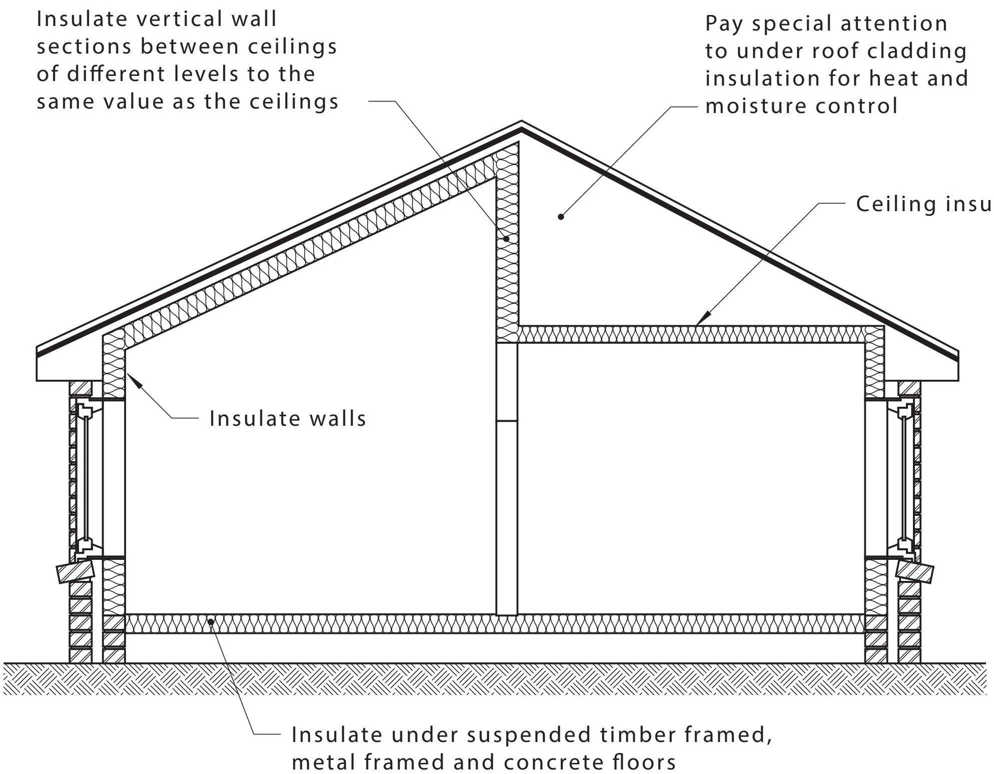

Figure 11. An exemplar of insulation installation requirements in AS3999 (2015).

Figure 12. Ceiling insulation showing change of plane in ceiling insulation from raked ceiling to flat ceiling. The plasterboard (marked in red outline in right figure) should have been insulated with wall insulation to the same insulation as the ceiling insulation, R-4.0 in this case.

Although this is the advertised R-Value, above this temperature batt insulation such as glass wool loses resistivity at the rate of 0.65% per Kelvin (AS4859.1, 2002, Appendix K, 'Standard assumptions'). This value is in general agreement with hot-box thermal metric testing done in the U.S. (Bailes 2013; BSC, 2013). In dark-coloured roofs of hot Australian climates such as Townsville, sol-air temperatures were both calculated and field-measured to exceed 90°C (Aynsley and Su 2005). In this context, glass-fiber ceiling batts would lose some 40% of the advertised R-Value, and this loss coincides during times of air-conditioning peak demand. Despite the double setback, the degradation of R-Value has not been acknowledged in the NCC or NatHERS software (Saman et al. 2013, 145).

As an alternative to increasing resistivity, the ABCB should adopt policies that include differential resistivities in roof-ceilings for warm-hot winterless climates, producing high R-Value 'down' during daytime, as well low R-Value 'up' which would facilitate rapid night time cooling. Foil insulations uniquely do this, whereas bulk insulations do not (Aynsley and Su 2005). This is also the advice of AIRAH (Australian Institute of Refrigeration, Air Conditioning and Heating), recommending that, 'radiant barriers should be included whenever radiation is a problem. This includes all of Australia' (AIRAH 2013). Such a policy coupled with natural ventilation, would require significantly less energy than air-conditioning and be inherently healthier. It is puzzling to know why the ABCB ignored this scientific information during the formulation of the NCC thermal regulations.

