Curtin University Sustainability Policy Institute

The Home System of Practice

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Doctor of Philosophy
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Author’s Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HU-RGS-05-14.

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24 November 2017

Statement of contributors

All of the written materials submitted as part of this PhD by publication (hybrid) were conceived and coordinated by Christine Moura Eon. I also undertook the majority of the writing and analysis for each publication.

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Abstract

The reduction of resource use in houses is often addressed through the improvement of the building system alone, with a focus on the implementation of efficient appliances, sealed and insulated building envelopes and renewable energy. This approach, however, overlooks occupant activities within and outside the building. The latter operate the building fabric and appliances on a regular basis and they are responsible for the decision-making processes affecting the home metabolism of resources such as energy and water. Whilst the influence of the physical system of the home is well documented, the social system is not yet fully understood.

This thesis investigates the interactions between occupants, the physical built environment and their impact on resource use. Elements of practice theory, socio-psychology, urban ecology and life cycle assessment have been combined to provide a holistic perspective of the home and in particular, occupant behaviour, practices and routines. The results were based on a two year longitudinal study of ten Australian living laboratories which are primarily energy efficient residential houses. The rich dataset was analysed through a mixed methods approach.

This thesis demonstrates that while the energy efficient houses perform better than standard Australian dwellings, they do not meet their full operational potential. Overall house performance is attributed to construction quality, maintenance, technology, lifestyle, family structure and house occupancy. At a micro scale, however, everyday house operation is driven by practices which are interlocked in a system. The home system of practice is a stable network of occupant practices and routines that are reproduced in a sequential temporal spectrum and may also be bound in space. Influencing this system requires disturbing existing stable connections and recreating new practices and new connections, which is challenging; especially when practices are highly interlocked in the system. Affecting the skill and meaning elements of practices is also unlikely and may only generate limited resource savings. The technology element of practices, on the other hand, is more flexible and more frequently acted upon. One-off changes in technology that do not impact on meaning, interlocked routines or lifestyle have a greater probability to be accepted by occupants and result in long term reductions in resource use.

Persuasive interventions aimed at affecting specific practices or behaviours may ignore the underlying reasons for their occurrence and their role in the home equilibrium. The effective modification of occupant behaviours and everyday practices requires a holistic understanding of the home. Alternatively, practices may be dis-interlocked from the home system of practice through the use of automation which operates independently of the occupants and is not constrained by time. While the utilisation of automation for improved house performance is not new, this thesis shows how this concept can be integrated within the larger home picture to enable effective long term change.

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Dedication

To my husband, David Campbell, for supporting, encouraging and listening. Thanks for holding my hands through all good and bad moments. And thanks for being my Excel guru.

To my parents who taught me the importance of education. Thanks for all your support and informal guidance during the course of the thesis.

List of publications included in the thesis

The following publications are the basis of this thesis and are provided as appendices following the exegesis. The publications are referred to in the exegesis in roman numerals. Copyright statements for published materials can be found in Appendix C.

Book chapter

I. **Eon, C.** & Byrne, J. (2017). Methods to enable residential building sustainability: integrating and evaluating energy, water, materials and liveability. Book chapter *edited by* Hartz-Karp, J. & Marinova, D. *Methods for Sustainability Research*. Edward Elgar, UK.

Journal articles

II. **Eon, C.**, Morrison, G. M., Breadsell, J. & Byrne, J. (2017). Integrating theories of practice and behaviour into home settings through living laboratories. Submitted to *Energy Research & Social Science*.

III. **Eon, C.**, Murphy, L., Byrne, J. & Anda, M. (2017). Verification of an emerging LCA design tool through real life performance monitoring. Renewable Energy and Environmental Sustainability, 2, 26. https://doi.org/10.1051/rees/2017017.

IV. **Eon, C.**, Morrison, G. M. & Byrne, J. (2017). The influence of design and everyday practices on individual heating and cooling behaviour in residential homes. *Energy Efficiency*. https://doi.org/10.1007/s12053-017-9563-y.

V. **Eon, C.**, Liu, X., Morrison, G. M. & Byrne, J. (2017). Influencing energy and water use within a home system of practice. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2017.10.053

VI. **Eon, C.**, Breadsell, J., Morrison, G. M. & Byrne, J. (2017). The home as a system of practice and its implications for energy and water metabolism. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2017.12.001

Relevant publications not included in this thesis

This thesis has led to further publications which the author has chosen not to include. However, these are available as a pdf on request.

Journal articles

Eon, C., Morrison, G. M. & Byrne, J. (2017). Unravelling everyday heating practices in residential homes. *Energy Procedia*, 121, 198-205. https://doi.org/10.1016/j.egypro.2017.08.018.

Eon, C. & Morrison, G. M. (2017). A systematic literature review to identify best practice business models for living labs. Submitted to *Technology Innovation Management Review.*

Magazine article

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Glossary of terms and abbreviations

AC	Air conditioner
BASIX	Building sustainability index
CO_2	Carbon dioxide
DTS	Deemed-to-satisfy
EU	European Union
GHG	Greenhouse gas
GAM	Generalized additive model
Home	Building fabric and occupants
House	Building fabric
HPH	High performance home
HSOP	Home system of practice
ICT	Information communication technology
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LL	Living laboratory
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
PLC	Programmable logic controller
PV	Photovoltaic
RW	Rainwater
SOP	System of practice
WA	Western Australia
ZEH	Zero emission house

Chapter 1 Introduction

This chapter starts with a discussion of the thesis context, which explains and justifies the need for this research. The analytical framework and thesis scope are then discussed, leading to relevant research questions. These were answered through a series of peer reviewed and/or submitted publications based on the results of the 10 House Living Lab project. The overall thesis organization is presented at the end of the chapter.

1.1 Research context

This section discusses the research background, justifying the need for the research and its position in relation to the broader international context. The background is then followed by a brief discussion of the theoretical framework which forms the basis of the thesis.

1.1.1 Background

The built environment is responsible for 19% of global greenhouse gas (GHG) emissions; 63% of these are indirect through operational electricity use (Victor et al., 2014). Worldwide, the energy consumption in the residential sector is currently three times higher than the commercial sector and will continue to rise as global population grows and more people gain access to adequate housing and electricity (Lucon et al., 2014). Energy use in the residential sector is exacerbated by other trends such as the decrease in the number of occupants per house (Ren et al., 2011). In low density cities, residential dwellings have also become larger (Moore et al., 2013), demanding higher levels of electricity as compared to smaller homes and also significantly impacting embodied energy (Stephan and Crawford, 2016). Ambient cooling and heating (*i.e.* air conditioner and heating) are the most energy intensive practices in the home, using 34% of house energy demand (Lucon et al., 2014). In Australia, this percentage is even higher, representing 40% of the domestic energy use (DEWHA, 2008).

Several jurisdictions have policies in place to address residential energy and GHG emissions. The European Union (EU) requires all new buildings to be nearly zero-energy by 2020 (European Commission, 2013). The state of California and the city of Vancouver, for instance, also have policies to achieve zero emission houses (ZEH) by 2020 and 2030 respectively (CPUC and CEC, 2015, City of Vancouver, 2016). In Australia, since 2012, all new residential detached and terraced houses need to meet minimum energy efficiency requirements under the National Construction Code (NCC). These can be met either through the Deemed to Satisfy (DTS) option, that is, through complying with prescribed provisions stipulated by the NCC; or by obtaining an energy rating of at least 6-Stars under the Nationwide House Energy Rating Scheme (NatHERS).

The latter rates buildings from 0 to 10 Stars according to the energy load required to maintain the building thermally comfortable through the year (DEE, 2015).

Meeting stringent policy requirements has generally focussed on improving appliances and building technologies, such as air tightness, insulation, solar photovoltaic (PV) panels, glazing and passive solar design (Eon and Byrne, 2017). This approach, however, overlooks occupant activities within and outside the building. According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 emissions from residential buildings are driven by the carbon intensity of energy sources, the energy intensity of energy-using devices, the energy intensity of the building envelope and the human activities inside the building (Lucon et al., 2014). While the technology aspects of high performance houses or nearly ZEH are cost-effective (Ren et al., 2011) and can be easily implemented (Lowe and Oreszczyn, 2008, Berry et al., 2014, Saman, 2012), occupant behaviours, their practices and interaction with building technologies and other household members are less understood (Moore, 2012).

Post-occupancy monitoring studies have revealed that low emission dwellings achieve better results than conventional dwellings (Berry et al., 2014, Hamada et al., 2003); however, they often underperform compared to their modelled design (Ambrose et al., 2013, Gill et al., 2010, Gill et al., 2011, Majcen et al., 2013). Barriers impeding the optimal performance of these houses include poor construction practices (IEA, 2008, DSD, 2014, DSD, 2015) and the insufficiency of house assessment software (Lopes et al., 2012, Lowe and Oreszczyn, 2008, Moore et al., 2014, Newton and Tucker, 2011). However, the unpredictability of house day-to-day operation constitutes one of the most influential factors (Bond, 2011, Lopes et al., 2012, Gynther et al., 2011).

Previous research has found that the use of resources in low energy houses can vary significantly due to differences in occupant behaviour (Blight and Coley, 2013) and rebound effects (Sorrell et al., 2009). For instance, Gill et al. (2010) found a variation of 11% in water use and 37% in electricity use between similar dwellings. Gram-Hanssen (2012) found that the electricity demand of identical houses can differ by up to five times and postulated that occupant behaviour is equal to or more influential than building design in relation to house performance. The extent of the savings that can be achieved through affecting occupant behaviour is unclear, but authors agree that these can be significant (Lopes et al., 2012, Gynther et al., 2011) and that behaviour should be addressed as an integral part of low energy building policies (Moore et al., 2014, Leaman et al., 2010, Moloney et al., 2010, Wood and Newborough, 2003).

1.1.2 Theoretical framework

Methods grounded in socio-psychology have been used since the 1970s to influence consumers in their homes (Delmas et al., 2013). These methods are based on established theories such as the theory of cognitive dissonance (Festinger, 1957), the theory of planned behaviour, (Ajzen, 1991), the theory of normative conduct (Cialdini et al., 1991, Cialdini, 2007, Schultz et al., 2007, Nolan et al., 2008) and the theory of habitual behaviour (Aarts et al., 1998). These methods are often applied to modify occupant behaviours by persuasively initiating a change in attitudes and values as well as providing information and breaking established habits (Abrahamse et al., 2005). Feedback technologies such as in-home displays and smart meters have become popular to promote resource consumption awareness given that information communication technologies (ICT) are increasingly cheap. Information campaigns through media advertisements are also popular amongst governing bodies and industry, who see this as a means for rapidly spreading awareness through society. Socio-psychology methods, however, have been criticized for their persuasive approaches (Brynjarsdottir et al., 2012) and short-lived impacts (Lockton, 2017, Hargreaves et al., 2013, van Dam et al., 2010).

