Transitioning to low carbon housing: Don't forget the users

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Abstract

There is increasing focus within the transitions literature on the role that housing, and households, will play in a transition to a low carbon future. Within this research there is a strong call to move past the technical or engineering-based focus to include more engagement with occupants about their housing energy practices. This paper presents three vignettes of low-energy housing and households in Australia and the UK which draw upon quantitative and qualitative analysis. The cases highlight several similarities, but also some key differences. For example, common across the studies occupants reported improved thermal comfort and lower utility bills, some improved health outcomes, but also some struggles to understand new technologies or design elements. It was also evident that occupants had a history of energy practices from previous housing experiences that may no longer be applicable for purpose built or renovated low-energy housing. If improved housing performance fails to engage with users and their practices, it is likely that a low carbon housing transition will be problematic. Houses and their installed technologies may be machines, but they exist only to satisfy the needs of humans, therefore policy makers and researchers should place the user at the focal point to ensure a nuanced understanding of the householder's role in such a transition.

Introduction

The residential sector globally has a significant impact on our environment and accounts for around 12% of annual greenhouse gas emissions and 24% of final energy consumption (IPCC, 2014). However, the housing sector, as with the broader built environment, has been identified has having abundant 'low hanging fruit' in terms of cost-efficient or cost-neutral strategies for improving performance outcomes (BZE, 2013; Edwards & Turrent, 2000; Hoppe, Bressers, & Lulofs, 2011). As such, the housing sector will need to play a critical role in a transition to a low carbon future, especially in the context of a rapidly growing population (IPCC, 2014; Lovell, 2004).

Numerous studies have demonstrated how cities, regions and countries can achieve low carbon outcomes for new and existing buildings, including housing, by the middle of the century (Berry, 2014; Boardman et al., 2005; BZE, 2013; IPCC, 2014; Kolokotsa, Rovas, Kosmatopoulos, & Kalaitzakis, 2011; Schimschar, Blok, Boermans, & Hermelink, 2011). Typically, the technological based strategies achieve low carbon outcomes by improving energy efficiency, reducing energy use and increasing the application of on-site renewable energy. Many proposed strategies have been demonstrated to be cost-efficient and technically viable (Berry, 2014; Boardman et al., 2005; Zhu, Hurt, Correa, & Boehm, 2009), and with the expected continuing reduction in technology costs (IEA, 2010; IPCC, 2014), economic viability should only improve. This is reflected in part by the increasing numbers of jurisdictions around the world who have introduced policies which will require new and existing buildings to meet zero (or near zero) energy/carbon performance outcomes (CPUC, 2011; European Commission, 2010).

The role of occupants in achieving sustainable housing

Purpose built or renovated low-energy housing can only be considered to have the potential for a low-energy use outcome. Actual energy end-use is related to how humans interact with the building through their practices, and importantly its appliances and equipment (Baborska-Narożny, Stevenson, & Grudzińska, 2017; Day & Gunderson, 2015; IPCC, 2014). The literature shows that whether we are investigating thermal comfort related energy use (Berry, Whaley, Davidson, & Saman, 2014b; Eon, Morrison, & Byrne, 2018), or total house energy use (Berry, Whaley, Davidson, & Saman, 2014a; Gram-Hanssen, 2013), household practices have a significant influence on energy end-use. Studies of near identical homes with similar sized families have been shown to have energy use differences of 500% highlighting the role of individual energy practices and the influence appliance selection and use (Berry et al., 2014a; Gram-Hanssen, 2013). Such outcomes are in part shaped not only by the dwelling and its fitout but changing social norms and access to cheaper technology (Moore, Ridley, Strengers, Maller, & Horne, 2017; Shove, 2003). For example , the rapid proliferation of air conditioners which within the space of a generation has shifted occupants from more adaptive thermal comfort practices to ones which are now reliant on mechanical heating and cooling to maintain a set band of comfort conditions (Chappells & Shove, 2004; Nicholls & Strengers, 2014).

This does not mean that building design is not important. The literature also notes that purpose built low-energy homes on average have a significantly lower energy use outcome than similar sized homes that were built to a lesser energy standard (Berry et al. 2014a). It could be argued that the designed and built energy performance standard provides the platform from which occupant practices ultimately determine the extent to which the house performs as designed.