In what can only be described as a half-baked effort to implement energy-efficiency into the NCC, one wonders why this has been made such a priority that the motion for 7-stars and net-zero energy is being entertained. This is all the more pressing since energy efficiency does not exist as an isolated provision but negatively impacts other priorities. The paper now turns to these other considerations that are at least as important, if not more so, than energy efficiency for the mere sake of thermal comfort.

8. Resilience (using natural ventilation) vs energy-efficiency

It may satisfy conventional logic that an energy efficient house will be more resilient in a heat wave since it uses less energy. However, this is not the case. The NatHERS climate files are based on historical averages (NIWA 2017) and thus a poor indicator of past temperature extremes and an even poorer predictor of future extremes in a changing climate.

If a designer is not cognisant of the balance between winter energy efficiency and summer heatwave resilience, the natural tendency is to focus on the mandated energy efficiency requirements. Thus, we find that the thermal performance of a house 'does not directly relate to performance under peak load conditions caused by heat waves' (Saman et al. 2013). Building researcher Terry Brennan says it well, 'If they lose only electricity, few buildings in the U.S. can provide as much comfort as my backpacking tent' (Wilson 2006).

The overemphasis on star ratings and accompanying increased insulation create houses that respond poorly to lengthy periods of hot weather. Moreover, thermal mass, which typically delivers a favourable star-rating, can be counterproductive at night during long heatwaves. The report titled 'Does the Australian Nationwide House Energy Rating Scheme ensure heat stress resistance?' highlights the following:

> It is important to note that AccuRate underrepresents the level of overheating. AccuRate neglects real-world factors that affect the building energy use due to insufficient Australian building energy efficiency standards compared to leading jurisdictions internationally and non-compliance issues. (Hatvani-Kovacs et al. 2016)

Energy efficiency is simply not synonymous with resilience. Energy-efficient buildings are assumed by the software to be air-conditioned on a hot day. Resilient buildings need to be habitable even when there is no power to operate air-conditioning, which is especially likely during heat waves. One key to heat stress resilience is natural ventilation. Besides offering resilience to extreme weather, natural ventilation is a primary means of preventing the spread of COVID-19 in buildings (REHVA 2020), it is thus pertinent to consider other methods of achieving indoor thermal comfort without resorting to air-conditioning. Sue Roaf describes the situation in the UK, which applies just as much to Australia:

> Building designers today often don't understand that they have been cheated by not being taught how to ventilate buildings naturally. Modern, fast, cheap design has three key drivers: one, the architectural fantasy that their main professional contribution to society is in sculptural art; two, what the building regulations require; and three, the limits imposed on designers by the almost universal use of flawed building simulation models that steer designers away from naturally ventilating buildings. (Roaf 2020)

When it comes to natural ventilation, once again the NCC falls short, requiring a 'ventilating area not less than 5% of the floor area of the room required to be ventilated'. The accompanying explanatory information clarifying that this refers to windows 'irrespective of the restrictions on the openable sash' (Vol Two 3.8.5 'Ventilation'). In the case of windows which pose a risk of a child falling through, window openings are restricted to under 125 mm. This, as an architect underscores, could be taken to the extreme such that an opening of 1mm could comply with being 'openable' (Hall 2020). The same architect explains the absurdity of this compromise between ventilation and fall prevention, stating:

> I find it incomprehensible that the Australian Building Codes Board (ABCB) – drafters of the NCC – would allow a non-true ventilatable area to be reduced for safety reasons when it is dead easy to solve the child danger problem and have the ventilation. Maybe they should ask their parents how they stopped them falling out of cots with more than 100 per cent ventilation area. (Hall 2020)

Heat waves are Australia's most deadly natural hazard (Hatvani-Kovacs et al. 2016). In a perfect world, houses would be designed both to be resilient and energy efficient. In a world where we are often forced to accept compromises, and with resilience and energy-efficiency in an opposing balance for the built outcome of natural ventilation, it should be obvious that the resilience of houses and preservation of life should always take precedence over energy efficiency. Especially so when its performance requirement cannot be said to accomplish reduced greenhouse gas emissions.