Practice theory offers an alternative to understanding occupancy by focusing on everyday practices as opposed to occupant knowledge and attitudes (Shove et al., 2007, Schatzki, 1996). This theory leads us to posit that individuals do not use energy or water resources directly, but rather as instruments to achieve specific outcomes (Hargreaves, 2011, Shove and Walker, 2014). For instance, energy is used in the practice of cooking with the objective of preparing food for consumption. Practices conducted by users are affected by three elements of meaning, skill and technology (Schatzki, 1996, Gram-Hanssen, 2014, Scott et al., 2012). Meaning (also termed image or engagement) is the reason behind the execution of a practice (*e.g.* eating dinner); skill (also termed knowledge or competence) is the understanding of how to execute the practice (*e.g.* knowing how to cook); and technology (also termed matter or stuff) encompasses the objects and infrastructure necessary to undertake the practice (*e.g.* an oven, a stove, a barbecue or a camp fire). The sequential repetition of practices in a habitual routine are interlocked (*i.e.* interconnected) in a system of practice (SOP) (Watson, 2012). Practices are also context dependent and evolve over time as new technologies emerge (Shove et al., 2015). It follows that affecting one or more elements of the practice should result in a modification of resource use and enable (as opposed to persuade) occupants to save energy or water while continuing to meet their intrinsic needs (the meaning element of the practice) (Brynjarsdottir et al., 2012).

Persuasive and enabling methods are often seen as two separate avenues to influence occupants and are seldom merged in research. These two schools of thought have been aligned in this thesis as they are believed to be complementary and have allowed us to uncover the complexities behind the use of energy and other resources in the home (Publication II).

1.2 Research positioning

The flow of resources through urban systems is often described and analysed through the concept of urban metabolism (Rodgers, 1997, Newman and Jennings, 2008, Girardet, 2010). This concept compares urban environments to living organisms, which consume and transform resources internally, generating waste as an output. House metabolism evolved from urban metabolism and describes the flows of resources through a building system (Harder et al., 2014) (Figure 1.1).

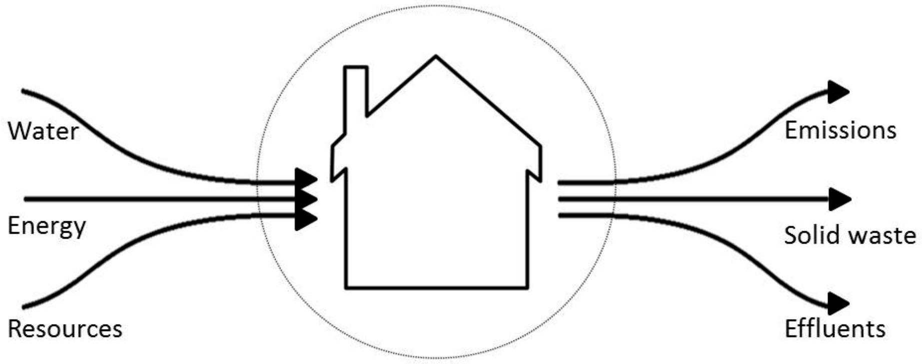

Figure 1.1. Resource flows through a house system (Source: Publication II).

While the influence of building technologies and materials is well understood, the home itself is a black box. Inside the house, occupants interact with each other and with building technologies; further, each occupant also has individual behaviours and everyday practices, which influence resource use (Figure 1.2).

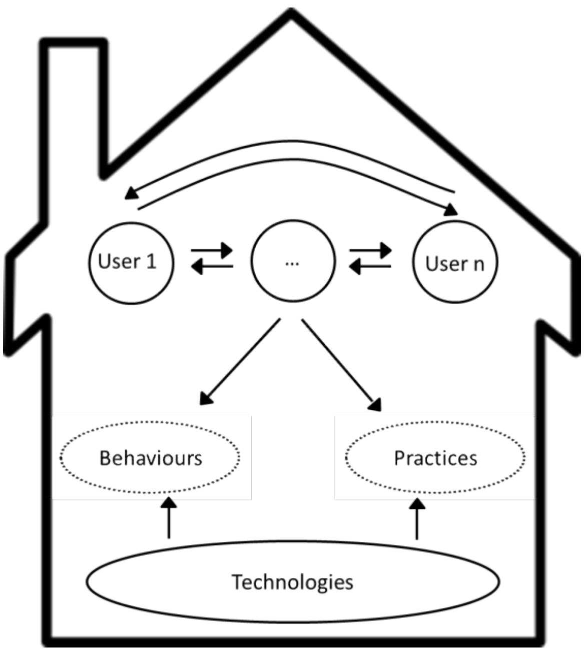

Figure 1.2. The home system (Source: Publication II).

The home can be considered as a combination of the physical building system (house) and the social SOP (Guy and Shove, 2000). The overlay of these elements provides a holistic approach to understanding the home system, which has been termed the home system of practice (HSOP) (Publication VI).

Previous SOP research has focused on broader societal systems and their effect on everyday practices (Watson, 2012, Macrorie et al., 2014). In this thesis, the SOP concept is scaled down to provide an understanding of how the different elements of the home affect resource use.

1.3 Research question and objectives

In light of the context presented above, this research is guided by the following overarching research question:

Can we explain the behaviour, practices and routines of home occupants in terms of practice theory, and if so, can this be defined as a home system of practice?

To answer this question, six sub-questions were posed. These address both the physical and the social elements that make up the home:

- How can the sustainability of residential buildings be assessed through their lifecycle?
- What are the theories and methods typically used to understand and influence home occupants?
- How do low energy residential houses perform from a carbon emission perspective and what influences the outcomes?
- How does design and occupant behaviour affect energy use in the home?
- How do practices impact resource use in the home and how can they be altered?
- Is there a home system of practice and if so, can it be influenced to enable the reduction of resource consumption?

This hybrid thesis by publication addresses each of these sub-questions in individual articles. Publications I and II are literature reviews and Publications III to VI are based on original data. The objectives of each paper and research question they address are outlined in Table 1.1 and Figure 1.3. The latter shows how the publications are linked together in this thesis to answer the overarching research question. Publication I discusses the different aspects of building sustainability and more specifically energy and water efficiency, which are affected by design and occupancy. The subsequent publications were separated into two branches (Figure 1.3); the left branch (Publications II, IV and V) focuses on the understanding of occupancy, while the right branch (Publication III) discusses the influence of building design. The findings from these four articles were merged in Publication VI, which discusses the HSOP.

Table 1.1. Research sub-questions, publications and objectives.

Sub-questions	Publications	Objectives
How can the sustainability of residential buildings be assessed through their lifecycle?	I. Methods to enable residential building sustainability: integrating and evaluating energy, water, materials and liveability Peer reviewed article - literature review	This publication describes methods used to evaluate the efficiency of residential houses from the perspective of the physical building system. It reviews the assessment of buildings at their design stage, after construction completion and during occupation.
What are the theories and methods typically used to understand and influence home occupants?	II. Integrating theories of practice and behaviour into home settings through living laboratories Submitted manuscript for peer reviewed journal – literature review	This publication reviews socio-psychology theories and practice theory as well as methods commonly employed to influence occupants in their homes. The objective of this article is to propose a method to integrate both schools of thought for a more effective understanding of occupant behaviour.
How do low energy residential houses perform from a carbon emission perspective and what influences the outcomes?	III. Verification of an emerging LCA design tool through real life performance monitoring Peer reviewed article	The objective of this publication is twofold: to determine the embodied and operational energy of low energy houses and to determine the accuracy of house design assessment predictions as compared to real house performance.
How does design and occupant behaviour affect energy use in the home?	IV. The influence of design and everyday practices on individual heating and cooling behaviour in residential homes Peer reviewed article	The objective of this publication is to investigate the influence of house design and occupant behaviour on the energy performance of low energy houses. This article discusses the causes for differences in energy use between and within similar house typologies.
How do practices impact resource use in the home and how can they be altered?	V. Influencing energy and water use within a home system of practice Peer reviewed article	The objective of this publication is to reveal the elements of practice affected through a persuasive behaviour change program. This publication discusses challenges and opportunities of change as well as occupant insights and the use of feedback technologies.
Is there a home system of practice and if so, can it be influenced to enable the reduction of resource consumption?	VI. The home as a system of practice and its implications for energy and water metabolism Submitted manuscript for peer reviewed journal	The objective of this publication is to describe how practices are aligned and interlocked in the HSOP and how the HSOP influences overall resource use. This paper provides insight into the home system and unveils underlying reasons behind energy and water use.

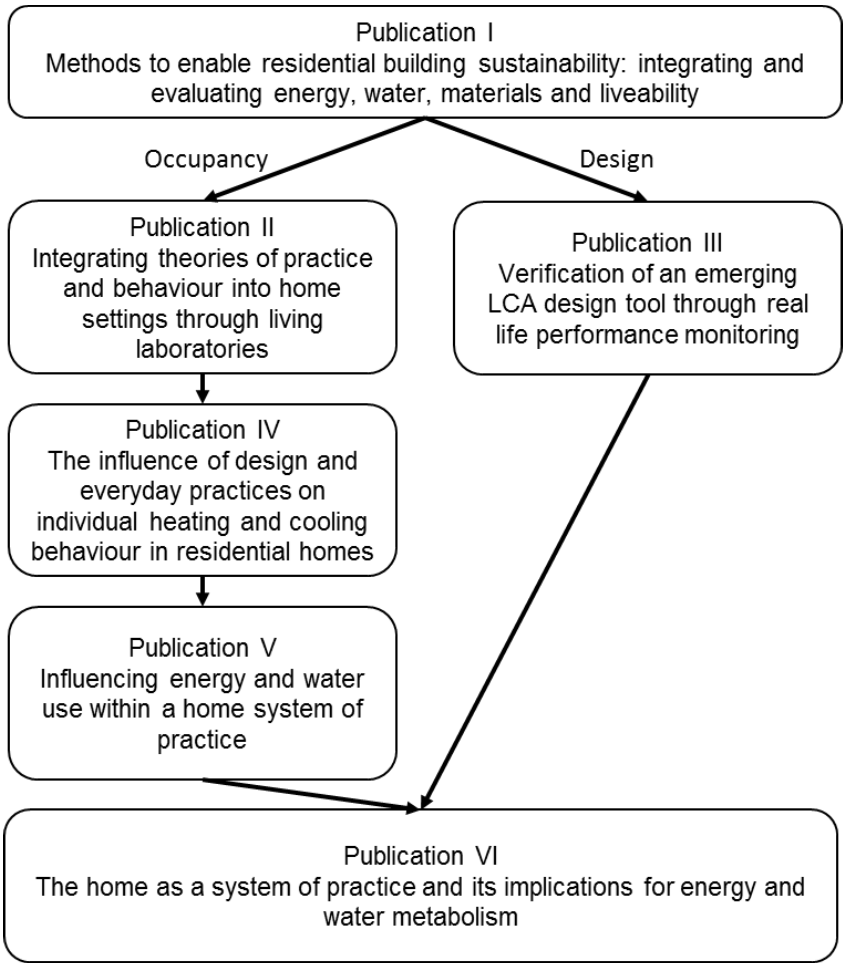

Figure 1.3. Research structure.

1.4 Thesis organization

Six peer reviewed and/or submitted publications provide the research basis for this thesis (Figure 1.3). The exegesis provides the context for and is an integrated synthesis of these publications. Chapter 2 describes the research design and methodology. Chapter 3 provides a summary of the literature review publications (Publications I and II) and Chapter 4 provides a summary of the results (Publications III to VI). Chapter 5 presents the key results from the publications and provides a general discussion, including emerging concepts and hypothesis. Finally, Chapter 6 concludes the thesis and offers recommendations for future research. The published articles and manuscripts are provided as appendices following the exegesis.

