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ORIGINAL ARTICLE

The influence of design and everyday practices on individual heating and cooling behaviour in residential homes

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Abstract Emerging results from practice-based research demonstrate that energy efficient houses often do not meet theoretical energy use based on the current standards of residential buildings. A factor influencing this inconsistency is related to user behaviour and everyday practices. The objective of this research is to uncover some of the complexities associated with the practices of heating and cooling in the home, which are influenced by motivations, knowledge and technologies, including the use of photovoltaic panels. For this purpose, ten Australian houses were established as embedded Living Labs and monitored for over a year. The results confirm the variation of energy use in houses; in this case, similar designs vary by up to 33%. The type of heating and cooling systems that houses rely on through the year was found to be a major determinant in energy use. However, energy variation between houses is also linked to intra-home practices and behaviours. This research found that individuals living in the same house may have different motivations and/or heating and cooling practices, affecting the overall energy use. For instance, one individual who is motivated to save on energy bills might turn on appliances during the day to make the most of solar panels or use the heater for brief periods of time, whilst another inhabitant of the same house might turn on the heater for extended periods out of habit or to achieve a hedonic experience. The adoption of an explanatory design mixed-method approach to study everyday practices in the home showed that the routines, household configuration, technology and varied occupant motivations impact on the practice of ambient heating and cooling, impacting its regularity, duration, time of the day and intensity.

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Introduction

Emerging results from practice-based research demonstrate that energy use in actual houses do not necessarily match modelled energy use based on the current standard assumptions (Guerra-Santin et al. 2009; Ambrose et al. 2013; Hens 2010).

Energy use in residential dwellings is influenced by numerous factors including building design, technology, user behaviour and everyday practices (Lucon et al. 2014). Stephenson et al. (2015) described the influences on energy use as energy cultures, where energy use is shaped by norms, practices and material cultures (technology and infrastructure), which in turn are influenced by external factors. However, energy use and emission reduction in buildings are usually effected through the improvement of the building envelope, the adoption of energy efficient technologies and the implementation of renewable energy sources, culminating in what is known as passive, low or zero-emission houses (Berry et al. 2013; Saman 2012). Whilst these system initiatives are important, they are based on technical innovations that do not necessarily consider the everyday practices of home occupants. It follows that occupant behaviour, the interactions between occupants and technologies and the activities occurring inside houses provides the social context that make up the home (Guerra-Santin 2017).

It has been demonstrated that changing occupant behaviour alone can achieve significant energy savings (Lopes et al. 2012; Gynther et al. 2011), but it is unclear how large these savings can be and how context affect them. The lack of understanding of home dynamics and intra-home practices and behaviours means that energy demand varies significantly between dwellings (Blight and Coley 2013) and one house can consume up to five times more energy than its identical counterpart (Gram-Hanssen 2012).

One approach to affect behaviour has been through knowledge on socio-psychology (see Ajzen 1991; Festinger 1957; Cialdini et al. 1991) where the emphasis has been on modifying behaviour through influencing attitudes, providing information and social norms and delivering feedback (Abrahamse et al. 2005; Steg 2008; McKenzie-Mohr and Smith 1999). However, this approach has been criticised as it attempts to prescribe how one should behave and persuade change from a top-down oriented approach without taking into consideration intrinsic motivations and needs (Brynjarsdóttir et al. 2012). Whilst technologies such as smart metering and in-home displays have been widely used to deliver feedback to households and make them more aware of their own energy use (see Ueno et al. 2006; Peschiera et al. 2010; van Dam et al. 2010; Vassileva et al. 2012; Fischer 2008), the effects of these persuasive approaches can be short lived as they may not become embedded in users' everyday practices (Lockton 2017; Brynjarsdóttir et al. 2012).

Modifying occupant practice is a different approach to influencing household energy demand. This approach posits that energy use is mainly affected by practice or by how a certain activity is carried out. Practices in turn are the result of habits, knowledge (skills, competence), motivations (image, meaning) and technology (stuff, material) (Gram-Hanssen 2014; Scott et al. 2012; Shove et al. 2012). They are also dependent on context, relationships within this context and the evolution of technologies and infrastructure over time (Shove et al. 2015). This means that unless a specified technology successfully meets a desired outcome and becomes embedded in everyday routines within a specific context, it will not be successfully adopted by households. In addition, knowledge about the specified technology is essential to avoid potential rebound effects (Sorrell et al. 2009). Individuals living in the same environment might also have different attitudes and act differently on a daily basis. An improved understanding of daily practices and needs in real homes may enable the development of effective technology leading to a more sustainable outcome, although the multifaceted layers of elements that influence practice and behaviours in the home are not well understood.

Living Laboratories (Living Labs) are existing places that enable the development and testing of innovative technologies for sustainable living in conjunction with users and other stakeholders (Liedtke et al. 2012). Several definitions of Living Labs have been developed in recent years (Burbridge et al. 2017; Leminen and Westerlund 2012; Leminen et al. 2015), but most of them feature Living Labs as real-life places that support the co-creation and testing of innovation whilst also focusing on user awareness and providing insights into user behaviour and daily practices. There are different scales of Living Labs; urban, dedicated and embedded (Rosado et al. 2015; Elfstrand et al. 2017; Liedtke et al. 2015). Embedded Living Labs consist of existing places, such as workplaces or residences, where the practices being studied occur. This approach enables the observation of users in their own ecosystem, interacting with familiar people and objects in an everyday context. Mixed approaches with varying levels of user involvement can be implemented in Living Labs; the first level consisting of understanding current user practices within homes and obtaining insights through both qualitative and quantitative perspectives (Herrera 2017; Liedtke et al. 2015).

The ten House Living Labs project, consisting of ten Australian embedded Living Labs, aims to obtain deeper insights into user practices and behaviours as well as to understand how these affect energy use at a home level. This research focuses on heating and cooling systems and the use of rooftop photovoltaic panels, which have been increasingly adopted in Australia and are currently present in 19% of Australian dwellings (ABS 2016). The research contributes to an understanding of how the integration of everyday practice in the physical house system can enable the transition from energy efficient housing to user-based energy efficient homes.

Methods

Ten house Living Labs

Ten Australian houses were established as embedded Living Labs for 1 year in order to reveal detailed patterns of energy use associated with different housing designs and to provide better insights into the behaviours and practices of occupants.

The selected houses are located in the City of Fremantle (Western Australia) within close proximity to each other and therefore in the same microclimate. Fremantle has a warm temperate climate, with yearly temperatures averaging between 10 and 27.9 °C (Bureau of Meteorology 2017). Regular afternoon sea breezes cool the city down in summer. Due to the mild Fremantle weather, heating and cooling systems are not used on a regular basis but reserved to extreme temperatures both in winter and summer.

The selected houses consist of single detached dwellings, which are the predominant residential typology in Australia. They have mixed occupancies, designs and heating systems (Table 1). The participant houses comprise of older dwellings that have been retrofitted to include energy efficient features such as added insulation and renewable energy (solar panels and solar hot water); modern houses that were built to meet the minimum current Australian building standard of 6 stars, and high performance houses rated 7 stars or above. This star rating system, which rates houses from 0 to 10 stars (10 being the best rating), is based on passive solar design principles, for instance, using shading and natural ventilation to cool the house down in summer and making the use of direct sunlight as well as thermal mass to warm the house in winter (McGee 2013). In theory, the higher the star rating, the lower the energy load per square metre required to keep houses thermally comfortable year round. The thermal comfort range in Fremantle is considered to be between 20 and 25 °C (DEE 2012), although some international studies suggest that the thermal comfort range can be wider in naturally ventilated environments (Manu et al. 2016; Kumar et al. 2016). Whilst the Australian Nationwide House Energy Rating Scheme (NatHERS) focuses on energy use for heating and cooling and does not predict the total operational energy demand of a house, the ratings are often used as an indicator of comfort and building energy efficiency since heating and cooling represent 40% of the typical energy use in Australian houses (DEWHA 2008).

Nine of the selected houses possess solar panels, and eight houses possess a solar hot water system. Renewable energy is not mandated by the National Construction Code (NCC) but is being adopted on a wide scale in suburban Australian houses (ABS 2016). Aside from the different designs and ratings, the houses in this project can be considered a higher technical standard than the average Western Australian house, which use on average 5595 kWh/year of grid electricity (IMO 2014) and 4726 kWh/year of gas (ATCO 2014). The houses selected for this research enables us to study user practices and behaviours under the influence of home energy systems with a significant renewable contribution.

Mixed methods for data collection

Several techniques with varying levels of user engagement can be employed in Living Labs depending on purpose. These can vary from the observation and understanding of daily practices to the co-creation and testing of new technologies and solutions where the user is central to the process (Herrera 2017). The first level of integration involves sporadic user engagement and is mostly descriptive as it aims to generate knowledge about baseline practices (Herrera 2017). The ten house Living Labs are positioned at this first level of integration. An explanatory design mixed-method approach was adopted for data analysis (Cresswell 2007), where in-depth qualitative data followed up on specific quantitative results to help interpret everyday practice (Creswell and Plano 2011).