Clearly, occupants will play a role in delivering more sustainable housing outcomes. The IPCC (2014) identify that in developed countries changes to occupant practices could reduce energy demand by 20-50%. However, while we recognise that occupants play an important role in typical housing, less research has explored the implication on, and for, occupants from low-energy/carbon housing. If a sustainable housing transition is to occur, it will be important that those occupants are also part of that transition journey given their importance to delivering more sustainable housing outcomes. This will not likely be an easy transition for households. As Brown, Swan, and Chahal (2014, p. 643) state, ensuring housing is used as designed "is further complicated as a result of apathy or apparent resistance from householders in changing the way they use their homes."

This paper contributes to addressing this research gap by presenting vignettes from three low-energy housing developments and their households in Australia and the UK. Two examples are from Australia (new owner-occupied housing at Lochiel Park in Adelaide, South Australia and a new social housing development in Horsham, regional Victoria) and one from the UK (a social housing retrofit to PassivHaus standard in Manchester) are presented.

Housing transitions research

Within the field of sustainability transitions research there has been a slow but emerging focus on environmentally sustainable housing (Bergman, Whitmarsh, Köhler, Haxeltine, & Schilperoord, 2007; Foong, Mitchell, Wagstaff, Duncan, & McManus, 2017; Gibbs & O'Neill, 2015; Horne, 2017; Laurentis, Eames, & Hunt, 2017; Martiskainen & Kivimaa, 2018; Smith, 2007; Tambach, Hasselaar, & Itard, 2010). The research in this area has typically focused on understanding the socio-technical dimensions of sustainable housing niches and exploring the dynamics and relationships between this niche and the existing housing regime (Smith, 2006, 2007). Broadly the research can be grouped into practice, policy and pathways.

In relation to practice, researchers have looked at sustainable housing from a range of scales as well as the processes and stakeholders involved. In his research Smith (2007) highlights significant differences between sustainable housing and the existing regime and the challenges this presents if sustainable housing is to become more than a niche. Others such as Boyer (2015) and Berry, Davidson, and Saman (2013) demonstrate this through their case study analysis of sustainable housing developments, finding limited evidence that sustainable housing delivery practices spread beyond the niche case study sites. This is contested by Gibbs and O'Neill (2015) to some extent who found some evidence from the UK that the broader housing development regime was becoming more open to environmentally sustainable housing concepts, although the investigation was generally focussed on whether developers were adding technical solutions rather than changing 'business-as-usual' practices. In addition, Martiskainen and Kivimaa (2018) and Fisher and Guy (2011) have explored the role of key intermediaries in the development of more sustainable housing and found they play a critical role.

From a policy perspective, researchers such as Tambach *et al.* (2010), Moore, Horne, and Morrissey (2014) and Gibbs and O'Neill (2015) have assessed existing housing policies around the world against socio-technical transitions frameworks. These researchers have identified that from a policy perspective there were key elements missing from current policies if a transition to a more sustainable, low-carbon housing and energy future was to be achieved. They identified elements such as a lack of a long-term policy agenda, a lack of up-skilling industry, fragmented co-ordination with other related government policies (e.g. greenhouse gas emission reduction targets), and limited engagement with social elements of housing. Furthermore, researchers such as Gibbs and O'Neill (2015) discuss how current policy approaches are pushing the built environment further towards solutions which engage with the technical but not the social.

In relation to pathways, there has been research looking at various ways that could deliver sustainable housing and the implications this would have for policy and practice. For example, Bergman, Whitmarsh, and Köhler (2008), assessed a transition to sustainable housing in the UK through the development of potential policy development pathways to 2050. They found that significant support must be given to protect niche sustainable housing developments if they are to challenge the imbedded regime. Svenfelt, Engström, and Svane (2011) present a back-casting study and identify how although we could technically deliver low-energy housing by 2050, governments will need to be more strategic to leverage key stakeholders who can drive change, alongside any changes to policy.

While there is important research emerging in relation to housing transitions, there has been limited engagement of the role of occupants in, and on, this housing transition. There has been calls for more engagement with occupants and their housing/energy practices and for this to be reflected in policy (Berry et al., 2014b; Brown et al., 2014; Moore et al., 2014), as there has been more broadly a call for more inclusion of social considerations in transitions research. For example, Svenfelt et al. (2011, p. 795) state that 'it is important to ensure that end-user interests are part of technical development, and also that issues concerning behaviour, research on actors and their networks, and innovations in these areas are given increased attention'.