Chapter 2 Methods

This thesis is based on the 10 House Living Lab project, which was a longitudinal study of ten low energy houses over the course of two years, the year preceding and the year of a persuasive behaviour change intervention. The selected homes were evaluated in terms of the efficiency of their design and their occupant behaviours and everyday practices affecting energy and water use.

Water was included in the scope of this research because of the high energy and carbon cost related to water supply in WA. The long term decline in rainfall (Bureau of Meteorology, 2016) and the high water demand (Water Corporation, 2009b) alongside a growing population (ABS, 2017) has caused the City of Perth to rely on seawater desalination. The desalination plant currently supplies 50% of the city's potable water and requires 4.1 kWh to generate 1 m^3 of potable water (Water Corporation, 2009b). This makes Perth the most energy intensive water-related user in Australia (Bureau of Meteorology, 2016).

The first monitoring year of the 10 house Living Labs was in 2015 and was used to establish a baseline of energy and water use in the houses. The baseline dataset was employed to understand resource use in the homes in relation to their design, practices and behaviours. The first year of data was also used to compare their operational energy and carbon emissions against predictions made by two assessment tools: NatHERS and eTooLCD. The latter evaluates houses from a life cycle perspective.

During the second monitoring year, 2016, the house occupants agreed to a persuasive behaviour change intervention. The data collected at this stage was used to evaluate the effects of the interventions and changes in occupant behaviour, in the elements of practice and to the physical building envelope.

Quantitative and qualitative approaches allowed the analysis of the varied aspects of house design and appliances, occupant behaviour, occupant everyday practices and occupant interaction with building technologies. The 10 house Living Lab data provided insights into the challenges associated with influencing everyday practices and helped to unveil the complexities of the HSOP.

This chapter will describe the methods employed for the selection of participants, data collection, behaviour change intervention and analysis of the data. Table 2.1 provides a summary of the methods used in each of the publications.

Table 2.1. Research methods reported in the publications.

Publication	Methods
I. Methods to enable residential building sustainability: integrating and evaluating energy, water, materials and liveability. II. Integrating theories of practice and behaviour into home settings through living laboratories.	Narrative literature review
III. Verification of an emerging LCA design tool through real life performance monitoring.	Real life house performance monitoring Life cycle assessment with the software eToolLCD
IV. The influence of design and everyday practices on individual heating and cooling behaviour in residential homes.	Explanatory mixed-method design: o Real life house performance monitoring - Analysis through plotlines and heat maps o Semi-structured interviews - Thematic analysis
V. Influencing energy and water use within a home system of practice.	Explanatory mixed-method design: o Real life house performance monitoring - Statistical tests: Generalized additive models, Wilcoxon signed-rank test and Mann-Whitney test o Longitudinal semi-structured interviews - Thematic analysis
VI. The home as a system of practice and its implications for energy and water metabolism.	- Explanatory mixed-method design: o Real life house performance monitoring - Statistical tests: histograms and Mann-Whitney test o Longitudinal semi-structured interviews - Thematic analysis

2.1 Project participants

Ten houses situated in the coastal City of Fremantle (adjacent to Perth) in WA, were selected for this research. Fremantle has a warm temperate climate with mild annual temperatures which average between 10°C and 27.9°C (Bureau of Meteorology, 2017). Regular sea breezes blow through the city every afternoon, which cool the urban fabric in summer and reduces the need for air conditioner (AC) use. All houses were located within three kilometres of each other and were therefore in the same microclimate. The proximity of the houses ensured that the participants had comparable socio-economic conditions and were exposed to similar external influences.

Nine of the ten selected houses consisted of single detached dwellings, which is the predominant housing typology in Australia (ABS, 2012). They had a mix of demographics (Table 2.2) and building designs (Table 2.3). However, all of them presented energy and/or water efficient design elements that distinguished them from the average Australian house. Four of the houses met the minimum required rating of 6-Stars under NatHERS and three houses were rated 7-Stars or above; this classification means they were considered low energy or high performance houses in Australia. Two of the dwellings were old houses that had been retrofitted to become more energy efficient through the installation of PV panels, solar hot water, insulation and shading devices. Finally, one of the houses was rated DTS, which means that while the house did not have its energy use modelled, it followed a series of prerequisites prescribed by the NCC. The NatHERS assessment is based on the energy required per square meter to keep houses thermally comfortable through the year. While this assessment tool does not predict total energy use, the ratings are often used as a measure of energy efficiency since cooling and heating make up 40% of domestic energy use (DEWHA, 2008).

Table 2.2. Participants and their occupations in the 10 House Living Lab project.

Home	Residents	Occupation
1	2 adults 1 young adult	Retired Works full-time
2	2 adults 2 children	Works 4 days per week/Works 1 day per week School/at home
3	1 adult 2 teenagers 1 young adult	Works full-time At school Unemployed
4	2 adults	Work full-time
5	2 adults 3 children	Works full-time/at home At school/at home
6	2 adults	Work full-time
7	2 adults 1 young adult	Work full-time Works full-time
8	2 adults 2 children	Works full-time/works part-time At school/at home
9	2 adults 2 children	Work full-time At school
10	4 young adults	University students

Table 2.3. House physical characteristics, technologies and NatHERS rating.

Home	Year built/ renovated	Floor area (m^2)	Cooling and heating technologies (ambient and water)	Water sources in addition to mains water supply	Major building materials	NatHERS rating
1	2013	218	Electric solar hot water, electric cooling, gas heating	N/A	Double brick walls, concrete slab	6-Stars
2	1950/ 2011	106	Electric solar hot water, 1.5 kW PV panels, electric cooling and heating	N/A	Timber walls and floor	Retrofitted
3	2013	147	Gas solar hot water, 2.66 kW PV panels, electric cooling and heating	Rainwater	Double brick walls, concrete slab	6-Stars
4	1899/ 2001	106	Electric solar hot water, 1.68 kW PV panels, no cooling, portable electric heater	Rainwater	Limestone and double brick walls, timber floor and concrete slab	Retrofitted
5	1901/ 2014	177	Instantaneous gas water heater, 3.5kW PV panels, electric cooling and heating	N/A	Timber walls, concrete slab, timber floor	6-Stars
6	2013	154	Gas solar hot water, 1.8 kW PV panels, electric cooling and heating	Rainwater	Double brick walls, concrete slab	6-Stars
7	2011	186	Instantaneous gas water heater, 2 kW PV panels, electric cooling and heating	Rainwater	Rammed earth and timber walls, concrete slab	7-Stars
8	2011	238	Electric solar hot water, 2.28 kW PV panels, no cooling or heating	Rainwater, greywater	Rammed earth and double brick walls, concrete slab	8-Stars
9	1920/ 2014	183	Gas solar hot water, 1.1 kW PV panels, electric cooling and heating	Rainwater	Double brick and timber walls, concrete slab, timber floor	DTS[1]
10	2009	177	Gas solar hot water, 1.2 kW PV panels, no cooling, gas heating	Rainwater, greywater	Double brick walls, concrete slab	8.5-Stars

[1] Deemed-to-satisfy

The ten houses followed principles of passive solar design (Department of Climate Change and Energy Efficiency, 2010); that is, they were oriented North and used direct sunlight and thermal mass for warmth in winter. In summer, natural evening breezes, thermal mass and external shading devices helped to keep the houses cool. While the NCC does not mandate the installation of PV panels on new builds, nine of the ten houses possessed them. These have been increasingly adopted by residential Australian dwellings and are currently present in 19% of houses (ABS, 2016), especially in the outer suburbs (Newton and Newman, 2013). The City of Fremantle also encourages the installation of rainwater tanks in new houses. These were present in seven of the participant houses and used in the garden and/or internally for the toilet and clothes washing machine.

The participant recruitment process was through a media advertisement in the local Fremantle newspapers and a mail drop directed at detached or terraced houses built or renovated after 2012, which corresponds to the year when the 6-Star NatHERS requirement was introduced. Individuals who demonstrated interest were further scrutinized based on their house design and household demographics. A further requirement included the availability of house design plans and utility bills.

2.2 Research design

The ten homes were converted into Living Laboratories (LLs) from December 2014 to December 2016. LLs consist of real life places, such as existing residences, where innovations are co-created with and tested by users (Burbridge et al., 2017, Dell'Era and Landoni, 2014). The LL lifecycle has four stages consisting of insight research, ideation, co-creation and venturing (Katzy and Bucker, 2015). This research is situated at the insight research stage, which aims to understand occupant needs, their baseline practices and interactions with building technologies (Herrera, 2017). Insight research is essential for the development of products and services that enable home sustainability.

The objective of the first year of data collection was to establish a baseline in terms of occupant behaviours and practices and to evaluate the homes from a design perspective. Contact with the occupants was kept to a minimum during that stage to avoid influencing their everyday life, including practices, routines and habits. Technicians were sent to some of the houses when required to fix problems related to the monitoring system; however, the researchers did not engage with the participants. While participants were aware of the nature of the research, the behavioural aspect was not emphasised during the first year. Instead, the emphasis was on evaluation of the house design. During the second year, participants joined the persuasive behavioural change program. The impacts were measured in terms of changes in behaviour, changes to the elements of practice and changes made to the physical building system in comparison to the baseline data.

Mixed-methods are a common approach to conducting research in LLs (Herrera, 2017, Foulds et al., 2013). This methodology combines quantitative and qualitative data for a more holistic interpretation of results. This thesis used an explanatory mixed-method design approach to collect and interpret data; which involved the collection of quantitative data followed by a qualitative data collection to provide a more holistic assessment (Figure 2.1) (Creswell and Plano, 2011). This method was chosen to overcome the weaknesses associated with purely quantitative or qualitative research. For instance, qualitative research that relies on reported accounts can be biased or inaccurate (*e.g.* Corral-Verdugo, 1997). Quantitative research, on the other hand, cannot necessarily explain all of the findings (Johnson and Onwuegbuzie, 2004). The rest of this section will describe the methods used for the quantitative and qualitative data collection.

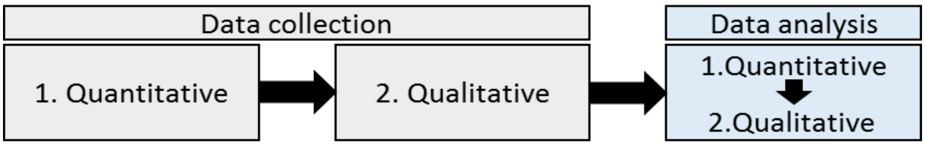

Figure 2.1. Explanatory mixed-method design (adapted from Creswell and Plano, 2011).

2.2.1 Quantitative data collection

A monitoring system was designed to collect detailed quantitative data about energy and water use as well as thermal comfort in the ten homes. The system had three primary objectives: to compare the modelled house performance to the actual house performance in terms of energy use, carbon emissions and thermal comfort; to provide an understanding of baseline resource use in the ten houses; and to enable a quantitative evaluation of the effects of the persuasive behaviour change program in terms of overall electricity, gas and water reduction.