Quantitative data collection

Monitoring equipment (Table 2) was installed in the participant houses for the measurement of temperature in the living area, grid electricity use, gas use and photovoltaic electricity generation in the nine houses that possess solar panels. The monitoring equipment consists of sensors that are coupled to existing metres and transmit electric pulses to a data logger. The data logger collects the data at 15-min intervals and transmits

Table 1 Building and occupancy characteristics

House	Year built	Occupancy	Building systems	NatHERS code/description	Total energy use in 2015 (kWh)
A	1950 renovations in 2011	2 adults and 2 children	Electric heating and cooling;1.5 kW PV; solar hot water with electric booster	Retrofitted	4411
B	2013	1 adult, and 3 teenagers	Electric heating and cooling; 2.66 kW PV; solar hot water with gas booster	6 stars	8425
C	2013	2 adults	Electric heating and cooling; 1.8 kW PV; solar hot water with gas booster	6 stars	7238
D	1901 renovations in 2014	2 adults and 3 children	Electric heating and cooling; 3.5 kW PV; gas water heater	6 stars	6558
E	2011	2 adults and 1 young adult	Electric heating and cooling; 2 kW PV; gas water heater	7 stars	7062
F	1899 renovations in 2001	2 adults	No cooling; electric heating;1.68 kW PV; solar hot water with electric booster	Retrofitted	3248
G	2013	2 retired and 1 young adult	Electric cooling; gas heating; solar hot water with electric booster	6 stars	8399
H	2009	4 young adults	No cooling; gas heating; 1.2 kW PV; solar hot water with gas booster	8.5 stars	7073
I	1920 renovations in 2014	2 adults and 2 children	Electric heating and cooling; 1.1 kW PV; solar hot water with gas booster	DTS	3567
J	2011	2 adults and 2 children	No heating or cooling 2.28 kW PV; solar hot water with electric booster	8 stars	5731

DTS or 'deemed-to-satisfy' means that the house follows prescribed principles of passive solar design, but the required energy loads for heating and cooling have not been calculated. Energy use in this table includes grid electricity, solar electricity and gas used in 2015

csv files to the researchers remotely once per week through a 2G wireless connection. In one of the houses (house E), the gas metre was located on the other side of a concrete driveway and connection between the metre and the data logger was not feasible. In this house, data collection for gas consumption was recorded on a local data logger Onset Hobo UX90 512 K and downloaded manually once per month. Photovoltaic electricity exports were not measured, but this information was obtained through electricity bills, requested from the occupants at the end of the project. External temperature data was collected from a weather station (Vaisala WXT520) belonging to another house monitoring project and also located in the City of Fremantle.

Over the period of 1 year, 35,040 data points were collected remotely for each metre in each house. A systematic approach was used to analyse the data. At first, the research focused on understanding the energy and thermal performance of the houses as compared with their designs. For that, the houses total energy use per square metre and internal temperature distribution over the year were analysed and compared with the levels of energy use and comfort estimated by NatHERS. The research then explored differences in seasonal energy use between houses and discussed the influence of technology. Energy used for heating and cooling were characterised by peaks over the baseload energy, baseload energy being the energy used in Spring

Table 2 Monitoring equipment specification

Parameters monitored	Metres and sensors	Data logger
Gas	Ampy 750 gas metre and pulse counter Elster IN-Z61 or Onset Hobo UX90 512K	Schneider Electric COM'X 200
Grid electricity	Schneider Electric iEM3110	
Photovoltaic electricity generation	Latronics kWh	
Internal temperature	Kimo TM110	

(September to November) and Autumn (March to May) when thermal control was not required.

The next step of the data analysis consisted in obtaining a better understanding of household daily practices and differences between households. Line and bar graphs showing average winter and summer diurnal energy use, internal and external temperatures were plotted for each house. This method, however, did not capture daily nuances in heating and cooling practices. Given the usually mild weather conditions in Fremantle, neither heating nor cooling are used on a daily basis in winter or summer, especially in modern houses such as the ones in this project, which are designed to require less heating and cooling energy loads. This means that monthly or weekly averages do not necessarily reflect thermal control practices. The coldest and hottest days of the year were therefore chosen to illustrate differences in heating and cooling practices between homes.

A more detailed understanding of everyday intra-home practices was obtained through the analysis of energy contour plots graphed by the software OriginPro. These contour plots highlight energy used for heating and cooling, as they are the highest energy uses in the home. Winter and summer energy (gas or electricity according to the house system) peaks were therefore attributed to the use of the heating and cooling systems, respectively.

An algorithm was also developed to run through the database to detect the moment that the heating and air conditioner systems were turned on through the months of winter and summer in houses possessing heating and/or cooling systems. The algorithm associated the use of the heater with an increase in energy greater than 0.6 kWh (electricity or gas according to the house system) followed by an increase in internal temperature. The location of the temperature sensor in the living area ensured that an increase in temperature due to cooking activities was not captured by the sensor. Similarly, in summer, an increase in energy use followed by a decrease in internal temperature was attributed to the use of the air conditioner.

Qualitative data collection

Qualitative data about individual behaviour and everyday practices was obtained through semi-structured interviews (Kallio et al. 2016) which were conducted at the participants' homes at the end of the data collection period in order to minimise interference. Whenever possible, all household members were involved in the interview process, which consisted of two stages. Firstly, the interview focused on understanding behavioural elements and included questions formulated based on the theories of planned behaviour (Ajzen 1991), normative conduct (Cialdini et al. 1991) and cognitive dissonance (Festinger 1957). Discussions revolved around individual attitudes concerning energy use and greenhouse gas emissions, perceptions of other people's attitudes (in the community), barriers and opportunities to reduce energy use in the house; attempts to reduce energy use in the past, and finally, support amongst household members with regards to saving energy. The questions were open ended, and discussions about other related topics and between household members were encouraged. The second stage of the semi-structured interview targeted everyday practices. The participants were shown a summary of their historical energy use resulting from the 12 months of quantitative data collection and asked to comment about any reasons for having consumed more or less energy in 1 month in comparison with another. This was followed by a home walkthrough whereby participants lead the way talking about their heating and cooling practices, use of standby on electrical appliances, experience of lighting and dishwasher use. The researchers took this opportunity to note the technologies present in the house and their respective efficiencies (with the occupants' consent).

The answers obtained from the semi-structured interviews and more specifically from the discussion about the quantitative results were used to interpret the quantitative data obtained through the house monitoring system. This method is based on the explanatory design mixed-method approach, which uses qualitative data to provide in-depth interpretation of measured quantitative data on a case-by-case basis (Cresswell 2007). This approach builds on previous practice research, which used integrated approaches to complement and explain practices in the home (Foulds et al. 2013).

Experimental design and constraints

Data collection started in December 2014. The first year of data collection, 2015, reported here has been used to determine energy use and baseline practices in each household. The observation of behaviours and practice were not emphasised to the participants during this year so as to minimise interference. The emphasis instead was put on the performance of the building envelope. Participants were asked to continue with their normal activities, and interactions between the researchers and the households were kept to a minimum. In a few cases, technicians had to be sent to the houses to solve data collection errors or equipment failure. Nevertheless, the researchers did not engage with the households until the end of 2015. The 1-year longitudinal nature of this experimental design ensured that everyday practice was not affected by the research in the long term (Keyson et al. 2017).

A software update between May and June 2015 caused data logging failure in multiple houses, resulting in 2 to 6 weeks of data loss. Additional data loss was also experienced in house H due to water damage to the data logger caused by intense rainfall. Data loss was estimated based on average values from the preceding and subsequent days to the loss.

House H was sold and vacated in November 2015, and whilst the new owners agreed to continue with the quantitative data monitoring, interviews were not carried out. House H has therefore been excluded from the results concerning occupant behaviour, practices and appliances.

The first 2 months of data collection for house I was hindered due to house renovation and occupant travel. The year of data collection for this house is considered as March 2015 to March 2016.

Results and discussion

This section commences with a discussion of the energy use in the houses over the first year of data collection and provides an analysis of the influence of design and technologies. After the initial overview, a close analysis of household dynamics, lifestyles and intra-home practices related to the use of heating and cooling systems is made.

House energy and thermal performance

Building design and performance standards play an important role in improving the energy performance of houses; however, day-to-day house operation is also largely affected by occupancy and lifestyle (Guerra-Santin et al. 2009).

Figure 1 collates the total energy use (gas, grid electricity and solar electricity) per square metre in each of the participant houses for 2015. The houses have been grouped in typologies according to their heating and cooling systems.