Method

To address the aim of this paper, three vignettes of low-energy housing and their relationships to and with households are presented. Two of the case studies are from Australia and one from the UK. Each has had broader evaluations and analysis of each development presented elsewhere (Berry, 2014; Berry et al., 2014a, 2014b; Moore, Ridley, et al., 2017; Moore, Strengers, & Maller, 2016; Sherriff, Martin, & Roberts, 2018). This paper however looks at these developments from a different perspective, that of the occupant within a transitions context.

The analysis draws upon semi-structured interviews with the households. The interviews explored how occupants were using, and not using, their dwellings and how design and sustainability technology elements were impacting on this. Each case study location had slightly different interview questions as they were part of separate projects, however each covered similar topics making them suitable for vignette analysis. Interviews were audio recorded and transcribed. Thematic analysis was conducted to draw out key ideas from the households.

The first case study comes from a purpose-built environmentally sustainable housing development at Lochiel Park in Adelaide, South Australia which contains just over 100 dwellings. The Urban Design Guidelines (Land Management Corporation, 2009) developed for Lochiel Park established a set of performance requirements designed to create near zero energy homes in a near zero carbon impact housing development. The minimum requirements for each dwelling included:

- 7.5 NatHERS Stars thermal comfort (a predicted heating and cooling energy load of <58MJ/m^2/yr)
- Solar water heating, gas boosted
- kW photovoltaic system for each 100m^2 of habitable floor area
- High star rated (low-energy) appliances
- Low-energy lighting (CFLs & LEDs)
- Ceiling fans in all bedrooms and living spaces
- Rainwater harvesting, feeding the hot water system
- Greywater harvesting, feeding toilet flushing

The Guidelines established a new, more stringent set of rules, calling for practices often outside existing institutional and professional norms, requiring the application of technologies and systems uncommon to the mainstream building industry, and the consideration of new performance indicators bringing new concepts to building design and construction practices. Research has been ongoing at Lochiel Park since 2007 with both technical monitoring and interviews with occupants undertaken.

The second case study is a new social housing development in Horsham, regional Victoria, built for low-income households who pay rent at less than market value. This development was completed in 2012 by the State Government to demonstrate exemplar low-energy housing and to inform future minimum building performance requirements. Four low-energy houses were built to improved building thermal envelope performance and overall sustainability through:

- Reverse brick veneer construction to increase internal thermal mass
- Double glazed windows
- Improved ceiling and wall insulation levels
- 9 NatHERS Stars thermal comfort (a predicted heating and cooling energy load of 25 MJ/m^2/yr compared to a standard 6 Star build 108 MJ/m^2/yr).

- 1.5kW photovoltaic system
- 60c/kW feed-in-tariff
- Households received a 2 hour tutorial on how to maximise the energy performance of dwellings.

A three year evaluation of the housing was conducted between 2012-2015 which monitored technical performance of the dwellings as well as conducting yearly interviews with the occupants.

The third case study concerns a retrofit to PassivHaus equivalent (EnerPHit) standard of 32 social housing flats in two blocks in Manchester, United Kingdom. The retrofit was completed, and decanted residents returned to the building, by May 2015, and between December 2015 and February 2016 research was carried out to both monitor thermal performance and interview residents about their experiences of living in the retrofitted flats. The interviewees were selected in liaison with the social housing owner (One Manchester), and the interview questions were drawn up with the cooperation of those involved in the retrofit development. The team sought to recruit a set of tenants that could provide a reasonable representation of the themes and issues arising through the entire retrofit process, including design and consultation, decanting, and returning to and living in the property.

The interview research was complemented by the monitoring of key physical characteristics of the properties to assess their thermal performance, using small wireless sensors installed in seven sample flats. The monitoring period reflected a need to understand performance across different climatic seasons, and flats were selected to give a range of geographical locations and situations (e.g. ground-floor, upper, corner property).

By bringing these case studies together this paper aims to identify and examine those similarities and differences between various types of low-energy housing developments and consumer markets, and discuss the implications of the research findings for building energy policy and practice as well as housing transitions research.