Monitoring equipment consisted of meters, sensors and a data logger (Table 2.4). These were installed in the ten houses to measure gas, grid electricity and mains water use as well as temperature in the living area. Houses with PV systems and/or rainwater tanks also had PV electricity generation and rainwater use measured. The data was collected from each meter at 15 minute intervals and stored in the data logger. This data in .csv file format was sent daily to a server/cloud via a 2G wireless internet connection (Figure 2.2). The exception was gas, mains water and rainwater use in house 7, where the meters were located outside the property and connection to the data logger was not feasible. In this house, data from the three meters were downloaded manually on site once per month. PV electricity use onsite was calculated from electricity bills requested from the households at the end of each calendar year. Weather data, such as ambient temperature, relative humidity, precipitation, and solar radiation were obtained from a weather station (Vaisala WXT520) also located in the City of Fremantle.

At the start of the second monitoring year, an online platform (Power Monitoring Expert 7.2) was configured for automatic data visualisation (Figure 2.3). This platform enabled viewing daily (previous day), weekly, monthly or yearly resource utilization summaries, and comparing use between the different project participants.

Table 2.4. Monitoring equipment in the ten homes.

Parameter monitored	Meters and sensors	Data logger
Gas	Ampy 750 gas meter & pulse counter Elster IN-Z61; Home 7: Ampy 750 gas meter & Onset Hobo UX90 512K	Schneider Electric COM'X200
Grid electricity	Schneider Electric iEM3110	
Mains water	20mm Elster V100 & MEB7454 'T'probe OR Actaris TD8 & Cyble sensor 2W K=1; Home 7: 20mm Elster V100 & Hobo pendant event data logger UA-003-64	
Photovoltaic electricity production	Schneider Electric iEM3110	
Rainwater	20mm Elster V100 & MEB7454 'T'probe Home 7: 20mm Elster V100 & Hobo pendant event data logger UA-003-64	
Temperature	Kimo TM 110	

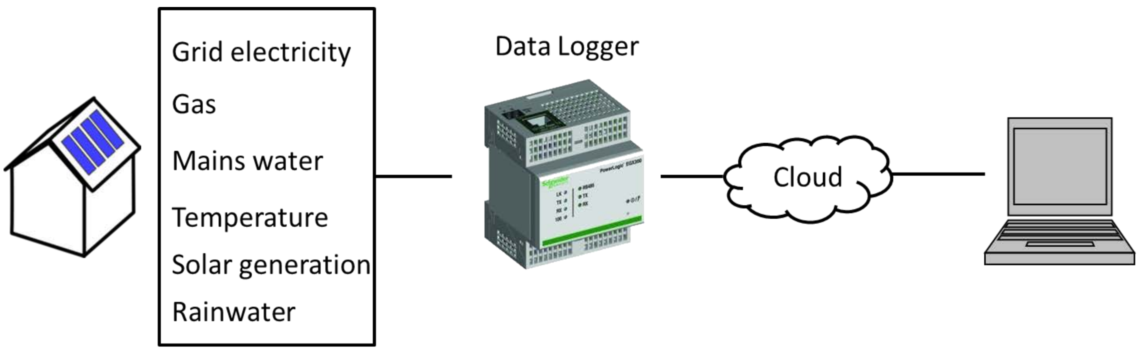

Figure 2.2. Quantitative data collection design in a single house. This configuration was replicated in the ten houses.

Figure 2.3. Snapshots of the Power Monitoring Expert 7.2 online visualisation platform.

2.2.2 Behaviour change intervention

At the start of the second monitoring year (December 2015), the house occupants joined the persuasive behaviour change program. The design of the program was based on a review of socio-psychology theories and 34 peer-reviewed articles reporting methodologies and quantitative results related to influencing energy and water use in the home (Publication II). A mix of approaches was combined in this research to reproduce best practices found in the literature. These included mixing technology-based interventions (*e.g.* feedback displays), social-based interventions (*e.g.* audits and coaching) and knowledge-based interventions (*e.g.* information material and emails) (Publication II). The combination of these approaches ensures that the interests of different audiences are captured (Strengers, 2011, van Dam et al., 2010). Moreover, they have different purposes; some target social norms, value activation, a change in attitude, others act as a reminder or simply increase awareness (Abrahamse et al., 2005). Technology-based interventions enable more frequent feedback over long term studies, although the use of the feedback technology may not become a habit (Hargreaves et al., 2013). Social-based interventions are more costly from a resource perspective and may be used in shorter studies (Publication II); in contrast, they create more supportive environments for change (De Young, 1996).

An audit marked the beginning of the behaviour change intervention at the start of the second monitoring year, in the early Australian summer (December 2015). This audit focussed on ways of reducing energy and water use in the home, focusing on resource intensive practices carried out during the summer period, including the use of the AC and garden irrigation. Principles of passive solar design were explained with the assistance of a thermal imaging camera (Figure 2.4), which helped to highlight heat gains into the house. Thermography was also used to identify other sources leading to thermal discomfort such as missing insulation from ceilings and walls (Publication I). Encouragement was provided to use appliances during daylight hours in houses with PV panels and the functioning of the latter was explained to the participants who were unclear about their operation. The energy used by appliances on standby mode was also measured with an electricity meter (Figure 2.5). Those consuming significant amounts of electricity were identified and the occupants were encouraged to disconnect them when not in use.

Figure 2.4. Thermal imaging camera Testo 870.

Figure 2.5. Arlec electricity meter.

The water component of the audits focused on the two most water intensive practices in the Australian home, which are garden irrigation and personal showers (Water Corporation, 2010). The local water authority encourages individuals to take short showers of 4 minutes or less and this message was reinforced during the audit. Regulations related to the use of the reticulation system are also in place for water conservation and these were also discussed with participants. As part of the water reduction audit, a gardening specialist provided tailored advice related to plant health, the water wise choice of plant species and garden watering requirements. Factsheets were given to each household at the end of the audit with a summary of the information discussed as well as other useful tips (Appendix A). A further report with tailored advice delivered during the audit was also provided by email following the house visits (Appendix B).

During this first house visit, participants were provided access to the online visualisation platform (Power Monitoring Expert) (Figure 2.3), which enabled homes to check their data on a near-real time basis. The website was updated daily to display not only individual household historical data (electricity, gas, water, rainwater, PV electricity and internal temperature), but also to enable homes to compare themselves against other participants. All the homes were coded to protect privacy and participants were given their unique codes.

The final part of the audit was a request to participants to set written energy and water reduction goals to be pursued through the year. These were designed to play the role of a commitment, acting as a motivator and a reminder of the behaviour change program (Pardini and Katzev, 1983).

A second audit occurred at the start of the Australian winter, in May 2016. This audit followed the same agenda as the summer audit; however, the focus was shifted to winter practices such as the use of ambient heating and showering with hot water. The thermal imaging camera was used once again to detect air infiltration into the houses and other sources of heat loss.

Throughout the second year, summary reports were emailed to all the participant homes every month. These acted as prompts to remind them to check the website and to continue their efforts towards reducing resource use in their homes. The monthly reports complemented the website with additional information, providing an interpretation of the data. Energy and water use was also provided in different and perhaps more tangible metrics with the expectation that occupants would better relate to the data (Jain et al., 2013, Jeong et al., 2014). Each monthly report contained the following information:

- Historical electricity, gas, water and rainwater use;
- Historical PV electricity production;
- Historical household GHG emissions and corresponding car mileage;
- Electricity, gas and water use comparison with the participants' average, which provided a descriptive social norm (Schultz et al., 2007);

- Electricity, gas and water reduction compared to the set goals;
- Cost savings or increase compared to the previous year;
- Word of encouragement or congratulation as a form of injunctive norm (Schultz et al., 2007);
- Tailored tips taking seasonal factors into account.

2.2.3 Qualitative data collection

Qualitative data collection occurred at three different instances during the behaviour change program: on the same occasion as the two audits (December 2015 and May 2016) and at the end of the project, during the decommissioning phase (December 2016). Each encounter consisted of firstly, a discussion of the previous quantitative data collection period and secondly, semi-structured interviews. The participants were shown summaries of their previous electricity, gas and water use and asked about changes to their everyday practices, routines or habits. Surprising results, for instance, the higher or lower use of energy in one month, were investigated during this conversation.

The three semi-structured interviews are longitudinal, that is, they aim to capture changes that occur with time along the behaviour change program. This method involves asking participants similar questions at each occasion to obtain their in-depth perspectives on the recurring themes (Hermanowicz, 2013). The advantage of the longitudinal approach is that frequent contact with the researchers helps to build trust and openness. However, there is also a risk that questions might become repetitive and lead to loss of interest (Hermanowicz, 2013). To prevent this from happening, questions were formulated differently each time and interviews were informal and limited to a maximum of 30 minutes. Moreover, the interviews were framed as an opportunity for participants to provide feedback about the usability of the website and reports. The feedback was used to improve reports when appropriate.

The interviews occurred, whenever possible, with all members of the household present and discussion between members was encouraged. Questions mostly addressed behavioural elements as they aimed to understand participant values, attitudes and social norms. The first interview also revealed participant occupation, lifestyle and interests about energy and water conservation. Aside from the primary objective of gathering data about participant backgrounds, the first interview also aimed to activate hidden values (Verplanken and Holland, 2002).

The two follow-up interviews questioned the use of the website and reports as well as challenges, barriers and opportunities for change. The final interview included questions about lessons learnt and the impact of the project on the participants.

2.3 Data analysis

The results are based mostly on the quantitative data from the house meter measurements. However, qualitative data from the longitudinal semi-structured interviews and audit observations were used to clarify, explain and enrich the data as described in Figure 2.1. The methods for data analysis are explained in this section.

2.3.1 Quantitative analysis

Each year of quantitative data collection resulted in a total of 35,040 data points per meter or sensor (gas, grid electricity, mains water, rainwater, internal temperature and PV electricity production) for each of the houses. With a total of 57 meters/sensors installed, each year of data collection resulted in a total of 1,997,280 data points. The quantitative data was used for the evaluation of the house design (further explained in section 2.4), for the understanding of baseline behaviours and practices in the home and for the assessment of the behaviour change program, including changes in overall resource use and changes in everyday practices.

The exploration of everyday practices was carried out through the analysis of cooling and heating, personal showering and garden irrigation. These practices were chosen for two reasons; firstly, they are responsible for the largest use of resources in the home (DEWHA, 2008, Water Corporation, 2010) which means that understanding them may provide strategies to lower home resource use; and secondly, they were distinguishable from the rest of the data given their high resources use intensity.

The examination of the data was systematic through graphs and statistical methods, which are described in the rest of this section.

2.3.1.1 Visual analysis

The data was analysed from a macro (yearly and monthly) to a micro (hourly and every 15 minutes) level to enable an understanding of the differences in energy use not only between different homes (inter-home), but also between occupants of the same home (intra-home). The evaluation of yearly, monthly and daily data was done visually through bar and line graphs plotted through the Microsoft Excel Power Pivot add-in. The latter enables merging and managing large amounts of data from diverse databases.

Contour plots were used for the visual analysis of energy use in the homes during the summer and winter months of the first year (Publication IV). Since cooling and heating represents the highest use of energy in the home, the darker shades in the contour plots were attributed to the use of the AC in summer and to the use of the heater in winter. This method enabled understanding and visually interpreting differences in the practice of thermal conditioning not only between different houses but also between occupants of the same home.