Heating and cooling are typically responsible for 40% of the energy use in Australian residential properties (DEWHA 2008), and there is an expectation that higher-rated houses will use less energy per square metre than lower-rated houses or older properties, which are generally draughty and built with little or no added insulation (Ambrose and Syme 2015). Results show that on average, the 6-star houses used more energy per square metre than high-performance houses and that the 7-star house used more energy per square metre than the 8-star house. However, we also found a variability of 33% between the total energy use per square metre of 6-star houses with similar designs (i.e. double brick walls, ceiling insulation and solar hot water). This is in accordance with Gill et al. (2010), who have found that similar houses can present differences of up to 37% in

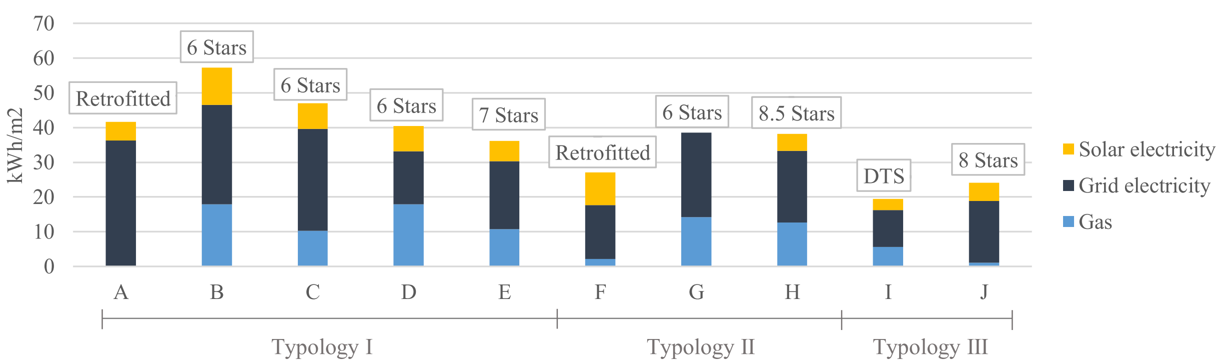

Fig. 1 Energy use per square metre in the ten homes in 2015 grouped by house typology. Typology I includes houses that possess mechanical heating and cooling; typology II are houses that only possess mechanical heating; and typology III are houses that do not possess or do not use mechanical heating or cooling. The implications of typology for energy use is discussed in detail in 'Annual profiles and typologies'

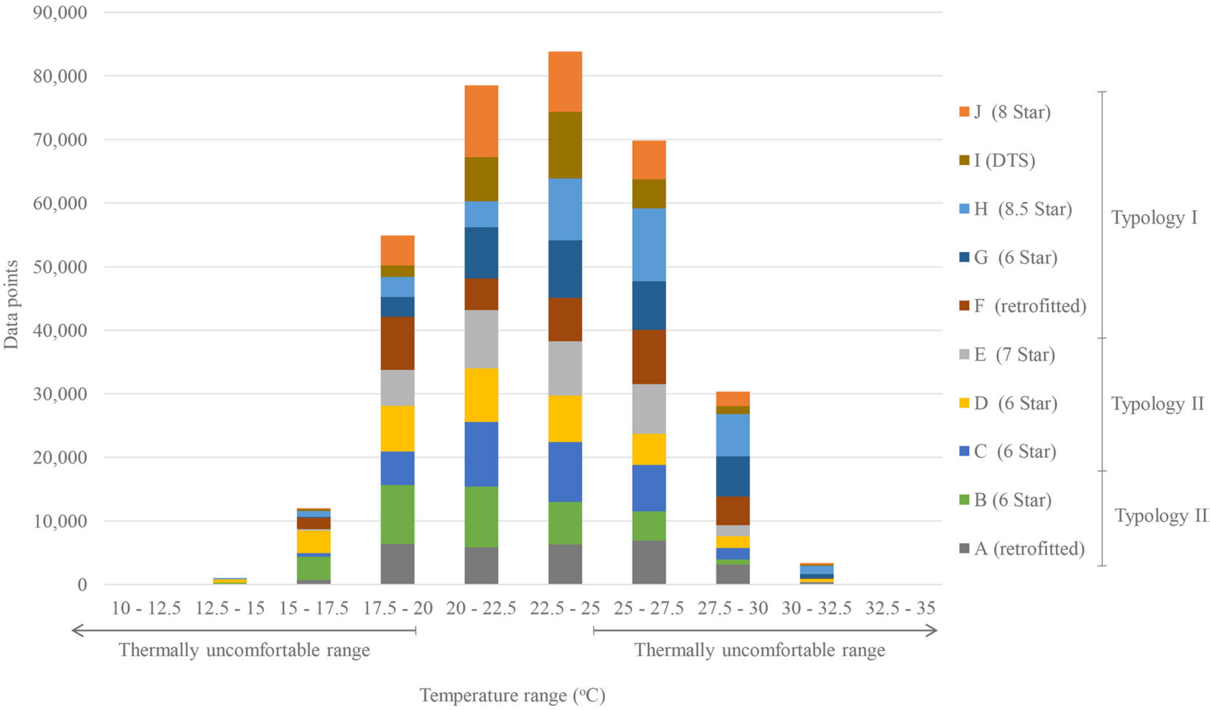

Fig. 2 Temperature distribution in the different houses throughout the year of 2015 (n = 35,040 per house). The higher the temperature distribution range, the higher the household occupants' discomfort in winter and summer

electricity use. Surprisingly, one of the old retrofitted houses (house F) performed better than most modern houses and the 8.5-star house performed poorly compared with the other two high-performance houses, the retrofitted house F and the DTS house (Table 1; Fig. 1).

The importance of occupant practice becomes even more evident when the internal temperature profiles in the studied houses are considered. Figure 2 shows the temperature distribution in the ten houses during 2015 and reveals that most houses are thermally uncomfortable for over 50% of the time. The retrofitted house F (Table 1) had some of the coldest temperatures throughout the year, with 29% of the internal temperature readings situated between 15 and 20 °C, which means that this house requires more heating in winter to maintain comfortable temperatures for its occupants. The occupants of house F endure cold temperatures whilst consuming the least energy per square metre. House D (6-star rating, Table 1) experiences a wide range of temperatures, with 33% of the temperatures situated between 12.5 and 20 °C in winter and another 21% between 25 and 35 °C in summer. However, this house does not consume as much energy per square metre as a comparable house, house C, which has relatively stable temperatures throughout the year. This study has found no apparent relationship between cooling or heating degree days and energy use in the houses. Although design influences thermal comfort and energy use in buildings, these results demonstrate that occupant behaviour and everyday practice are affecting energy performance in the participant houses. Previous studies have found that the latter has the potential to impact the performance of houses to the same level as design (Lopes et al. 2012).

Annual profiles and typologies

Occupant practice, which is directly reflected in energy use, is affected by available technology, knowledge about the technology, habits and motivations (Gram-Hanssen 2014). As such, technology present in the house and interactions between occupants and the technology directly influence energy use. Looking further into the annual energy profile of each individual house and specifically at the energy used for climate conditioning, it was noted that they represent three distinct typologies according to their ambient heating and cooling technologies and their interactions with the technology (see Figs. 1 and 2).

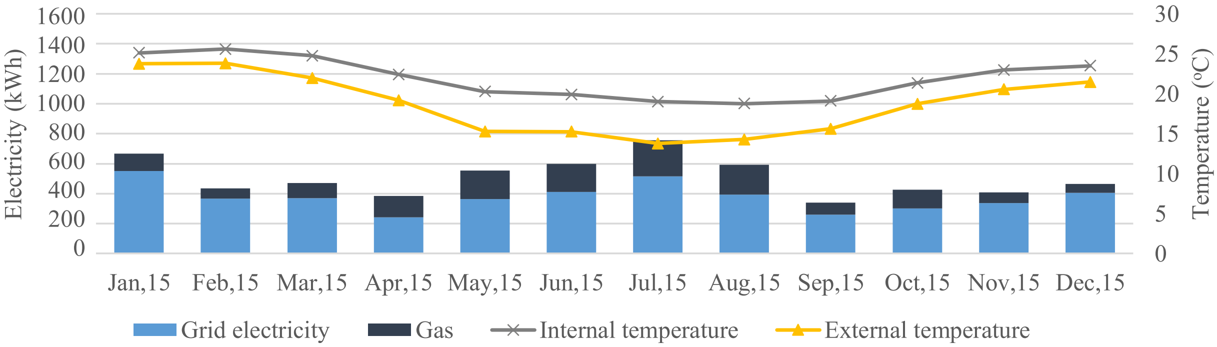

Fig. 3 House C is an example of typology I, which consists of houses that possess mechanical heating and cooling. Their annual energy profiles comprised two peaks, one during the Australian summer (December to March) and one in winter (June to September). The house shown in this example has a ducted air conditioner for both heating and cooling

We defined typology I as all houses that possess and use mechanical cooling and heating technologies to maintain house comfort through the year. These houses have high energy use during winter and summer and drop their energy use during the transition periods of autumn and spring when climate conditioning is not required. Figure 3 provides an example of an annual energy and temperature profile characterised as typology I. This was the most common typology found in this study, with half the houses fitting this description. Houses A (retrofitted), B (6 stars), C (6 stars), D (6 stars) and E (7 stars) were all grouped into typology I. They are not rated the same, their building envelopes differ and their internal temperatures also vary (Fig. 3); nevertheless, they have technologies and annual behaviours in common. Houses A, D and E have reverse-cycle air conditioners (Table 1), and houses B and C have ducted air conditioners to provide cooling in summer and heating in winter (Table 1). In winter, house D uses additional underfloor heating for warmth (Table 1) and house A uses additional electric oil heaters in the bedrooms (Table 1). With two annual electricity peaks, it is not surprising that four of these houses are the top energy users per square metre in this study (Fig. 1).