Vignettes 1 – Lochiel Park

To expand our understanding of the experiences and perceptions of residents in near zero energy homes, qualitative data was gathered through a set of 25 in-depth interviews with Lochiel Park households. This augments quantitative data from the homes which found they performed well in comparison to standard housing across a range of metrics (Berry, 2014; Berry et al., 2014a).

This quantitative performance is supported in the most part with the qualitative data from the households. Almost all households perceived their home to be more thermally comfortable than their previous home, while only one household recalled similar levels of comfort at their previous home. The following comment from a household highlights the tone of statements offered by the interviewees:

> *'More comfortable, heaps more. When you get up in the morning it's not cold. … It seems to run about ten degrees lower [from the maximum] in summer, and ten degrees higher [from the minimum] in winter.'*

Some households noted that indoor temperatures were more consistent throughout each day and across the seasons, and similar from zone to zone (downstairs). For example, a household stated:

' … the thermal comfort is fantastic. Particularly the even nature of thermal comfort throughout the year. The performance in the cooler months is particularly good, during the coldest day the outside temp was zero degrees, but inside it registered 18 degrees, and we hadn't switched on any heating.'

However, this experience of comfort was not uniform across the seasons. Whilst many households expressed positive perceptions of thermal comfort for much of the year, particularly during spring and autumn, the region experiences numerous days in summer when the ambient temperature exceeds 38°C and two fifths of the households mentioned that they suffered periods of discomfort during summer heatwaves. More specifically, almost every household expressed that the upstairs areas were uncomfortable during summer's higher temperatures which highlights an ongoing challenge for multi-level houses and comfort. Despite this, in general households were positive about the level of thermal comfort experienced across the different climate seasons.

As touched on earlier, purpose built low-energy homes are technology rich in comparison with those built to the minimum standard in Australia. In relation to the added technology elements at Lochiel park, overall there was reasonably positive acceptance of the energy technologies by the households. Most of the households expressed that they found the energy systems and technologies easy to operate, however two households expressed being uneasy or unsure about how to optimise the settings on their solar water heater, an issue which is also picked up in the other vignettes. Operating a passive solar house was not perceived to be difficult, with most households stating they felt it is easy to operate the various shade and ventilation options to maintain desired levels of thermal comfort.

The homes at Lochiel Park were designed to be energy efficient and meet much of that lower energy demand from renewable energy sources. This was reflected not just in the technical performance data, but also in the household interviews. Every household expressed a positive story that their energy costs were lower when compared to their previous home, with most suggesting the total energy costs were significantly lower. As summed up by one household in response to energy costs:

'Yes, there is no doubt that this is a lot less to run than our last house.'

Every household also expressed that they believed they were able to live more environmentally sustainably than in their previous home. In particular, households noted that the inherent design of the homes and that of the estate facilitated a more environmentally sustainable lifestyle. The following quote is typical of the responses:

'It's easier to live more sustainably now. In the last house we spent a lot of money with little effect, but here it is much easier. It's also easier because a lot has been done for us and it has been cost effective to invest in improvements.'

This case study has found that the experience of households in these purpose built low-energy homes is overwhelmingly positive, and although residents were quick to point out that these homes are far from perfect, the experiences are appreciated by the occupants and lead to lower net energy use for thermal comfort and the provision of typical household energy services.

Vignette 2

As part of their remit, the Department of Human Services (a Victorian state government department) provides low-income housing to more than 80,000 households in Victoria, Australia (DHS, 2013). As with other low-income housing providers, the department faces an ongoing challenge of balancing the need to provide more overall housing to address increasing numbers on waiting for a home with improving housing quality and liveability of their housing stock. This is what drove the decision by the department to test the outcomes of low-energy housing, in terms of capital costs and occupant impact. The research presented below is from a three-year evaluation into the housing and the occupants.

From a technical performance the houses performed as expected. In comparison to the average performance of new housing, the low-energy houses purchased 62% less electricity, had 50% less CO_2 impact and were thermally comfortable (without air conditioning) 10% more of the time for the living areas and 7% more of the time for the bedrooms compared to standard houses (with air conditioning). Furthermore the low-energy houses were found in the middle of a heatwave to be more than 16°C cooler, *without* air conditioning, than standard department housing *with* air conditioning (Moore, Ridley, et al., 2017).

These outcomes were not just restricted to technical performance improvements but had tangible impacts on the occupants. The most significant implications for the households, as self-reported, was in lower energy bills and improved thermal comfort. This had led to broader improvements to quality of life and health outcomes such as reduced stress around finances and a reduction in cold related health issues. For a cohort with limited means, these changes had been significant for them.