The understanding of resource intensive automated practices such as the use of reticulated irrigation and the use of a pump for cleaning the swimming pool in home 6 were also analysed visually through contour plots and line graphs that depicted the average hourly energy and water use through the year.

2.3.1.2 Statistical analysis

Behaviour change evaluation

The weather conditions varied considerably between 2015 and 2016; with 46% higher average daily precipitation and 4% colder daily temperatures in 2016 compared to 2015 (Publication V). This affected the use of the cooling and heating systems, the use of hot water and the practice of watering the garden. Consequently, the comparison of resources between the two years was not straightforward. Statistical methods were necessary to differentiate between the impacts caused by environmental factors and the impacts caused by the behaviour change program.

Generalized additive models (GAMs) were employed to estimate the influence of weather condition on energy and water use. This method is similar to generalized linear models, except that it replaces the linear predictor with an additive predictor which is the sum of smooth (or scatterplot smoothers) non-parametric functions of the type $\sum s_j(x_j)$ (Hastie and Tibshirani, 1986). These functions attempt to fit sections of the data into smooth curves, subsequently adding them up. Overfitting is avoided by GAMs through the control of the smoothing and wiggliness of the predictor function (Sullivan et al., 2015). The advantage of GAMs over other statistical methods such as multiple regression models or machine learning methods, is that GAMs are easy to interpret and they are flexible as they do not assume linearity between the dependent and independent variables (Wood, 2017).

The influence of the different weather variables on resource use in each of the participant homes was modelled with GAMs using the statistical software package R. Weather and resource variables were combined differently for each home depending on the building system and available technologies (Table 2.5). The use of ambient cooling and heating, water heating and irrigation may be influenced by weather conditions such as outdoor temperature, humidity, solar radiation and precipitation. Cooking or the use of other domestic appliances, on the other hand, are not affected by environmental factors and therefore act independently of the weather.

Table 2.5. Environmental factors contributing to energy and water use in different homes. The variables include temperature (Temp; °C), Solar radiation (SR; kW/m^2), relative humidity (RH; %) and precipitation (Pcpn; mm). N/A means environmental factors do not influence energy use in the home.

Home	Parameters	Grid electricity	Gas	Water
1	Variables Use/Purpose	Temp, SR, Rh Cooling, solar hot water	Temp, SR, Rh Heating	SR, RH, Pcpn Irrigation and internal use
2	Variables Use/Purpose	Temp, SR, Rh Cooling, heating, solar hot water	N/A N/A	SR, RH, Pcpn Irrigation and internal use
3	Variables Use/Purpose	Temp, SR, Rh Cooling, heating	Temp, SR Solar hot water	SR, RH, Pcpn Irrigation and internal use
4	Variables Use/Purpose	Temp, SR, Rh Heating, solar hot water	N/A Cooking	SR, RH, Pcpn Irrigation and internal use
5	Variables Use/Purpose	Temp, SR, Rh Cooling, heating	Temp Hot water	SR, RH, Pcpn Irrigation and internal use
6	Variables Use/Purpose	Temp, SR, Rh Cooling, heating	Temp, SR Solar hot water	SR, RH, Pcpn Irrigation and internal use
7	Variables Use/Purpose	Temp, SR, Rh Cooling, heating	Temp Hot water	SR, RH, Pcpn Irrigation and internal use
8	Variables Use/Purpose	Temp, SR Solar hot water	N/A Cooking	SR, RH, Pcpn Irrigation and internal use
9	Variables Use/Purpose	Temp, SR, Rh Cooling, heating	Temp, SR Solar hot water	SR, RH, Pcpn Irrigation and internal use
10	Variables Use/Purpose	Temp, SR, Rh Heating	Temp, SR Solar hot water	SR, RH, Pcpn Irrigation and internal use

The sum of residuals and intercept was viewed as a true indicator of occupant behaviour once the influence of the environmental factors was excluded from the data. A Wilcoxon signed-rank test was subsequently applied to determine variations in grid electricity, gas and water use caused by a change in occupant behaviour between the two years.

The Wilcoxon signed-rank test is a non-parametric statistical test that assesses variations between two matched samples when the populations are not normally distributed (Rosner et al., 2006). This test assumes that the three following conditions are met (Laerd Statistics, 2015b):

1. The dependent variables are measured at the ordinal or continuous level;
2. The independent variables consist of two related groups;
3. Under the null hypothesis, the difference between the pairs are symmetrical in shape.

The software package SPSS Statistics was used to run the Wilcoxon signed-rank test to evaluate the significance of the null hypothesis at a 95% confidence level (p-value = 0.05) and determine whether occupants increased or decreased their energy or water use between the two years.

Change in everyday practice

The evaluation of everyday practices was carried out to provide a more detailed understanding of the changes affecting resource use between the two years.

Given that only total grid electricity, total gas and total water use were measured through the meters and sensors, the first step of assessing changes in practices consisted of the identification of the resource use relating to the practices in question (cooling, heating, hand watering and personal showering).

Microsoft Excel algorithms were used to run through 70,080 data points collected over 2 years for each meter (grid electricity, gas or water) and automatically detect resource consumption relating to the targeted practices. Cooling and heating are the most energy intensive practices in the home, using the most energy in summer and winter (DEWHA, 2008). The practice of cooling in summer was identified by a significant increase in electricity use above the usual electricity baseload alongside a sudden decrease in internal temperature (T) as compared to previous readings (T_1-T_2>0). Similarly, the practice of heating in winter was identified by an increase in electricity or gas use (above ~ 0.8 kWh per 15 min interval, depending on the heating system in the house) alongside a sudden increase in internal temperature compared to previous readings (T_1–T_2<0). The placement of the temperature sensor in the living area ensured that kitchen practices were not mistaken for the use of the heater. However, this also restricted the analysis of the cooling or heating practices to the living room area. Secondary ACs or heaters located in bedrooms, bathrooms or kitchens could not be considered in this research.

Garden irrigation is the most water intensive practice in Australian homes (Water Corporation, 2010). Accordingly, the highest water use peaks in summer (above ~ 120L per 15 min interval) were attributed to the practice of garden hand watering. Two of the houses have dedicated rainwater tanks for irrigation, which was separately metered and directly associated with the practice of hand watering.

The practice of personal showering is the second most water intensive practice in Australian homes and represents the highest water use in winter, during the irrigation ban period. Therefore, peak water use in winter occurring concurrently with an increase in electricity or gas use for water heating was attributed to the practice of personal showering. A wide water volume range of 50 to 120 L per 15 minutes was captured by the algorithm, which is aligned with average shower volumes per person identified in Australian literature (Water Corporation, 2009a). The water volume ranges for personal showering found during the winter months in each house were extrapolated to the rest of the year, when energy for water heating is reduced due to the use of solar hot water systems in most homes. In order to guarantee that this method did not incorrectly capture water used in the dishwasher and clothes washing machine, the appliance models were checked for the volumes of water used in each filling cycle. These were found to be considerably less than the volume of the water used in the shower, and therefore did not influence the results. Personal showering practices were analysed in terms of shower length, which was calculated by dividing the total shower volume by the volumetric flow rate of the shower head. While this method could not differentiate between a shower and a bath, it is assumed that baths are negligible since they are a practice of only 5% of the Australian population (Water Corporation, 2009a).

Practices were evaluated in terms of cooling and heating duration, time of use and temperature setting; volume of water used per irrigation session; and personal shower length. Differences in everyday practices between the two years were analysed with the use of the non-parametric statistical test Mann-Whitney *U*-Test. The latter tests the null hypothesis (H_0) that two populations distributions are equal (have the same median) (Nachar, 2008), where $H_0 : P\ (x_i > y_i) = \frac{1}{2}$.

The Mann-Whitney *U*-Test assumes that the following four basic conditions are met (Laerd Statistics, 2015a):

1. The dependent variable is measured at the ordinal or continuous level;
2. The independent variable is an independent group;
3. The observations are independently observed;
4. Under the null hypothesis, the two distributions have the same or a similar shape.

The fourth assumption enables the comparison of the two populations in terms of their medians. In the case this assumption is not met, the populations must be compared in terms of their mean ranks. The software package SPSS Statistics was used to check the fourth assumption and to conduct the Mann-Whitney *U*-Test to evaluate the significance of the null hypothesis.

The non-parametric Wilcoxon-signed ranked test was initially considered instead of the Mann-Whitney *U*-Test to evaluate everyday practices. However, the population samples were not paired as the number of showers, irrigation and cooling and heating events were not equal between the two years.

Home system of practice

To understand the home system, the interlocking and alignment of practices in the HSOP was investigated mainly through the analysis of personal showering and hand watering practices (Publication VI). The frequency distributions of these everyday practices were plotted as histograms depicting the practice length (showers), volume (hand watering) and time of the day when they were undertaken. Weekdays and weekend showers were analysed separately due to an identified difference in routines. The histogram bin sizes were standardized to 1 minute for histograms depicting shower lengths, 5 litres for those depicting irrigation volume and 30 minutes for those depicting time of day. This was done systematically for all participant houses.

The graphic software OriginLab Pro 2017 was subsequently used to analyse the histograms. These were fitted with one or more curves according to the number of identified significant peaks. The curve parameters such as coefficient of determination (R^2), coefficient of variation (CV), mean (μ), mode (Mo) and standard deviation (σ) were calculated by the software according to the shape of each curve. These parameters were used to interpret the practice elements according to practice theory.

The differences in the practice of personal showers between weekdays and weekends as well as between weekday mornings and afternoons were analysed through the statistical non-parametric Mann-Whitney *U*-Test.

2.3.2 Qualitative analysis

Qualitative data obtained through the semi-structured interviews, thermal images and other house observations were used to support and elucidate the quantitative data analysed through the methods described in Section 2.3.1.

The recorded semi-structured interviews were fully transcribed and analysed thematically (Braun and Clarke, 2006). The discussed topics were themed according to the three elements of practice (meaning, skill and technology), behaviour components (attitude, habits, norms, value) and other contextual elements affecting daily resource use in the home. Since the interviews were used uniquely as supporting material, only relevant extracts were used to illustrate the results and discussion (Publications IV, V and VI).

The analysis and processing of the thermal images was through the Testo software IRSoft.

2.4 Life cycle assessment

The evaluation of energy and carbon emission performance of each house was carried out through life cycle assessment (LCA) using the software eToolLCD (Publication III). The latter was chosen as it was developed in WA, being tailored to the local market and taking local industry construction practices into account. eToolLCD calculates the building embodied and operational energy over its lifetime based on the design specification and construction materials entered by the user. The user is able to specify information such as the source of the construction materials or specific building construction methods; but the software also possesses existing templates with assumptions based on common local industry practices and international databases (Haynes, 2010). Templates were used in this research when specific information was unavailable.

eToolLCD presents the carbon emissions and energy use broken down into the different stages of the building lifecycle: material manufacture, transportation, assembly, building maintenance, operation over the building lifespan, demolition and disposal. Estimations of building lifespan are based on the density and redevelopment potential of the building site, the ownership type, the house typology (*e.g.* strata complex, detached house, villa, and apartment) and the quality of the building design. The retrofitted homes are also heritage listed, which implies that their facades need to be preserved. However, they have undergone major internal renovations, with the addition of extensions and energy efficient features. The calculation of the lifespan was based on these renovations while the LCA was carried out for the entire building.