The second house typology that was identified, typology II, consists of houses that possess or use mostly mechanical heating (Fig. 4) and therefore have only one energy peak per year, during winter. Houses F (retrofitted), G (6 stars) and H (8.5 stars) all fit this description (Table 1). Whilst house F reaches low minima in winter and clearly needs climate conditioning, house H is the warmest house on average and has quite stable conditions throughout the year; however, it uses more energy per square metre than house F. What these three houses have in common, though, is the presence of portable heating devices, usually less efficient than reverse cycle air conditioners. Houses G and H possess fixed gas connections for the installation of gas

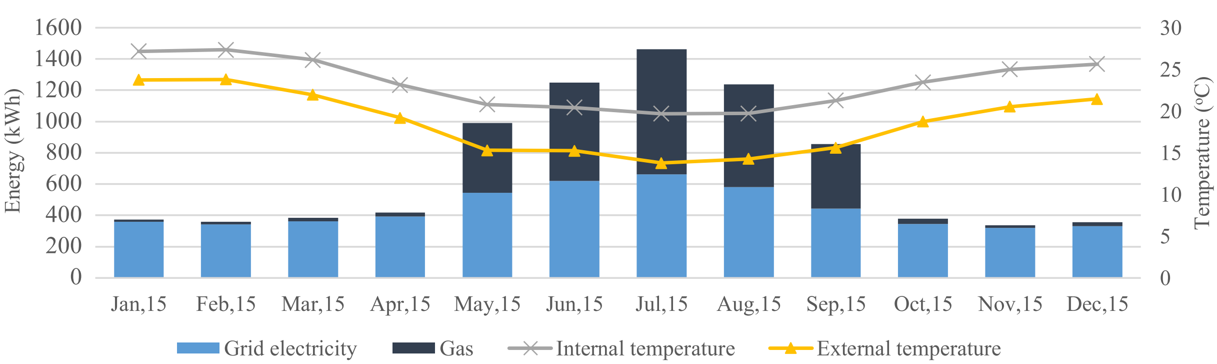

Fig. 4 House G is an example of typology II, which consists of houses that possess mechanical heating only. Their annual energy profiles comprise of one energy peak in the Australian winter (June to September). The house shown in this example has a portable gas heater which is used in winter

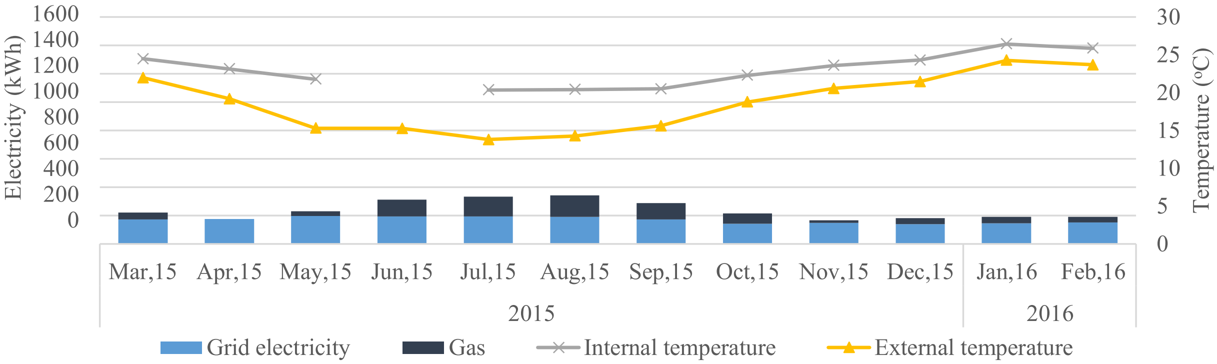

Fig. 5 House I is an example of typology III, which consists of houses that have very limited or no mechanical heating or cooling, keeping a fairly constant energy profile through the year. The slight increase in gas use in winter is due to water heating

heaters in the living area, and house F uses an electric oil heater, which is also in the living area.

The third house typology, typology III, consists of houses that do not possess or choose to limit their use of mechanical heating or cooling (Fig. 5). These houses have a fairly constant electricity consumption throughout the year, and the small increase in electricity use in winter is due to less photovoltaic generation and in some houses, due to water heating. There are two houses in this study that meet this criterion, houses I (DTS) and J (8 stars). Both houses were designed according to passive solar principles and in theory do not require much additional heating or cooling to remain thermally comfortable. These houses are both fitted with ceiling fans to keep the house comfortable in summer. House I has a reverse cycle air conditioner and house J has a portable gas heater, but these are only used in extreme temperatures. Both houses also possess fireplaces that are used occasionally for heating, but the fireplaces are mostly decorative and are not part of the main heating system. These houses also have in common the fact that their temperature range throughout the year is quite narrow, although with occasional extremes of too hot or too cold (Fig. 2). It is not surprising that due to the very low or perhaps non-existent use of heating or cooling, these two houses are the lowest energy consumers per square metre in this study (Fig. 1).

Whilst the design of heating and cooling systems influences energy use in houses, the way they are employed is also significant. In this research, houses classified as typology I were found to be the highest energy users per square metre independent of their designs; typology II houses were found to be average users per square metre; and typology III houses were found to be more frugal energy users, consuming low amounts of energy per square metre throughout the year.

Variations of household practices

To this point, the analysis has compared houses at a macro level, according to their designs and heating and cooling mechanisms. Whilst some of the variations in energy use between houses can be explained by differences in design and technologies, there are more elements at play. Homes are dynamic places, influenced by occupant routines, everyday practices, interlocked practices, norms, knowledge and motivations (Shove et al. 2012; Shove et al. 2015; Shove and Walker 2014). This section considers heating and cooling practices in winter and summer, combining the findings from both the quantitative data and semi-structured interviews. Due to limited knowledge on the occupant practices in house H, this house has been excluded from this section.

Winter diurnal heating practices

Eight houses in this study possess mechanical heating that is used in winter to maintain a comfortable temperature, presenting electricity or gas use peaks during that season. However, the practice of heating differs significantly between households (Eon et al. 2017).

Winter temperatures in the City of Fremantle are mild, and it is not a common practice for households to use the heater regularly. This is particularly true for houses built more recently, which tend to have better insulation materials and passive solar design properties. The coldest days of 2015 were therefore chosen to illustrate differences in heating practice between the

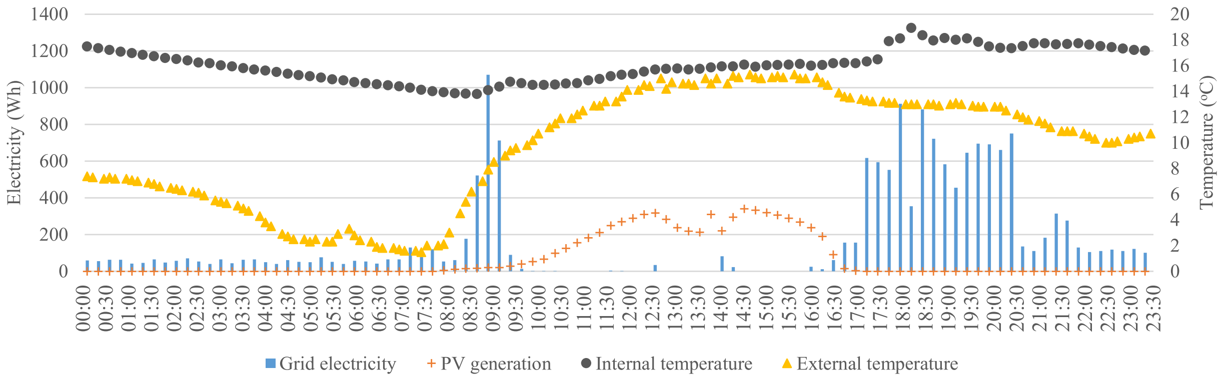

Fig. 6 Diurnal electricity profile of house B on the 9th of July, coldest day of 2015. The minimum temperature in this house was 13.8 °C at 08.45. This house has a ducted air conditioner for heating. The noticeable increase in internal temperature alongside a high electricity consumption indicates the use of the heater, which was turned on in the morning (08.45) and in the evening (18.15). The energy use during the day is very low and most of the solar electricity generated is exported to the grid

different participant homes. The selected days, being the 9th (Thursday) and 13th (Monday) of July, were days when the occupants were following their usual routines, that is, they were not on holidays. The external temperatures reached a minimum of 1.5 °C at 07.00 on the 9th and a minimum of 3.9 °C at 06.40 on the 13th. The occupants of houses B (6 stars), C (6 stars) and E (7 stars) turned on their heater during the early hours of the morning and evening, before and after work (Fig. 6). In house F (retrofitted), the heater was only used in the evening after the occupants returned home from work (Fig. 7). Households A (retrofitted) and G (6 stars) used the heater during periods of the morning, afternoon and evening as they are usually at home during the day (Fig. 8). Finally, household D (6 stars) only used the heater during the late morning and afternoon (Fig. 9) in spite of experiencing the lowest internal temperature of all houses in this study (Table 3).