In relation to energy costs, all households (except one who had not lived out of home previously) reported significantly lower energy bills in comparison to their previous residence, similar to what was found at Lochiel Park. Combined with the feed-in-tariffs, two households reported being in credit on their bills after three years of occupation, while another mentioned being in credit at different times of the year. This had a measurable impact for the households who found they had reduced stress around paying energy bills and had additional funds for discretionary shopping. For example, one household stated:

> *'Look I haven't paid any off my power bill in six months and I'm still in credit…$882 [currently in credit]'.*

Another had a similar outcome saying:

> *'…I've saved so much money in the time I've been here because not paying, you know, so much electricity bills and stuff so my bank account's sort of got up a bit and it's like wow this is alright.'*

This improvement to energy bills seems to have been driven mostly by the high feed-in-tariff rates (60c/kWh) and by a reduced need for heating energy and not having any air-conditioning eliminated the majority of energy for cooling, although there were two low-energy ceiling fans in living areas which were used during warmer periods. When asked to talk about how they consumed energy in other parts of the home (e.g. appliances, lighting, cooking) the occupants did not feel that they had changed their energy practices for these activities from how they were in their previous, standard housing. The main changes they had made to their energy consumption was using their heating less and not having air-conditioning.

However, while the occupants were appreciative of the financial benefits, it was not all positivity for the solar systems on the dwellings. While the system was included with the house at hand over to the occupants, the systems had not been through the final connection commissioning process. It was several months before the occupants realised they were not getting benefits from the solar. The occupants then struggled to work out how to have the systems properly connected. In the end the department oversaw the final connection of the solar panels. In addition, there was at least two examples of technical challenges with one of the systems being faulty and another example of a system being accidently switched off. In both cases it took several bill cycles to identify there was an issue as there was no in-house monitoring of the solar generation. One of these impacted households estimates that they lost at least $200 in solar feed-in-tariffs.

In relation to thermal comfort the occupants were surprised at how the design of the homes meant they required little heating and cooling inputs in comparison to previous housing they had lived in. For heating they had a single gas wall heater in their living area which they found more than sufficient for keeping the house warm in winter, even with the temperature dropped outside to below zero degrees, although most households found that there were cold spots in the house such as the bathrooms which they would like addressed. Overall though, they were very happy with the thermal comfort. As one of the occupants remarks:

> *'Well, we both feel the heat pretty well but when it was 42 degrees outside, it only got to 29[^{o}C] in here…when it was three degrees below zero this was 15 degrees inside on that morning, that's without any heaters being on, 15 degrees. So that's good.'*

The houses were designed to not require mechanical air conditioning. However, one of the households retrofitted a reverse cycle air conditioner for health reasons. Analysis of the thermal performance data of that particular house found that it performed as per the other houses and the occupants rarely used the air conditioning system – it seemed to have been installed more as a security blanket for the aging occupants in case it was needed. This reflects the challenges households have in letting go of certain household practices, even though the household was told by experts how the house would not need the cooling system.

In the absence of mechanical cooling, the households did find that even though the homes did not get too uncomfortable, that they were required to engage in adaptive comfort practices to ensure the house performed as designed. For example, lowering the blinds in the mornings to block out the sun and opening the windows in the evening to vent any build-up of heat. While some of these practices were ones they had undertaken in previous houses, it was clear that the new houses had required them to engage with these practices on a more regular basis. Generally, these practices were accepted by the households as what needed to be done to maintain thermal comfort during summer, and especially extreme weather days. However, one of the households disagreed with one of the design elements which they were meant to engage with. In this case the architect had placed celestial windows on one side of the home to help with venting hot air. The particular household felt the windows were on the wrong orientation and would let hot air in due to the wind direction rather than vent it out. No amount of discussion with the architect would convince them otherwise.

Another challenge was that ceiling fans in living areas had a reverse direction on them to help in both summer and winter. However, the reverse switch was on the fan itself which required occupants to call out a department maintenance worker to fix. This was seen as problematic and there was some evidence that not all households were aware of this requirement to reverse the ceiling fan between seasons. Several of the households mentioned that they would have liked a ceiling fan in the bedroom as well to help during heatwaves.