House design information was obtained through plans that were requested from the participants following the recruitment process. Missing design specifications and appliance information were verified onsite during the audits, with permission of the occupants.

The quantitative energy use data from the first year was compared against the LCA operational energy predictions in order to verify the accuracy of the software. The qualitative data obtained during the first audit was used to identify possible causes for discrepancy between predicted and actual energy use in the house. These included findings from the building thermography, semi-structured interviews and other design observations. The embodied energy of the ten houses were also compared in order to provide insight into the relationship between operational and embodied energy.

2.5 Research constraints

This research encountered several constraints; some related to the experimental design and others related to the real-life trial.

2.5.1 Experimental design constraints

The first limitation of this project was in the participant selection process. While the research intended to obtain a sample of the average Australian house owner, the voluntary nature of the recruitment process resulted in the selection of households that were already interested in energy efficiency and sustainability. Further, the research focused on low energy houses and the participants pre-disposition to sustainability could have resulted in bias. However, this also presented the opportunity of studying the insights into low energy house owners as well as intra-home behaviours and practices.

Another constraint was the limited number of recruited households due to a limitation in budget. This means that each household was treated as an individual longitudinal case study. On the other hand, the small number of homes was more manageable and a strong relationship between the participants and the research team was developed over time. The small sample of homes enabled them to be understood in depth, which would not have been possible with a larger number of participants.

Finally, the number of meters and sensors installed in the houses was another limitation of this research project. Ideally the AC, the heater, the shower and the irrigation circuits would have been monitored separately to provide more accurate data relating to the everyday practices of thermal control, personal showering and irrigation. While algorithms were developed to detect these practices, it is possible that they did not capture unusual practices. Similarly, due to budget constraints only one temperature sensor was installed per house, limiting the understanding of thermal comfort and AC/heating use in locations other than the living area.

2.5.2 Real-life trial constraints

As a requirement to become a participant in this research, households had to confirm that they did not have plans to undertake major renovations or move houses during the duration of the project. Despite confirmation from all house owners, house 10 was sold in November 2015 and the owners of house 3 moved out in July 2016. Consequently, house 10 was excluded from the analysis concerning the effects of the behaviour change program. The effects of the behaviour change intervention for house 3 were only observed from January to July 2016.

Another constraint was related to equipment failure and the occasional interruption of the quantitative data collection. All the houses experienced data loss to a certain extent, either related to power outages, weather damage or accidental cable disconnection. However, the main data loss was after an update of the data logger software, which resulted in two to six weeks of data loss affecting all the houses. The data logger in house 9 also stopped working following a power outage while the occupants were on holiday. This caused a significant delay in the replacement of the data logger and three months of data were lost. In addition, this house also experienced intermittent interruptions to the temperature and gas measurements, leading to its elimination from the analysis of everyday practices (Publications V and VI). Resources used during data loss periods were estimated based on the average values from the days of the month preceding and after the loss.

Finally, home 5 did not provide their electricity bills to the researchers at the end of the project, which hindered the calculation of the PV electricity use in this house.

Chapter 3 Literature review summary

This chapter provides a summary of the literature reviewed for this thesis. Section 3.1 describes methods used internationally and in Australia to assess residential building energy efficiency and sustainability through the building lifecycle (Publication I). Section 3.2 reviews the existing literature relating to influencing home occupant behaviours and practices (Publication II).

3.1 Methods to enable residential building sustainability: integrating and evaluating energy, water, materials and liveability

3.1.1 Introduction

The sustainability of buildings can be appraised at three different instances during their lifecycle: at the design stage; during construction or following construction completion; and during their operation, while occupied. International policies have focused on the design stage often imposing minimum standards for energy efficiency. However, these usually disregard other important factors contributing to carbon emissions and occupant well-being. These factors include the embodied energy of building materials, water use, accessibility to public transport, proximity to commerce and services, biodiversity, house adaptability and affordability (VillarinhoRosa and Haddad, 2013, Maliene and Malys, 2009). Moreover, buildings do not always perform optimally as designed and issues related to poor building construction and operation have been observed (DSD, 2015). This section provides an overview of the existing assessment tools and methods to evaluate the sustainability of residential buildings over their lifecycle, focusing on Australia.

3.1.2 Assessment tools

There are three categories of rating tools for building assessment during the design stage (Bragança et al., 2010). Performance-based design tools evaluate the energy performance of buildings, and are the most common. Life-cycle assessment systems consider embodied energy from building materials as well as emissions from building construction, transport, building demolition and disposal. Finally, sustainable building ratings enable a holistic approach to sustainable building design.

In Australia, there are two mandatory rating tools: the Building Sustainability Index (BASIX) and NatHERS. The latter is mandatory in five out of the six Australian states, including WA, and is classified as a performance-based design tool. NatHERS focuses on reducing residential energy demand for cooling and heating per square meter and rates houses from 0 to 10 Stars.

10-Star houses require virtually no mechanical cooling or heating to maintain comfortable temperatures year-round (Table 3.1). NatHERS is based on a simulation of the thermal building performance and considers aspects such as climate, building orientation, habitable area, insulation, thermal mass and glazing type. However, it has been criticised for its narrow scope, since it does not mandate the inclusion of other major house design elements that affect energy use, such as water heating, lighting, renewable energy or energy intensive appliances. Moreover, the house accreditation process is not always carried out by qualified assessors, leading to errors. Building inspections are also not required by the NCC and the built form does not always reflect the accredited design (DSD, 2014).

Table 3.1. Cooling and heating energy loads for each NatHERS Star band (MJ/m^2.annum) in selected Australian cities (adapted from Department of Climate Change and Energy Efficiency, 2012).

Location	NatHERS Star rating									
	1	2	3	4	5	6	7	8	9	10
Perth	387	251	167	118	89	70	52	34	17	4
Sydney	230	148	98	68	50	39	30	22	13	6
Melbourne	559	384	271	198	149	114	83	54	25	2

Several voluntary building assessment alternatives have been developed in Australia to complement NatHERS and deliver more comprehensive house evaluations. eToolLCD, for instance, rates building carbon emissions from cradle to grave. This life cycle analysis also provides insight into other building impacts such as water use, land use, cost, toxicity and ozone depletion. Living Key consists of a multi-criteria assessment which evaluates not only the building envelope and operational emissions, but also its connectivity, liveability, surrounding biodiversity, community and water efficiency.

3.1.3 Construction verification

Incorrect ventilation leading to mould and condensation in the building is a cause of major health problems (Howden-Chapman et al., 2005, Shorter et al., 2017). Leaky buildings with insufficient insulation require up to 50% more cooling and heating compared to other buildings (Fernández-Agüera et al., 2011). When coupled with fuel poverty, poorly constructed buildings can be a major cause of death in winter (Howden-Chapman et al., 2012). Australian buildings underperform from an air tightness perspective, their air leakage rates being much higher than international best practices (Ambrose and Syme, 2015).

The most common methods to conduct inspections for verification of the building envelope performance are through the blower door test and thermography (Ambrose and Syme, 2015, Balaras and Argiriou, 2002). The blower door test verifies the building tightness by pressurizing the house and measuring the rate of air infiltration. Thermography can be used in conjunction with the blower door test to detect leakage points, which are usually located in joints, around doors and windows, chimneys and ventilation systems (Alfano et al., 2012). Thermal imaging cameras are also effective on their own to identify missing insulation in ceilings, walls and floors as well as other heat losses and gains.

3.1.4 Operational house monitoring

During the house operation stage, the evaluation of house performance is usually done through meters, sensors and a data logger or a programmable logic controller (PLC). The data logger or PLC gather and store the data, which can then be downloaded manually or transmitted to a cloud for further analysis by specialist software.

The data can be used not only to verify the thermal performance of the building, but also to increase occupant awareness. In-home displays have been increasingly adopted to influence home occupants with the belief that real-time feedback can lead to major resource savings (Ehrhardt-Martinez et al., 2010, Yew et al., 2012). However, these are often short-lived solutions as they stop being effective once the novelty wears off (Hargreaves et al., 2013, van Dam et al., 2010).

3.1.5 Conclusion

Several obstacles prevent high performance buildings from operating optimally including the limitation of design assessment tools, poor construction and occupancy. Tools have been developed to predict, verify and monitor parameters that affect thermal comfort, resource use and home sustainability through the building lifecycle. However, occupant behaviour remains a challenge that needs to be further understood and more effectively addressed.

3.2 Integrating theories of practice and behaviour into home settings through living laboratories

3.2.1 Introduction

Socio-psychology theories have been developed to interpret human behaviour and understand how individuals are influenced by wider society. Methodologies that promote pro-environmental behaviour change are often framed by these theories and focus on modifying individual attitudes, knowledge and values.

Practice theory also originates from social theory, but adopts a different approach to explaining human resource use. Rather than focusing on individuals, practice theory focuses on the practices being carried out, which are directly responsible for the use of resources.

These two schools of thought are rarely combined and research relating to home occupant resource use is usually founded in one of the two schools of thought. Living Laboratories offer a place where both theories can be used in conjunction to enable a deeper understanding of the complexities that affect resource use in the home.

3.2.2 Persuasive interventions

Behaviour change interventions that aim to influence individuals' knowledge and attitudes are mostly based on the theories of planned behaviour, cognitive dissonance, normative conduct and habitual behaviour. The theory of planned behaviour suggests that behaviours are a result of individual attitudes, subjective norms and perceived control (*i.e.* how much individuals believe in their ability to influence the outcomes) (Ajzen, 1991). Cognitive dissonance explores how individuals tend to align their beliefs and their behaviours (Festinger, 1957). When individuals perceive an inconsistency between both, change is likely to occur. Normative conduct posits that individuals are largely influenced by the judgement of wider society and implicit social norms, which can be descriptive (*i.e.* they define what the customary behaviour is in a given situation) or injunctive (*i.e.* they prescribe how one should behave either by approving or disapproving of the behaviour) (Cialdini et al., 1991). Finally, habitual behaviour considers that everyday habits become unconscious when they are repeated frequently (Aarts et al., 1998) and therefore, habits are only revised when prompted or following a change in context (Steg and Vlek, 2009).

Methods to persuade behaviour change are based on the theories above. Common interventions include: the provision of information and feedback to increase awareness; the delivery of social norms to make accepted and unaccepted behaviours explicit; the request for a clear commitment or the highlight of hidden personal values to promote cognitive dissonance;

and the delivery of prompts to break established undesirable habits (Abrahamse et al., 2005, McKenzie-Mohr, 2011).

These interventions have been deployed in previous research through a range of approaches that generally fall into three categories classified here as social, technological and knowledge-based interventions (Table 3.2). The use of in-home displays and websites have become popular for the conveyance of information, feedback, norms, cognitive dissonance and prompts; the reason being that house metering technology has become more accessible and enables real-time and long term feedback that is often not possible through more conventional methods. However, opinions about the effectiveness of feedback displays is divided; some researchers claim that they are effective in the reduction of resource use and identification of faulty equipment (Berry et al., 2017, Stromback et al., 2011), while others have found that they are not effective in the long term as they do not become embedded into user's routines and their use is discontinued after the novelty wears off (Brynjarsdottir et al., 2012, Hargreaves et al., 2013). It is also argued that feedback technologies are developed by researchers and do not necessarily meet user requirements.