Four different practices were observed on the coldest days of the year. All houses experienced temperatures below 16.4 °C in the early hours of the morning, but the differences between practices were mostly due to different occupants' lifestyles and household configuration, also seen in Guerra-Santin et al. (2016).

Summer diurnal cooling practices

Five houses in this study possess air conditioning (AC) systems to keep cool in summer. But similarly to winter, practices differ considerably between households.

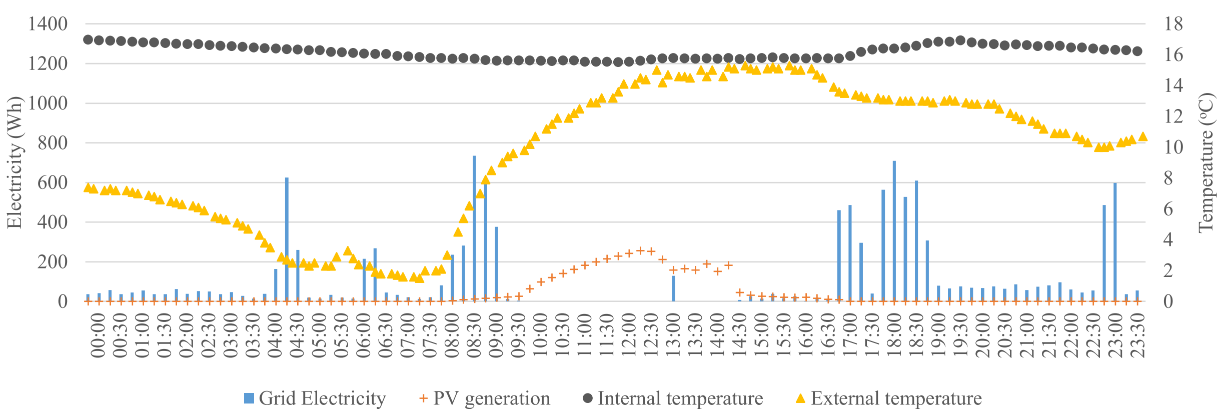

Fig. 7 Diurnal profile of house F on the 9th of July, coldest day of 2015. The minimum temperature inside the house reached 15.7 °C at 07.30. This house has a portable oil heater powered by electricity. Electricity use is higher in the morning and evening, but the temperature increase in the house only occurs in the evening. The morning peak, where no increase in temperature is observed, is most likely due to water heating, which is also electric

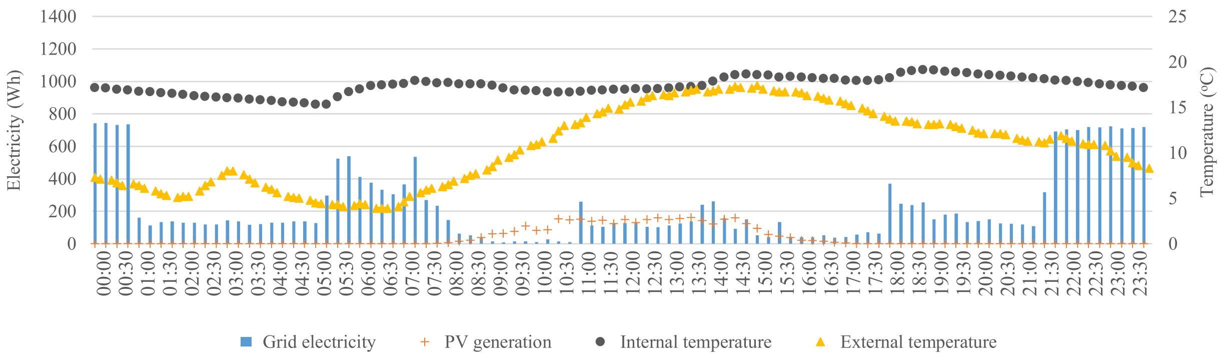

Fig. 8 Diurnal profile of house A on the 13th of July, second coldest day of 2015. This date was chosen here as this house experienced data loss on the 9th of July. This house reached a minimum internal temperature of 15.3 °C at 05.00. This house has a reverse cycle air conditioner for heating. An increase in electricity use concurrently with an increase in internal temperature indicates that the heater is on. On this day, the heater was turned on at 05.00, 14.00 and 18.00

Summer temperatures in the City of Fremantle are mild, and the use of the air conditioner is limited to more extreme weather conditions. Accordingly, the hottest day of the year was used to illustrate differences in cooling practices in the different households. The hottest day of the year was the 5th of January 2015, with the external temperature reaching a maximum of 41.3 °C at 12.40. That day was a Monday during the summer school holidays, so it is assumed that some of the households might have been at home during the period.

On the 5th of January, the occupants of houses A, B and E turned on the AC during the hottest hours of the day, as shown, for example, in Fig. 10. However, whilst households A and B turned it off when the external temperature began to drop, household E kept the AC on until 22.00. On that same day household C turned on the AC in the evening, a few hours at a time as can be seen on Fig. 11. Finally, household D did not use the AC on that day. In all cases, the temperature inside the houses were higher than the external temperatures in the evening and night after the AC was switched off, indicating two things: that the house insulation and thermal mass are not sufficient to keep the house cool for an extended period of time and that the house occupants are not taking advantage of the low night-time temperatures to cool the house down naturally (for example, by allowing sea breezes to cool the houses through secure window screens). Indeed, in houses A and B, the internal temperatures were not only higher than the external temperature during the evening but also increased as soon as the AC was turned off. The temperature profile for house A (Fig. 10) also shows that whilst the AC was on, the internal house temperature was still increasing, that is, the AC works inefficiently and is not able to keep up with the external weather conditions. As observed for winter, we found three different practices in the group of five homes possessing mechanical cooling systems (Table 4).

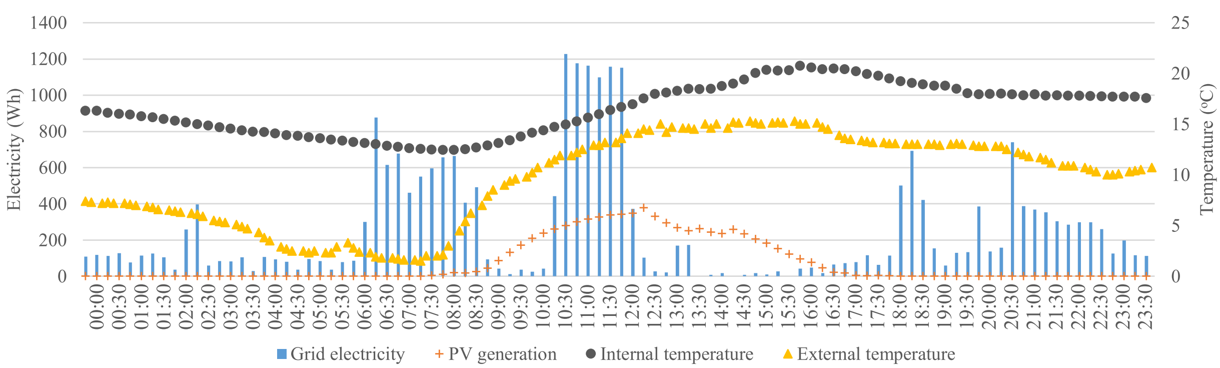

Fig. 9 Diurnal profile of house D on the 9th of July, coldest day of 2015. The minimum temperature in the house was 12.4 °C at 08.30. This house has an electric floor heater in the living area. It is assumed that the use of the heater is associated with an increase in internal temperature alongside an increase in electricity use. This only occurs at 10.30. The early morning and evening peaks are most likely due to the use of other electric appliances

Table 3 Maximum and minimum winter internal temperatures during the coldest day of the year (Eon et al. 2017)

House	Min temperature (°C)	Max temperature (°C)	Heater on	Occupant lifestyle
A	15.3	19.1	Morning, afternoon, evening	Home during day
B	13.8	18.9	Morning, evening	Work full time
C	16.4	20	Morning, evening	Work full time
D	12.4	20.7	Afternoon	Home during day
E	16.4	20.3	Morning, evening	Work full time
F	15.5	16.9	Evening	Work full time
G	16.4	20.8	Morning, afternoon, evening	Home during day
I	14.4	19.3	NA	Work full time
J	16.0	18.4	NA	Home during day

The maximum temperature in houses possessing heating systems (A to G) corresponds to when the system is on

The experience of warmth in winter

Warmth could be considered to be the most important aspect of comfort (Huebner et al. 2013); however, the way individuals seek warmth can differ significantly. Common practices to warm up include layering up, changing position, closing windows and doors, making a hot drink, having a warm shower or bath and turning on or turning up the heating system (Renström and Rahe 2013). Ambient heating practices are often sensorial and are not necessarily effective long-term solutions (e.g. having a hot drink) (Renström and Rahe 2013). Heating practices might therefore be related to habits, individual perceptions and motivations in addition to as design, technology and lifestyles, as discussed above.