Overall, it was clear the occupants in the houses loved them and were very house proud during all the site visits for the research. While the houses were designed to not require significant occupant engagement for sustainability and comfort, there was still some requirement for households to follow some basic principles of adaptive comfort to maximise outcomes. Some occupants broadly followed the 'use' requirements, while others seemed to pick and choose which of the adaptive practices they followed.

Vignette 3 – PassivHaus Standard Retrofit in Manchester, UK

One Manchester manage 12,000 homes in central, south and east Manchester. In upgrading part of their stock to PassivHaus standard, they aimed to help reduce residents' bills, created new community greenspace, and make the area, which had a reputation for rundown buildings and anti-social behaviour more appealing. As part of the retrofit process tenants were decanted to housing in other areas. Whilst this caused some disruption it was considered to be preferable to the impacts on physical and mental health of continuing to live on-site whilst the substantial works were taking place.

A before and after study was not within the scope of the research. Physical monitoring carried out on the retrofitted dwellings found that the monitored properties were 'highly controllable and comfortable' (Sherriff et al., 2018). The data found some variation in an acceptable range and that many of the flats evidence a high level of comfort across the majority of the monitored period.

The household interviews verify this and the vast majority of interviewees were also positive about the retrofitted dwellings. These responses are not atypical:

'Yes, I know, it's lovely. It's like this all the time, even in winter it's like this'

'It's perfect. It's never too hot and it's never cold. Perfect.'

Some, but not all, residents had lived in the building before the retrofit. They were able to make a comparison which highlights the improvements achieved through the retrofit:

'Previously, when we were here... on a day like this, we would [be] in this room, be sat with coats and, oh my God. Oh, it was horrendous and when we came in here, it's like, wow. It was different. It was warm. It was all warm but it was nice.'

However, while the majority of households were pleased with the retrofit, a minority reported some issues. One household raising the issue of draughtiness and another household stated that it could be stuffy at times:

'It is very fresh when you come in. If it's absolutely scorching outside, I always come in and it's nice and cool. It can, to be fair, feel very stuffy, like there's no air from time to time.'

Another noted that indoor temperature was affected by occupancy, observing that it *'generates of our own energies, so you could massively tell when other people were in'*.

Tenants associated these improvements with increases in their wellbeing. One tenant saw improvements in terms of their asthma whilst another remarked that her son had been able to sleep better since the retrofit and that '*because of the quietness as well he's got time to study'*. In general, reductions in the costs of heating were also noted and these could be expected to reduce financial stress for tenants on relatively low incomes.

A further element of wellbeing, not directly related to energy, was aesthetic improvements to the building. There was an implied sense of pride and positive effect on social relationships as summarised by this household: '*If you look outside, they look brilliant. Any friends of mine who come, I get in touch and they are invited around and they come, they can't believe the change.*' And, they thought, provided contrast to the surrounding area '*It's lovely once you're here, it's just getting to here.*'

Levels of understanding of the PassivHaus retrofit and the new heating system varied as seems to be the case in the other two vignettes. It was clear that the housing provider had provided extensive information in different forms, including a booklet, face-to-face meetings, and telephone support. Tenants felt that support was available if they needed it:

> *'… then if it's something that they should talk me through on the phone they will talk me through. If they need to send someone, they will send someone'*

Interestingly, there was some sense that tenants felt that there was a 'correct' was to live in the properties: '*to manage the properly according to how they expect me to manage it'*. On the whole, however, tenants felt they did not understand the detail of the system or at least struggled initially:

> *'None of us really got the scientific part… and, to be honest, it was very high tech for a lot of people round here'.*
> *'Myself and my partner finally got it after about two or three days of reading'*

These concerns about understanding the technical features notwithstanding the evidence suggested that these did not impede their enjoyment of the homes. Most said they rarely touched the control panels and had little need to because the climate was reportedly highly comfortable. Some implied a sense that it was better in any case to let the system regulate itself.

Unlike Vignette 2, there was little reference to adaptive practices, which may reflect the period of time over which the tenants experienced the building in terms of their exposure to long periods of hot weather. One of the examples that was given was opening the child's bedroom half an hour before going to bed '*because he's got the hottest room in the house*.'