9. Condensation vs energy-efficiency

Interstitial condensation 'resulting from increases in thermal insulation and decreases in ventilation' is causing prolific building damage in New Zealand with an estimated government payout of NZ$11.3 billion to homeowners (Aynsley and Shiel 2017).

In the 2010 update to the NCC, besides increasing the stringency of energy efficiency provisions, a new standard was included for construction in bushfire-prone areas. The industry, in response to making buildings more thermally efficient, had to also make them tighter. Air tightness of buildings not only contained heat better, it was also better at keeping cinders from blowing into the buildings as a way of reducing bushfire risk. However, with increased air tightness, the industry started noticing a disturbing new trend: many new residential buildings were encountering copious amounts of condensation. The persistent damp from condensation has led to other problems with mould and its deleterious effects on human health (Law 2018). The combined drive for energy efficiency, bushfire legislation and increased thermal comfort expectation in an industry with a rudimentary understanding of vapour management has been proposed as the reasons for the rise in condensation cases in buildings (ABCB 2016b). In the ABCB funded condensation scoping study that compared the NCC against the building codes of U.S., Canada, U.K., New Zealand and the E.U., it was found that:

> Most countries reviewed provided extensive national education and explanatory documents for building occupants, building designers and the construction industry which discuss why condensation control is needed and how it can be managed. The main driver changing building design is energy efficiency. It is known to impact all aspects of the building, including risks associated with vapour management, condensation, moisture and mould. There is growing awareness of the need for an integrated approach for vapour control and moisture management with each step [of] improvement in energy efficiency. (ABCB 2016b).

Having already observed that energy efficiency led to condensation and mould, the condensation scoping study highlighted the need for more research to minimise the potential for unintended consequences as new provisions were introduced into the code. Despite these caveats, the 'Condensation Management' provisions were introduced without funding further research or consultation with the researchers who authored the scoping study and recommendations.

One of the new stipulations was to require vapour permeable pliable building membranes in Class 1 and 2 residential buildings in the cooler climates. On the surface that sounded reasonable, except that the NCC had adopted a new definition of 'pliable building membranes' to mean, not any of a variety of sarking type membrane as we find in AS4200.1 (Standards Australia 2017), but only the ones that were classed as water barriers (NCC Vol Two Schedule 3 'Definitions'). To qualify for classification as water barrier under AS4201.4 (Standards Australia, 1994b), the membrane was to hold a column of dyed water 100 mm high for 24 h without any blotting to the filter paper on the other side of the membrane. Under this new definition, all types of foil membranes with perforations to meet vapour permeability classifications were categorically rejected.

Aluminium foil as sarking and thermal insulation has had its application in Australia throughout its construction history (Renouf 2019). The abandonment of foil makes no scientific sense. With a proper understanding, every building product can have a correct application. As a case in point, construction with oriented strand board (OSB) is common in the U.S. even though this form of sheathing is very susceptible to mould growth. The solution was not to reject it outright, but to learn to use it with the appropriate protective measures (Lstiburek 2009). Foil has its place, especially as a radiant barrier for heat stress resilience, and when used in applications where combustibility is a safety risk that cannot be tolerated.

10. Fire safety vs condensation problems caused by thermal performance

Energy efficiency provisions in the NCC resulted in condensation problems requiring the introduction of condensation provisions in the 2019 version of the NCC. However now, in another instance of myopic problem solving, the condensation provisions have introduced a new fire hazard.