Households respond differently to a cold day, and this can be attributed to lifestyles, as some families work full time and do not require their house to be comfortable during the day, whilst others are home more often and consequently use thermal conditioning with a higher frequency. However, subtler variations in behaviours and practices can be observed internally within households. We call these internal differences intra-home variations.

Intra-home practices Household B is a family of four; one single mother who works full time from 09.00 to 15.00, two teenagers in school and one young adult who works part-time and stays at home the rest of the time (Table 1). The semi-structured interview with this family revealed that the individuals have different behaviours which results in different heating practices.

This household uses the heater in winter on a daily basis, but the operation of the heating system is largely inconsistent. During the month of July 2015, the heater is mostly turned on in the evenings; however it is also briefly switched on during a few cold mornings, such as the 9th of July (Fig. 7), and on occasions in the afternoons (Fig. 12). The time period the heater is turned on and the duration of its use is irregular. Occasionally, the

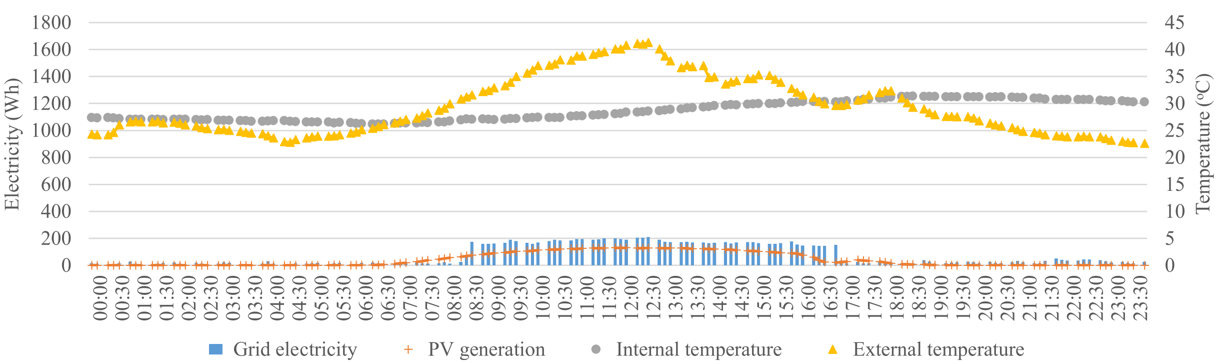

Fig. 10 Diurnal profile of house A on the 5th of January, hottest day of 2015. The air conditioner was on during the hottest hours of the day and was turned off as the external temperature started to drop

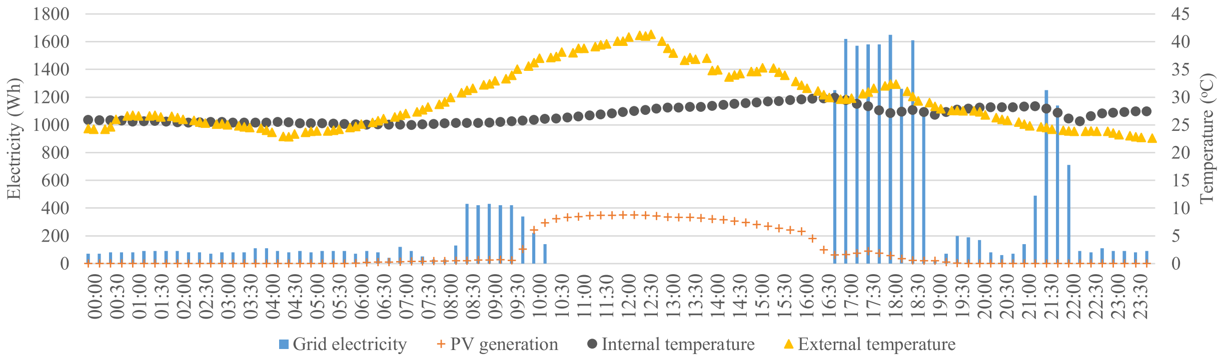

Fig. 11 Diurnal profile of house C on the 5th of January, hottest day of 2015. The air conditioner is turned on in the evening a few hours at a time

heater is on for brief periods, and on other days, it stays on for several hours, such was the case on the 10th, 23rd and 28th of July (Fig. 12).

The erratic operation of the heater (Fig. 12) could be related to the different behaviours and everyday practices of the four occupants. For instance, the mother is motivated by a reduction in greenhouse gas emissions as well as costs. Since moving to the 6-star house fitted with solar panels, she has become more aware of energy use and has actively tried to modify habits, such as the times she turns the dishwasher on to make the most of the electricity generated by the photovoltaic system:

> "(…) we were required to put those things (solar panels) on this house. I'd been renting before and it just brought my awareness … well I've got these cells in, maybe I should try and do something differently"

However, the children do not have the same motivations, choosing not to acknowledge the relevance of greenhouse gas emissions and the monetary aspects of saving energy. Engaging them in energy saving has proven to be challenging as they forget to turn appliances off and enjoy using the climate control. As the mother says:

> "you try and tell a 17-year-old to get out of the shower. He's just standing there thinking. And turning the lights out, I don't think they remember"

Unlike her children, the mother says that she does not require much climate control. It can be assumed that she is therefore the one turning on the heater in the mornings and evenings, for only the amount of time required to achieve thermal comfort. The teenagers and young adult, on the other hand, are presumed to turn the heater on for extended periods including week day afternoons, either as a hedonic experience or due to forgetfulness. For example, the heater was left on from 20:00 on the 10th of July to 09:00 on the 11th of July (Fig. 12). Just

Table 4 Maximum and minimum summer internal temperatures during the hottest day of the year

House	Max temperature (°C)	Min temperature (°C)	AC on	Occupant lifestyle
A	31.3	26.1	Morning, afternoon	Home during day
B	29.4	25.1	Morning, afternoon	Work full time/teenagers at home
C	29.8	24.9	Evening	Work full time
D	31.9	24.9	Not on	Home during day
E	27.7	25.7	Afternoon	Work full time
F	28.0	25.5	NA	Work full time
G	32.6	26.3	NA	Home during day
I	32.1	27.5	NA	Work full time
J	29.5	24.5	NA	Home during day

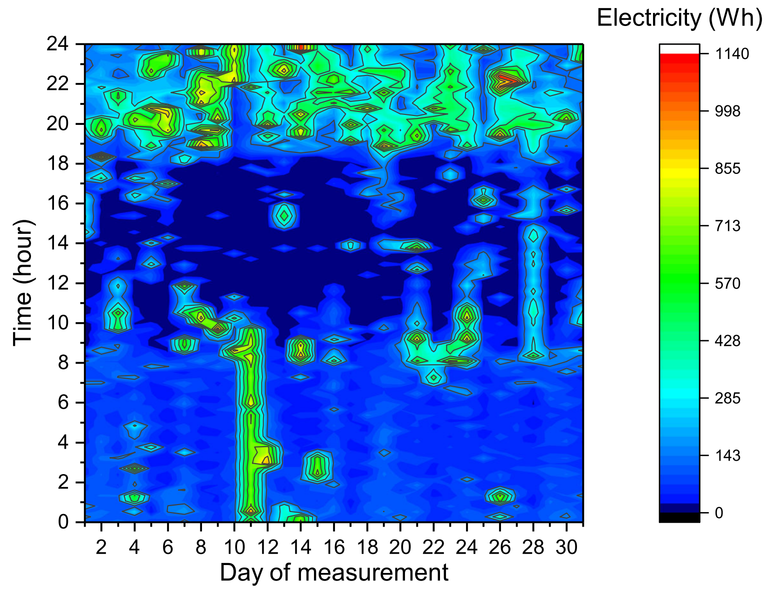

Fig. 12 Grid electricity contour plot of house B in July 2015 at 15-min intervals. Five hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by the photovoltaic panels, which reduce the need for grid electricity. However, solar electricity generation, is not enough to cover ambient heating loads, requiring additional grid electricity

before the heater is turned on, the internal temperature in the living area is on average 18.7 °C and during the use of the heater, the heater thermostat setting (living area temperature) varies between 21 and 25 °C. Whilst other factors could be influencing these practices, this range of temperatures could also be indicative of intra-home practices, where one individual enjoys higher temperatures than others. The use of the heater may not necessarily relate uniquely to the feeling of cold but may also be used for the experience of comfort.

Differences in awareness, motivations, attitudes (Ajzen 1991) and experience of comfort (Renström and Rahe 2013) all influence the various user practices within the same home. Whilst one occupant might make efforts to reduce resource consumption, the overall house energy use might still be high due to other occupants' conflicting practices and behaviours. Intra-home variation in practices could explain the reason why house B is the highest energy user per square metre in the study (Fig. 1).