Table 3.2. Persuasive behaviour change interventions.

Insights and interventions	Social interventions	Technological interventions	Knowledge-based interventions
Information provision	Audit, coaching	Website	Mass campaign, letters, emails, factsheets
Feedback	-	Website, SMS, in-home display	Bills, letters, emails, direct meter readings
Social norms	Social interaction	In-home displays, website	Letters, marketing campaign
Commitment	Verbal or written	Website, in-home display	-
Value activation	Coaching, audit, peer interaction	-	Survey
Prompts	-	SMS, email, in-home display, website, alarms	Stickers, written reminders

3.2.3 Enabling interventions

Practice theory (Shove et al., 2007, Schatzki, 1996) focuses on the elements that influence the undertaking of everyday practices, which include meaning, skill and technology. This theory is based on the fluidity of people's interests and context over time. As technologies and infrastructure evolve, existing social practices become obsolete and are replaced by new ones (Shove et al., 2015). Practices are also place dependent, being adapted to the configuration of different settings and circumstances. Moreover, some practices are interdependent and interlocked in an established routine (Watson, 2012). For instance, the practice of composting is interlocked with the practice of cooking; in other words, composting cannot exist unless food waste is generated during the activity of cooking.

Practice theorists posit that rather than persuading individuals to change behaviour and realign existing routines, the elements of practice should be targeted. Innovative or improved technologies, however, must be designed to meet occupant needs and avoid potential rebound effects (Sorrell et al., 2009).

Enabling change should be conducted through practice-oriented design, which comprises the following steps: understanding user baseline practices in terms of meaning, skill and technology; challenging the practice *status quo* by identifying innovative alternative solutions together with users; and co-creating solutions with users (Scott et al., 2012).

3.2.4 Living Laboratories

Since practices are place and context specific, their understanding requires the observation of individuals in everyday settings, such as LLs. These are defined as real-life places for the co-creation and testing of innovation together with users, business, academia and government (Burbridge et al., 2017, Dell'Era and Landoni, 2014). Several scales of LL have been found in the literature: urban, dedicated and embedded. Urban LLs consist of large scale precincts (Chen et al., 2016, Makarainen-Suni, 2016), dedicated LLs are places that have been built specifically for the purpose of testing innovation (Baedeker et al., 2014, Elfstrand et al., 2017) and embedded LLs are existing locations, such as homes (Hyysalo and Hakkarainen, 2014, Ståhlbröst, 2012). The homes selected for this research are considered embedded LLs and are a place for insight.

LLs draw on the areas of engineering and smart automation, design and behavioural science and sustainability (Rodgers et al., 2011, Scott et al., 2012, Bettencourt and Kaur, 2011) enabling both social and technical innovation. While the primary objective of LLs is to co-create sustainable innovation with users, the LL process starts with insight research, where researchers observe and gather information about user interaction with technology as well as baseline everyday practices and behaviours (Katzy and Bucker, 2015).

3.2.5 Merging the theories in LLs

Homes are multidimensional environments, where individuals are influenced by their own behaviours, the behaviours of other household members, external factors, technical innovation, the context and the place. While socio-psychology and practice theories are perceived as conflicting approaches, these two schools of thought are seen in this research as addressing different aspects of resource use. Socio-psychology theories address resource use with a top-down approach and practice theory works with users, finding solutions that are bottom-up driven. Top-down approaches are important, although often short-lived as they do not necessarily become engrained in the user's routines. A change in technology through practice-based design, on the other hand, enables more permanent changes by addressing underlying needs.

Behaviour change strategies should adopt a holistic approach and address all the elements that influence the decision-making process in the home. These include the sense of place for an individual or a household, the everyday practice and behaviours of the home occupants and social and technical innovations in the home environment (Figure 3.1).

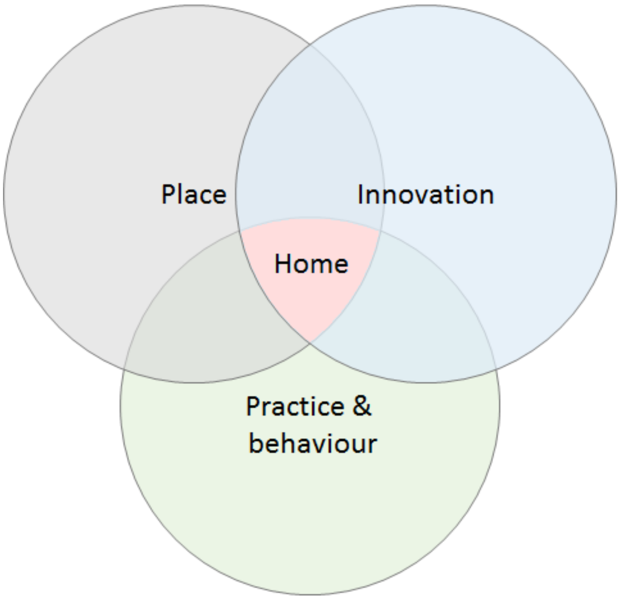

Figure 3.1. The three essential elements to achieve change in the home..

These notions can be tested in embedded LLs, where home occupants can be observed interacting with each other and with existing technology. LLs can help overcome a limitation of many research studies which tend to perceive homes as a single static unit instead of a dynamic multifaceted place

Chapter 4 Results summary

This chapter provides a summary of the results from publications III to VI. The full publications can be found following this exegesis. Section 4.1 considers the results from the LCA as well as impacts of the physical building elements on energy performance (Publication III). Section 4.2 discusses baseline energy use in the ten homes drawing on design and behavioural differences encountered between them (Publication IV). Section 4.3 integrates the results of the behaviour change intervention in terms of practice theory (Publication V). Finally, Section 4.4 posits the home as a system of practice (Publication VI).

4.1 Verification of an emerging LCA design tool through real life performance monitoring

This section aims to answer the following research question:

How do low energy residential houses perform from a carbon emission perspective and what influences the outcomes?

The ten houses from the 10 House Living Lab project were assessed with the eTooLCD software in addition to NatHERS. The assessment outcomes were compared to the first year of house data monitoring and qualitative information from the house audits enabled clarification of the results.

4.1.1 Embodied energy

Embodied energy considers energy use and therefore carbon emissions from material production, transport, construction, maintenance, demolition and disposal. In the ten houses, material production alone generates 41% of the total embodied carbon emissions (Figure 4.1). The building structure is the main contributor to carbon emissions from material production. Therefore, the choice of structural materials and the floor area are influential factors driving overall building embodied emissions.

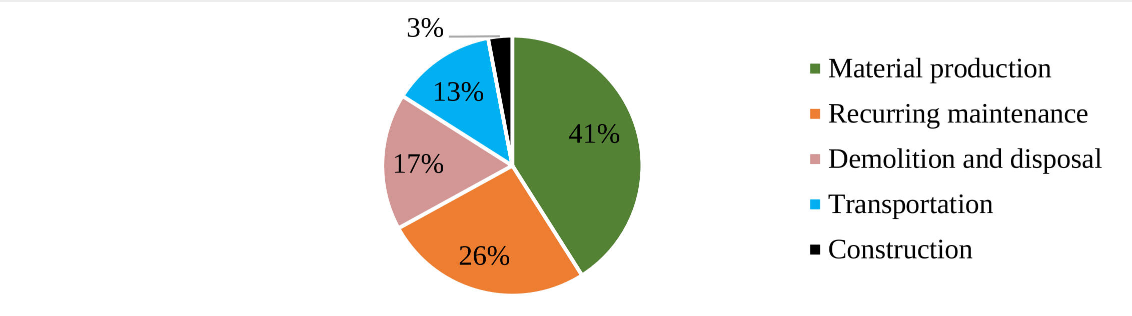

Figure 4.1. Average embodied energy of the 10 houses.

The LCA results revealed that modern houses built in the last 10 years (6-Stars NatHERS and above) have the highest embodied energy per square meter as their structure includes energy intensive materials such as brick, concrete and steel. Older retrofitted houses, on the other hand, have more timber and most of their emissions are related to maintenance rather than material production. Furthermore, newer houses also tend to be larger. The average floor area of houses built before 2006 in this study was 130 m^2, while newer houses averaged 186 m^2, making them even more carbon intensive despite their superior operational energy performance (Figure 4.2).

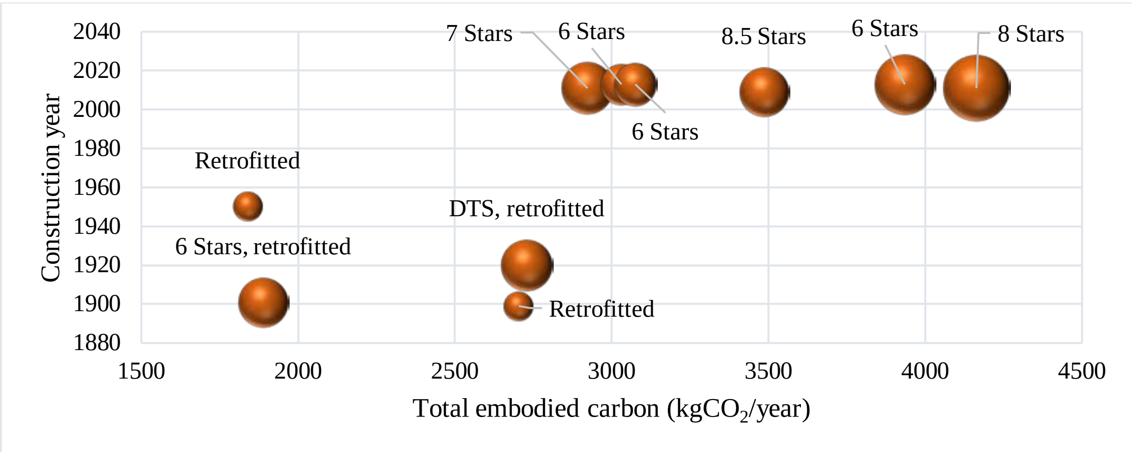

Figure 4.2. Relationship between house construction year and their embodied carbon. The bubble sizes are proportional to the building floor area. Modern houses have a higher embodied carbon due to the energy intensive materials of their structure and large floor plans.

4.1.2 Operational energy

The first year of data monitoring revealed that higher NatHERS star-rated houses tend to use less energy per square meter than lower NatHERS star-rated houses, as expected (Figure 4.3). However, variations of up to 33% were found between the energy use of houses with similar designs, which is in accordance with previous research (Gill et al., 2010).

Figure 4.3. Total energy use per square meter in the ten participant homes in 2015 (adapted from Publication III).

The eToolLCD annual energy use prediction considers elements such as appliances, hot water systems, solar panels and lighting in addition to cooling and heating. Differences between predicted and measured energy use per year varied on average 17%, with discrepancies ranging between 1% and 58%.

PV panels offset on average 51% of the total operational GHG emissions, having reduced operational carbon emissions to 41% of the total building emissions. Consequently, building materials became proportionally the main contributors to GHG emissions in houses. The solar offsets, however, could have been even larger as this research revealed that the PV system in four

of the houses did not operate optimally. Problems included incorrect PV installation, lack of maintenance and unforeseen interruptions to the PV electricity generation, which were not promptly detected by the house occupants.