Although overall tenants felt that they needed to interfere with the heating system less than before, some frustration was expressed at a general lack of control over water temperature and the fact that boilers were now locked away, accessible only to maintenance staff. Additionally, the consolidation of energy services at building level meant that tenants were obliged to go with an energy supplier chosen by the housing provider.

Some additional non-energy issues were raised by the tenants. These are important to note here not only because they illustrate the way non-energy, and to some extent unexpected, features are important to the residents but also because many of them relate directly to the ambition of maintaining the low-energy performance of the building. One example is window cleaning. Out of concern for the external fabric of the building, and its thermal performance, the housing provider were concerned that only approved window cleaners could operate. However, interviewees remarked upon the frequent of cleaning, saying they would have them cleaned more often if allowed to bring in their own cleaners: '*we're not allowed our own window cleaners because of what the building's made of, but as a women there's no way I'm putting up with just twice a year cleaning of windows.*' Tenants questioned the assumption that another window cleaner would not be able to be sensitive to the fabric of the building.

Another example related to satellite television. One resident who had been effusive in his positive feedback on thermal performance and financial savings, '*the most important thing*' he wanted to share with the interviewer was that he had felt unable to maintain links to a wider cultural and linguistic base: '*what we want is our native channels'*. Out of concern for the fabric of the building, the housing provider had placed a restriction on affixing satellite dishes to the sides but provided a communal antenna, but the direction it was set at did not reach the channels this interviewee was interested in.

There were also concerns about wider parts of the development including the gardens. These had been re-landscaped and limitations placed on the types of planting and species of trees allowed. Whilst unrelated to the energy development, this appeared to add to a sense of imposition:

'I quite like gardening. So that was a bit disappointing.'

Like the other case studies, the Manchester residents were generally very positive about their retrofitted home. Relatively low-energy use and high thermal comfort were important elements of this, but broader wellbeing, including health and children's study time was also mentioned, as were the aesthetic elements of the retrofit. To an extent this is a methodological point – that interviewers can lose or overlook considerations of value to the residents if they focus purely on energy – but it also reflects the nature of this development, which amounted to a complete overhaul of a building that substantially improved not only thermal performance but also the whole look and feel. In noting these broader benefits, however, we need to remind ourselves of issue not directly related to energy that not only detract from tenant wellbeing but are also likely to influence their views on energy efficiency measures, and the stories they tell to their housing providers, friends and neighbours. In this case many of these non-energy issues, such as window cleaning, cat flaps and satellite dishes, stem directly from concern for the PassivHaus standard and therefore the energy performance.

Discussion

The cases highlight several similarities, but also some key differences. For example, across the studies occupants reported improved thermal comfort and lower utility bills, with some mentioning improved financial and health outcomes. It was also evident that occupants had a history of energy practices from previous housing experiences that may no longer be optimal for low-energy housing. This is an important consideration if such housing is to perform as designed. There is a real danger than unless occupants learn to engage with low-energy housing practices, or that designs allow for bringing these old practices, that they may find that housing performance is not optimal. This is a challenge for designers to ensure that the housing can help guide occupants to create new/revised practices but also for occupants to understand that low-energy housing may require different ways of using the dwelling. Winter (2016, p. 384) argues that the current focus on the fabric and technology of buildings needs to be complemented with 'a more expansive discussion, one that seeks to sustain low carbon practices'. As mentioned earlier Brown et al. (2014) talk about this challenge after finding evidence that some households were unable, or unwilling, to engage with new energy practices.

Across the case studies, whilst improved indoor conditions and energy savings superficially tell a very positive story, the occupants self-reported new challenges. Examples of challenges include some residents struggling to most effectively use unfamiliar technologies or the homes not performing as expected in all conditions, such as cold UK winters and overheating in extreme Australian summer weather events. There were further examples of energy-related factors impinging on other aspects of life. Some households in case studies 1 and 2 had issues with their renewable energy systems not working to their expected performance, but due to a lack of occupant knowledge, or in case study 2 a lack of in-home monitoring, underperformance was not able to be identified until the quarterly energy bills were received – this meant that they were not getting the full benefit of using the renewable energy. This impacted both the amount of electricity they had to buy, but also financial benefits from the associated feed-in-tariff for surplus electricity sold to the grid. However, several of these houses in both case studies 1 and 2 were net zero cost energy housing, being in credit on their energy bills, even after three or more years. Many of the Manchester residents found they could let the home regulate itself in terms of thermal comfort, this may reflect the difference in international contexts – particularly heating dominated rather than cooling dominated climates. These residents had not experienced a prolonged hot spell since moving (back) in, but the intensifying of heat waves as a result of climate change may put the building's tolerance to the test and a need for adaptive comfort practices may become apparent.