Intra-home behaviours Household E is a family of one adult working full time, one adult working 4 days/week and one teenager studying and working full time (Table 1). The semi-structured interview with all members of household E revealed that different individuals have different values, attitudes, levels of knowledge and perceptions of thermal comfort; nevertheless, only one heating practice prevails. This household uses the heater on a daily basis for extended periods in winter mostly in the evenings between 17:00 and 23:00 and also briefly some mornings and whole days, especially at weekends (Fig. 13). Whilst family E perceives their 7-star house to be more comfortable than the average Australian house, they still feel the need for heating and cooling, as expressed by the mother:

> "I hate being cold, whereas the boys are probably the opposite, they hate being hot"

A closer look at the data revealed that just before the heater is turned on, the average internal temperature is 19.33 °C and the average external temperature is 14.11 °C. Whilst the external temperature is considered to be low from a comfort point of view, the internal temperature is much higher than other houses, indicating that either the occupants of this house feel colder than other participants or that turning the heater on is not necessarily related to feeling cold. The fact that the heater is turned on every day at approximately the same time could indicate that the individuals in this family have developed a habit of turning the heater on when at home in spite of their divergent attitudes toward energy savings.

Each individual in household E has a different opinion concerning greenhouse gas emissions and energy savings. The mother for instance, is committed to the idea of reducing carbon emissions, although she

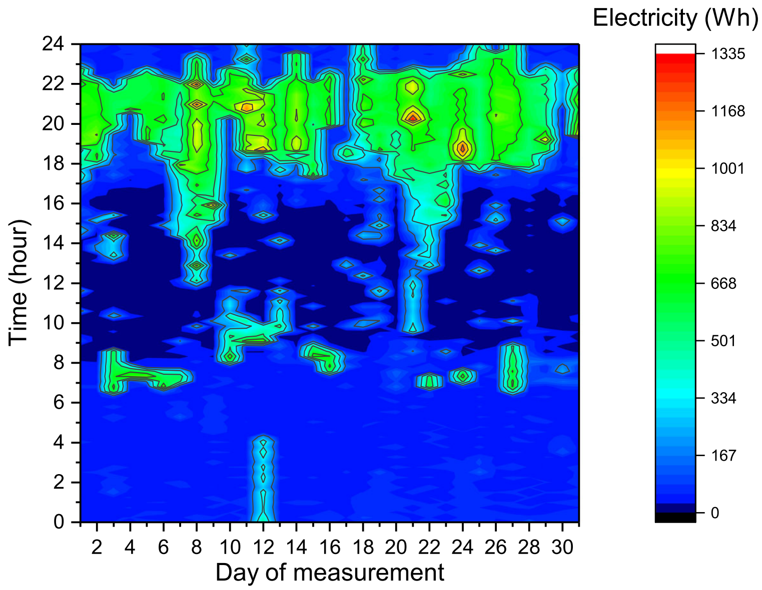

Fig. 13 Grid electricity contour plot of house E from the 10th of July to the 9th of August 2015 at 15-min intervals. Five hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by photovoltaic panels, which reduce the need for grid electricity. However, solar electricity generation is not enough to cover ambient heating loads, requiring additional grid electricity

perceives her family as low resource users compared with others. She would nevertheless make an effort to save energy provided that it does not impact on comfort or represents an inconvenience to her lifestyle. The father, on the other hand, believes that greenhouse gas emissions are insignificant at the domestic scale:

> “personally I don't care because I think we actually are focusing in the wrong area”

His only motivation to saving energy would be from a financial standpoint; however, he also perceives that economic benefits would not be large enough to have an impact on the family economy. Interestingly, he also mentions that he does not actively pollute whilst explaining that he does not throw bottles out of his car. As research has pointed out, the use of electricity is intangible for many, and consequently, there is a disconnect between the use of appliances in the home and environmental burden (Burgess and Nye 2008).

In addition, the family perceives that living in a higher performance house with solar panels is enough to reduce energy use. However, they do not entirely understand how the PV technology functions as revealed by the interview with the mother:

> “I still don’t know that I fully understand the whole thing about the solar power and when you use it and that sort of thing”

The habitual behaviour of using the heater on a daily basis for extended periods of time could be related to rebound effects caused by not fully understanding the technical system of the house (Sorrell et al. 2009). Additionally, whilst the mother finds the reduction of carbon emissions important, she also has the perception that others in society, including persons in her social network, use more energy than her family does, which reduces her willingness to reduce her energy use (Nolan et al. 2008). The household members also perceive a limited personal ability over being able to change the situation and suggest that the outcomes of saving energy are not worthwhile in terms of greenhouse gas savings and monetary benefits, supporting the theory of cognitive dissonance (Ajzen 1991).

Warmth for comfort Household D consists of a family of five; one adult working full time, one adult who stays at home with the children and three preschool children (Table 1). The semi-structured interview with this family revealed that all the adult members are like minded and have similar heating practices.

In this house, the ambient heating system is only used occasionally for brief lengths of time (Fig. 14) as the occupants prioritise wearing warm clothes over the use of mechanical heating systems to achieve warmth. According to the father, the house is warmer in winter compared with their old house and they rarely need to turn the heater on:

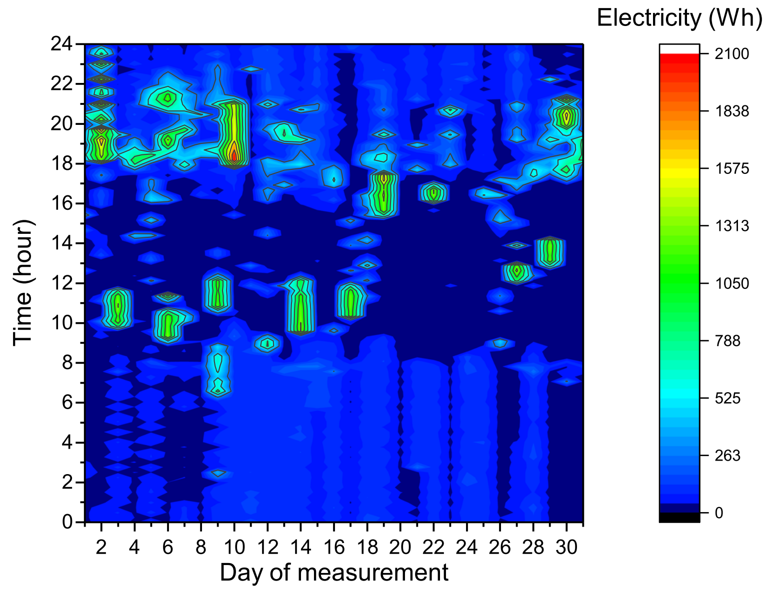

Fig. 14 Grid electricity contour plot of house D from the 3rd of July to the 2nd of August 2015 at 15-min intervals. Seven hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by photovoltaic panels, which reduce the need for grid electricity use. However, solar electricity generation is not enough to cover ambient heating loads, requiring additional grid electricity

> "You could just walk around with a jumper on and a pair of jeans. It's not like you're sitting there thinking … I'm freezing cold!"

The practice of changing clothing for regulating warmth for comfort can be related to the occupants' subjective norms, values and perceived behavioural control (Ajzen 1991). They perceive that their social network is a community of people who are aware of their environmental impacts and are positioned against consumerism. Living simply and economically is a lifestyle and habit that is valued by household D as expressed by the father:

> "my parents were English and very economical (...) everything was literally ... shut the door! turn the light off! shut the fridge door! … so that part of it has stuck with me"

Given the occupants' practice of wearing warm clothes to achieve thermal comfort, the temperatures experienced by this family inside their house are lower than those experienced by other households (Fig. 2). Just before the heater is turned on, the internal house temperature is on average 18.1 °C and the external temperature is on average 14.5 °C.

The heater is consciously turned on during the day when the solar panels are producing electricity (Fig. 14). The couple is familiar with the house design and technologies and consciously make the effort to turn on the electric floor heater during the day, rather than in the evenings or early mornings, in order to reduce electricity bills, as expressed by the father:

> "(…) we went electric (heater) purely because we knew we would put solar on the roof and then the intent was that you just put it on for a couple of hours during the day when you get the maximum from your panels and then the thermal mass keeps the heat"

Occasionally, the practice and system of the home is insufficient and during some of the coldest days of the year, such as the 6th, 9th and 10th of July 2015, the heating system was also turned on in the evenings and/or early mornings for periods varying between 1 and 3 h (Fig. 14). However, the operation of the heater in house D appears to be a very conscious decision driven by both the technologies present in the house and the feeling of cold. Occupants' behaviours and practices make house D the lowest 6-star house energy user per square metre within the typology I category (Fig. 1).