In the newly introduced 'Condensation management ' section, one of the requirements was for all buildings in climate zones 6, 7 and 8 to have vapour permeable membranes (National Construction Code, ABCB 2019, Vol. One F6.2, and again in Vol. Two 3.8.7.2). Multistorey apartment buildings, would fall under Type A and B fire-resisting construction. In either case, external walls are required to be *non-combustible* (Vol One C1.9 ' Non-combustible building elements') meaning individual wall components are to be tested and pass AS1530.1 (Standards Australia, 1994a).

However, vapour permeable sarkings are permitted to be used where non-combustible building elements are required so long as they 'do not exceed 1 mm in thickness and have a Flammability Index not greater than 5' (NCC 2019 Vol One C1.9(e)(vi)).

The *flammability* test (AS1530.2, 1993) is much less rigorous and only requires a flame source in unspecified room conditions, as opposed to a furnace setup in a fire-testing facility for the *non-combustibility* test (AS1530.1, 1994). Furthermore, the validity of this test is questionable for vapour permeable membranes since the test is 'unsuitable for materials which melt readily or shrink away from an igniting flame' (AS1530.2, 1.1 'Scope').

Now, what are vapour permeable membranes made from? From the datasheets of the main Australian manufacturers, they are listed as polypropylene and polyethylene (Fletcher Insulation 2020), or polyolefin (CSR Building Products Ltd 2019). It should be noted that polyolefin is the chemical category that includes polymers such as polyethylene and polypropylene. Importantly, unless treated with chemical fire retardants, all polyolefins are combustible and burn with hot flames (Green 1982). The location of the membrane at the drained cavity (Vol One F6.2(b)) would allow any fire to spread rapidly through the cavity, bypassing fire compartments whilst remaining inaccessible to fire fighters.

To summarise by way of application, the NCC now requires that in multi-storey apartments (all requiring non-combustible external walls) in places such as Melbourne (Climate zone 6) the walls must be wrapped with vapour permeable membranes – sarking that is exempt from the non-combustibility test, and adopting a flammability test method that is ill-suited to plastics – made from the same material found in the cores of combustible cladding that the Victoria government is spending A$600 million to replace. Simply put, should vapour permeable membranes be installed in walls that were intended to be non-combustible? In terms of NCC compliance, yes; in terms of public safety, no.

When the condensation provisions were introduced in 2019, there was not a single membrane in Australia that was a trifecta of being a vapour-permeable non-combustible water-barrier. However, since sarking is exempt from compliance with non-combustibility, it is not mandatory for a non-combustible membrane to be specified. Thus, in high-rise apartments, it falls to building practitioners to voluntarily raise their standards above the NCC's hazardously low levels.

11. Conclusion

Energy efficiency, as is implemented through the NCC, has not been about abating greenhouse gas emissions. There is scant evidence that the provisions of energy efficiency in the NCC has delivered a better outcome climatically, economically, or even by way of measured energy consumption. The contrary evidence, ones that show that energy efficiency has been driven injudiciously, are on the other hand plentiful. The NatHERS software has become the de facto reference by which energy efficiency is determined. This does not appear to be the intent or purpose of the software, and this paper has elucidated its many real-world limitations. Moreover, the industry is not making actual progress if the assumptions in the energy model used for simulation are not properly understood by architects, energy assessors, building surveyors and builders. There is a very limited appreciation for applied thermal performance in the industry, perpetuated by facile definitions such as that for *Total R-Value* in the NCC.

If the objective of NCC is genuinely about setting 'the minimum required level for the safety, health, amenity, accessibility and sustainability' of buildings (Vol Two 'Introduction'), then it behooves the ABCB to stop pursuing higher requirements of poorly defined energy efficiency objectives at the expense of the other more pressing concerns such as fire safety of high rise residential apartments, health & amenity in mould-free housing, access to buildings without discriminating against people with environmental sensitivities, resilience of houses to extreme weather events, and measurable climate change mitigation. 6-star construction needs to be done properly by all practitioners, before the industry is in a position to entertain a proposition for 7-stars.

It is high time to stop pushing for changes to the construction code without first funding building research and listening to the advice from architectural scientists.

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