Whilst residents in the Manchester retrofit reported a wide range of wellbeing improvements, both directly and indirectly related to the energy performance of the building, they also raised concerns about restriction placed upon them, such as use of their own satellite dishes, being able to arrange their own window cleaners and having letter boxes and cat flaps. This is likely to become an ongoing challenge for all households as we deliver more sustainable housing, that they will require careful consideration of any major, or minor, changes or additions in order to not impact on overall performance. It is also a reminder that issues that appear to be non-energy related may become uppermost in the list of occupant concerns, despite these being potentially the most difficult to anticipate. In the case of social housing these may bring about a sense of resentment or imposition that outweighs the benefits. This is an important point when considering resident, and housing associations, 'buy in' and the importance of creating a positive narrative (Brown et al., 2014) around low-energy new build and retrofit.

Furthermore, the low-energy housing presented in this paper all still required some level of occupant engagement to ensure that maximum performance was achieved, especially in relation to thermal comfort. It is interesting however that this was true to a far lesser extent in the Manchester case study, perhaps indicating that this issue becomes more pressing in low carbon housing in cooling-dominated climates or the improved performance of the PassivHaus standard. This raises questions over if such adaptive thermal comfort practices, no matter how minor, can be undertaken by everyone, as has been raised elsewhere (Brown et al., 2014; Moore, Ridley, et al., 2017). For example, should we expect that elderly occupants put blinds up and down and could occupants of any age do this if they have say a bad back? In case 2 where there was a requirement to change the direction of the ceiling fan with the switch being located on the unit demonstrates the problematic nature of some of these occupant requirements.

On the other hand, there are sustainability elements such as solar photovoltaics which provide a benefit without the occupant doing anything. Of course, the benefit is magnified if the occupant understands about using the energy when it is generated (depending on the feed-in-tariff rate). This prompts questions about how much of the design should be passive and how much should be left to be active by occupants. As stated by Moore, Nicholls, Strengers, Maller, and Horne (2017)'tenants engaged with their dwellings in a range of ways (predictable and unpredictable) that both supported and undermined sustainability objectives'. In case study 2, with no air conditioning installed, it meant that the occupants could not use it, and so had to change their practices accordingly.

This research adds to a growing focus in transitions research on housing (Horne, 2017; Laurentis et al., 2017; Martiskainen & Kivimaa, 2018; Smith, 2006; Svenfelt et al., 2011). While this previous research has not ignored the occupant as part of their research, there was a need to more clearly bring the occupant into the discussion around housing transitions. It is evident from the research in this paper that this is not just about the ‘end point’ for a housing transition (whatever that might look like) but also ensuring that the occupant is brought along on the transition journey. This may mean that policy makers and researchers need to start looking more closely at what improved standards of housing mean for different use practices and how to bridge any disconnect between current practices and those which may be required in the future. Considered design of housing will be part of this outcome, but so too will be the need to engage occupants on a far deeper level if a sustainable housing transition is to occur.

Conclusion

Sustainable housing is an increasing focus of transitions researchers and policy makers. To deliver such housing will require improvements to design and technology. The occupant has been found to be important in determining the energy performance of housing, although there is less research which has looked at their impact in more sustainable housing. This paper has added to the emerging research in this area by exploring three cases; two from Australia and one from the UK of more sustainable housing and their households.

What was clear from the case studies is that the user is a critical element if the expected low-energy and carbon outcomes are to be achieved. If improved design, performance, technologies and building systems fail to engage with the users and their practices, it is unlikely that a transition to a low carbon housing future will be expeditious and smooth. This applies to practices related to staying warm and cool as well as practices that at first appear to be unrelated to energy but can be shaped or restricted by energy-related changes. Providing an improved quality of life for all occupants is not only intrinsically important but influences how people perceive low carbon housing and the acceptability of a low carbon transition. Houses and their installed technologies may be increasingly machine-like, but they exist only to satisfy the needs of their occupants, therefore policy makers and researchers should place the user at the focal point to ensure a more nuanced understanding of their role in such a transition.

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