Inter-home comparison for the experience of winter warmth

As exemplified in the houses discussed above, behaviours and winter heating practices vary

Table 5 Mechanical heating practices in winter

Houses that use electric/gas heating	Median time heater is turned on	Average internal temperature (°C)	Average external temperature (°C)
A	12:00	19.53	14
B	17:22	18.68	14.11
C	18:00	18.47	12.68
D	11:45	18.15	14.53
E	17:37	19.33	14.11
G	16:45	19.42	15.1

considerably between houses. Heating practices in these houses seem to be dictated respectively by comfort, habits and consciously by the feeling of cold. Lifestyles and the use of solar panels can affect the time that the heater is turned on. But behaviour, awareness or motivation to save energy may also change people's priorities, that is, households can choose to put on warmer clothes before turning on their heating system. As such, people can change to adapt to colder temperatures. For instance, house D prioritises putting warm clothes on first and only turns on the heater when the internal temperature reaches 18.1 °C. House E, on the other hand, turns the heater on at higher internal temperatures (19.3 °C). On average, houses in this study turn the heater on when the internal temperature is between 18.1 and 19.5 °C (Table 5), which is lower than the lower limit of the thermal comfort range (20 to 25 °C) suggested by the NCC (DEE 2012). Whilst these results cannot be generalised to a larger population, they support Manu et al. (2016), who suggest that in naturally ventilated environments, the thermal comfort zone could be widened.

The presence of solar panels in these case studies has had a double effect. On the one hand, it has acted as a trigger for practice change as some households have become more aware of using energy and have tried to maximise the use of appliances during daylight hours and take advantage of the solar panels. But on the other hand, it might also have caused rebound effects. Not all individuals that possess a PV system are familiar with its use and might be using electricity indiscriminately with the belief that the panels are offsetting all their electricity use. In fact, the heating systems in the studied houses generally use more electricity than the solar panels generation capacity, so turning on the heater during the day also requires grid electricity in addition to the electricity produced by the PV system. Some households also expressed their dissatisfaction with the solar system, by explaining that they cannot take full advantage of the system as they are not at home during the day.

The experience of cool in summer

Household C consists of a young couple working full time (Table 1). In summer, this couple only uses the AC on a few occasions, usually in the evenings after work or at weekends during the day (Fig. 15) when the internal house temperature reaches on average 26 to 27 °C. The AC is not used daily though, and it is usually turned on briefly to cool the house and if necessary, turned on again at a later instance for another short period of time. On the 5th of January, the hottest day of the year, the AC was turned on from 17:00 to 19:00 and at 21:00 again for 1 h after the internal temperature increased once more (Fig. 11). The semi-structured interview with this couple revealed that they value living in a comfortable house as they spend most of their weekends and evenings at home. But they are also mindful of their energy use and turning on the AC too often. They are motivated to reduce their energy bills so they can spend the money elsewhere as expressed by the husband:

> "we like to have a nice holiday every year, and if you can get the bills to save that sort of money […] maybe your life would be better"

As such, their preferred method of keeping cool consists of turning on the ceiling fans rather than the AC and they only operate the AC in case of extreme temperatures.

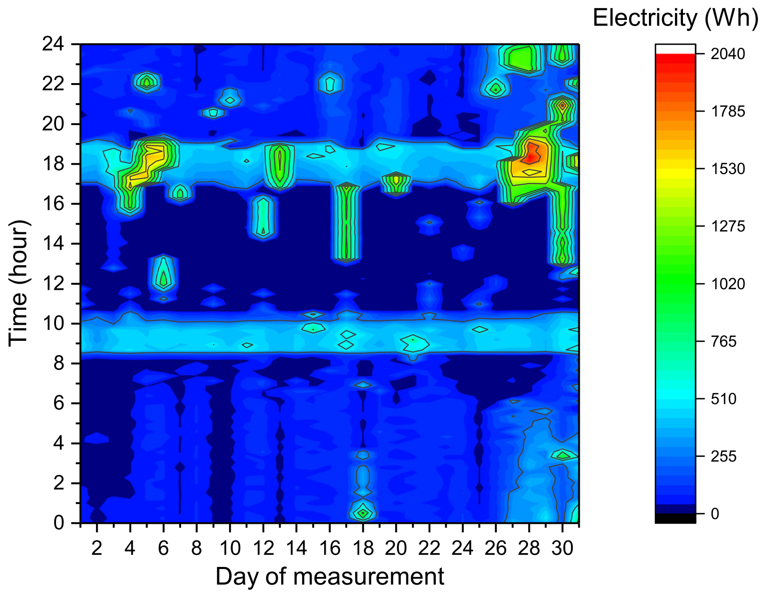

Fig. 15 Grid electricity contour plot of house C in January 2015 at 15-min intervals. The navy band during day hours shows the impact of the photovoltaic panels on grid electricity consumption. The PV system covers small electricity needs, but higher loads such as ambient cooling requires additional grid electricity. AC systems are the highest users of electricity 800 Wh or higher electricity use (green shades) can be attributed to the use of the AC. The twice-daily electricity use, from 08.15 to 10.15 and from 16.45 to 18.45, is related to the pool pumps, which are set on a timer

According to the couple, the main barrier to reducing energy use further is related to habits. However, they also mention that some of their appliances are set on a timer so they can make use of the solar system when it is generating electricity. This applies to the dishwasher and the pool pump, the latter being turned on twice per day (Fig. 15, 08.15 to 10.15 and 16.45 to 18.45).

The cooling practices in house C demonstrate that the occupants are both conscious of their energy use and turn on the AC purely to achieve thermal comfort during very hot days. They are the second highest energy users per square metre in the study (Fig. 1), although this is partly due to the regular use of the pool pump.

Inter-home comparison for the experience of summer coolness

Similarly to winter, the AC in the participant houses is often turned on when the internal temperature is higher than the thermal comfort range (20 to 25 °C) (Table 6). This practice could be simply due to routines or the fact that the houses are unoccupied during hot hours. However, these results are aligned with a previous research that indicates that thermal comfort ranges in naturally ventilated climates could be wider (Manu et al. 2016; Kumar et al. 2016). Additionally, as discussed in Sect. "Summer diurnal cooling practices", some of the households that have the practice of using the AC in the evenings do so at times when the external temperature is actually lower than the internal house temperature. For these households, turning on the AC might be their first choice to remain cool, instead of opening the windows or turning on a ceiling fan. Other cooling practices found in this study consist of spraying oneself with water (house I) and using natural ventilation, capturing the afternoon sea cooling breezes (house J).

Table 6 Mechanical cooling practices in summer

Houses that use electric cooling	Median time AC is turned on	Average internal temperature (°C)	Average external temperature (°C)
A	13:45	27.94	30.21
B	17:30	27.18	26.38
C	17:45	26.64	27.66
D	19:45	28.49	25.58
E	15:00	27.42	26.93

Conclusions

This research unravelled some of the layers influencing house energy use through detailed quantitative and qualitative data from ten Australian embedded Living Labs. First, the systems of the houses were considered and then the analysis focused on understanding household dynamics and occupants' everyday practices related to heating and cooling.

We initially discussed the energy use in the different houses as compared with their designs and found that although there is a relationship between design and energy use, similar houses varied by up to 33% in energy use per square metre between them. We also observed that all houses spend at least 50% of the year outside the thermal comfort zone (20 to 25 °C), but there does not seem to be any direct correlation between internal temperature and energy use. Energy use was found to be less related to design and more related to the choice of appliances and technology used inside the house, in particular related to heating and cooling systems. In our sample, households that use both mechanical heating and cooling through the year tend to be heavy energy users, which we classified as typology I users. Houses that only use mechanical heating but no AC tend to be medium users (typology II), and households that use other methods to keep warm or cool were low energy users (typology III). We recommend that this hypothesis is tested further with a larger sample or houses, as the relationship between typologies and energy use in this study could be coincidental or due to other hidden factors.

Further differences were also found to be linked to lifestyle, that is, household daily routines, time that occupants are at home and family structure. Families with young children, for instance, use more energy during the day, whilst working couples tend to use more energy in the evenings. Additionally, heating and cooling practices vary significantly between and within households. We found that in the same house different occupants may have different beliefs in, attitudes to and motivations for energy use and greenhouse gas emissions, which ultimately affects practices. For instance, an individual motivated to save on energy bills may choose to put on more clothes to achieve warmth or to open windows to keep cool rather than using mechanical heating or cooling; whilst another individual in the same house may turn on the heater as a first choice and at higher temperatures. The reasons for turning on the thermal control may not be uniquely related to the feeling of cold and warmth; this research found that some individuals may also turn on the heater as a habit or as a hedonic experience. However, whether the heater or AC are turned on to achieve comfort or not, all houses in this study turn on the heater when the internal temperature is below what is considered the lower limit of the thermal comfort range (20 °C) and the AC is usually turned on when the internal temperature is above what is considered the higher end of the thermal comfort range (25 °C). We recommend that further research is carried out with a larger sample of houses to better determine occupants' drivers to turn on the heater and cooling system and to better understand the relationship between comfort and the use of thermal control.

The presence of renewable energy or other energy efficient technology also exert an influence on everyday practices as some individuals consciously choose to use appliances (including heating and cooling) during the day to make the most of the solar panels. However, the presence of solar panels may also be causing rebound effects as some individuals do not understand the technology or when to use it.

This research demonstrates that factors influencing intra-home personal dynamics are related to lifestyle, awareness, attitudes, motivations, technology, habits and pleasure. These impact on the frequency, timing and intensity of heating and cooling practices. We recommend that further research concerns the integration of the technical aspects of houses and the practices inside the home to create a new typology classification based on integration of both the technical system and occupancy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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