4.1.3 Operational energy discrepancy causes

The audits detected that most houses possessed one or more sources of heat gain or heat loss, preventing optimal thermal operation. Insulation gaps were common next to ceiling cornices, around downlights and above attic hatch doors. Most houses also had inadequate or no shading devices to protect windows exposed to the summer sun.

Interviews with home occupants also revealed that the assumptions made by house assessment software, which are based on typical appliance use and average occupancy, do not necessarily reflect everyday practice. Unexpected practices and behaviours significantly impacted on house performance and should be considered for further research.

4.1.4 Conclusions

While current policies target the reduction of operational residential GHG emissions through improved design, this research shows that embodied energy should be part of the scope. Construction practices, maintenance and house monitoring should also be addressed. Moreover, occupant behaviour and everyday practices need to be better understood to enable the attainment of optimal home performance.

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

This section responds to the following research question:

How do design and occupant behaviour affect energy use in the home?

The results from the first year of data monitoring and the answers from the initial semi-structured interviews were combined to answer this question. The analysis of the results started with a discussion of design components affecting energy use. The scope of the analysis was then narrowed down to individual behaviours in each home.

4.2.1 Thermal performance

The thermal comfort range in Fremantle is defined as temperatures between 20 and 25^{o}C, which is the assumption used by the NatHERS modelling software (DEE, 2012). The analysis of the internal temperature distribution in the ten houses over one year revealed that most of them are thermally uncomfortable for around 50% of the time. However, the internal house temperature does not necessarily relate to energy use. For instance, some of the houses with the widest range of internal temperatures are also some of the lowest annual energy consumers. Conversely, houses with relatively stable temperatures throughout the year are high energy users. Although design influences house performance (Publication III), other factors cause the difference between thermal performance and energy use in the house.

4.2.2 The influence of technology

The annual energy profile of each of the ten houses was analysed and grouped into three distinct profiles based on their use of cooling and heating through the year (Table 4.1).

Table 4.1. Home typology according to their use of cooling and heating.

Typology	Description
I	Homes that possess and use cooling and heating technologies to maintain house comfort through the year
II	Homes that possess or use only mechanical heating, having only one energy peak through the year
III	Homes that do not possess or choose to limit the use of mechanical cooling and heating systems

Typology I, which consists of houses that have high energy use in winter and summer, was the most common profile found in this research, with five houses fitting this description (one retrofitted house, three 6-Star houses and one 7-Star house). These houses do not have the same rating, building design or annual temperature distribution; but they share common cooling and heating technologies and their occupants have similar seasonal behaviours and practices, making them high energy users per square meter. Typology II were average annual energy users and typology III were frugal energy users.

4.2.3 Variations in household practices

The coldest and warmest days of the year were chosen to exemplify differences in everyday cooling and heating practices between the homes. These specific days were selected rather than seasonal averages due to the mild Fremantle climate, which does not necessarily require the use of the cooling and heating systems on a daily basis.

Despite all occupants experiencing uncomfortable temperatures in the early mornings and evenings of the coldest day of the year, distinct practices were observed in the homes that use mechanical heating systems. Some households used the heater twice, before and after work; others used the heater only in the morning or evening; and occupants who were at home during the day used the heater throughout the day (Table 4.2). The temperature of the living room while the heater was on also varied considerably between the houses, showing a variation in practice and possibly in the perception of comfort (Table 4.2).

Table 4.2. Living room temperature during the use of the heater and AC in the coldest and hottest days of the year.

Home	Internal temperature when the heater in on (°C)	Heater on	Internal temperature when the AC in on (°C)	AC on
1	20.8	Morning, afternoon, evening	-	N/A
2	19.1	Morning, afternoon, evening	26.1	Morning, afternoon
3	18.9	Morning, evening	25.1	Morning, afternoon
4	16.9	Evening	-	N/A
5	20.7	Afternoon	-	N/A
6	20	Morning, evening	24.9	Evening
7	20.3	Morning, evening	25.7	Afternoon

Practices relating to the use of the AC in summer also varied across the homes possessing mechanical cooling systems (Table 4.2). The latter was used throughout the warmest times of the day, intermittently in the late afternoon and evening or not at all. Summer cooling practices also revealed that the house occupants do not take full advantage of the Fremantle sea breezes to cool the house naturally in the evenings, turning on the AC even after the external temperature became lower than the internal temperature.

These differences in the cooling and heating practices between homes were mostly related to different occupant lifestyles and household configuration.

4.2.4 The influence of behaviour

Differences in practice can be observed not only between homes, due to variations in lifestyle and routines, but also within, or intra-home. Three types of intra-home behaviours resulting in different home practices were revealed in this research.

The first type consists of households that comprise individuals with distinct behaviours; that is, divergent attitudes, values, knowledge, views of social norms and perceived control. This results in inconsistent practices. For instance, in one of the homes, the heater was used daily during the month of July 2015; but the time it was used and duration of its use was irregular. While one individual tried to reduce electricity bills by minimizing the use of the heater, the other occupants were mostly driven by comfort, using the heater for extended periods at a time.

The second type of intra-home behaviour consists of households that comprise individuals with different behaviours but only one prevailing practice. For instance, one of the homes used the heater most evenings during the month of July 2015, having it on regularly between 17:00 and 23:00 irrespective of the internal temperature. This practice could be indicative of a habitual behaviour and/or rebound effects, since the occupants of this house did not fully understand the operation of the PV panels.

Finally, the third type of intra-home behaviour consists of houses where occupants share the same views, attitudes and knowledge. These homes have similar heating practices. For instance, one of the homes used the heater sporadically and consciously during daylight hours to make the most of the PV electricity generation. Moreover, they prioritised wearing warm clothes before using mechanical heating for warmth. The operation of the heater in this home was consciously driven by the house technologies and by the feeling and perception of feeling cold.

These examples do not encompass all possibilities of intra-home behaviours and practices, but they help to explain home dynamics. The heating practice in the homes exemplified above were driven by different factors, such as comfort, habits or by the conscious feeling of cold. Behaviours, awareness or motivation to save energy may impact on people's priorities and their practice. For instance, some may choose to put on warm clothes as a first option, while others switch the heater on instead. This is in accordance with previous research which has shown that the same meaning can be achieved through different practices (Renström and Rahe, 2013). Conversely, practices can also be carried out with different objectives (Shove, 2004, Shove, 2003, Gram-Hanssen, 2010).

4.2.5 Conclusions

For the most part energy use inside houses was found to be correlated to design, family structure, house occupancy, lifestyles and specific appliances. These aspects appear to drive general annual trends and represent the main differences between distinct homes. However, practices also vary between and within homes, in part, due to divergences in attitudes, awareness, knowledge, motivations and perceptions. Moreover, the reasons for using cooling or heating vary between occupants of the same home and are related not only to the feeling of cold or warmth, but also to habits and comfort.

The presence of renewable energy and efficient appliances also affects the decision-making process, acting as an enabler or being the possible cause of rebound effects. All these factors have an impact on the frequency, intensity and timing of cooling and heating practices in the home and need to be further investigated.

Given the complexity of household practices and behaviours, influencing and changing them is challenging and requires a further understanding of the HSOP.

4.3 Influencing energy and water use within a home system of practice

This section responds to the following research question:

How do practices impact resource use in the home and how can they be altered?

The answer to this question was provided from the analysis of the effects of the behaviour change program in the 10 homes. Overall changes to resource use as well as changes to specific practices and to the building system were investigated through the combination of statistics and qualitative methods. Practice theory and the concept of SOP were used to frame the results.

4.3.1 Overall change in resource use

The evaluation of resource change between the two years, before and after the persuasive behaviour change program, was not straightforward as the weather conditions were significantly different, affecting the results. Statistical methods were therefore employed to separate the interference of the weather from the influence of the intervention.

The statistical analysis revealed that five of the eight homes (two of the initial ten homes were excluded from the analysis for the reasons mentioned in Section 2.5.2) achieved savings in energy or water (Table 4.2). However, only one of them made significant improvements in both categories. Two of the homes increased their electricity use in 2016 and one of the homes did not make any significant changes (Table 4.3). Water savings were achieved more frequently than energy savings; possibly due to their higher visibility (Burgess and Nye, 2008).

Table 4.3. Gas, grid electricity and water use variation between 2015 and 2016. The arrows show whether there the resource use increased (↗), decreased (↘) or remained constant (-) between the two years.

Resource	**Home**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Grid electricity	-	-	↘	-	-	↗	-	↗
Gas	↗	N/A	↘	-	-	-	↘	-
Water	↘	↘	↘	↘	-	-	-	-

4.3.2 Changes in everyday practice

Significant energy and water use practices (*i.e.* personal showering, garden irrigation, cooling, heating and pool cleaning with the use of a pump) were analysed with a mixed methods approach. Other practices were discussed based on occupant personal accounts.

Personal showering

Statistical analysis revealed that only half the homes changed their personal showering practice by reducing the length of showers; 59 seconds on average. Showering lengths in 2016 ranged between 5 and 8.8 minutes. The shorter shower, however, is still higher than the 4 minute shower length recommended by the local water authority.

Technologies and the implicit know-how associated with personal showering are relatively constant over time; meaning being the most influential element. Personal showering can have several meanings such as getting ready for the day ahead, cleanliness, relaxation and warmth (Shove, 2004, Shove, 2003, Scott et al., 2012), which impact the practice of personal showering by making it longer (*e.g.* for the purpose of reflection or warming) or shorter (*e.g.* for the purpose of freshening or waking up). These results revealed that changing meaning is challenging and can only generate limited or insignificant savings.

Garden irrigation

Water used for the practice of garden hand watering was reduced in two of the three homes that irrigate their garden manually with a hose. Both homes modified elements related to the practice technology, which are relatively variable over time. One of the homes added mulch to the plants, reducing evaporation rates, while the other reduced watering frequency once the plants became established.

Automated irrigation practices also changed considerably between the two studied years. Most home occupants corrected their watering days and times in 2016 according to local mandatory requirements. Moreover, the volume of water used per irrigation session was frequently readjusted throughout the year. The reasons for changing the reticulation settings were related to modifications to the technology elements of practice, such as establishing new plants and installing new irrigation systems. Moreover, some participants also gained skills following the water audit and reduced unnecessary irrigation.

Cooling and heating

Four homes made changes to their heating and cooling practices in 2016. These consisted mostly of the reduction of the thermostat setting on the heating system (*i.e.* change in technology); although a change in skill also occurred, when one of the homes started taking advantage of the PV panels for cooling in summer.

Pool cleaning

The only home that has a swimming pool uses a pump that is turned on automatically twice daily, in the morning and in the afternoon for the practice of cleaning. In 2016, the pump functioning time was altered to make better use of the PV system. It was delayed in the morning and advanced in the afternoon, decreasing the use of grid electricity on average by 300Wh per day.

Reported changes in practice

Other changes in practice included the automation of the dishwasher to function during daylight hours and the automation of standby power, switching appliances on and off automatically according to the household daily routines.

4.3.3 Changes to the building system

Participants also made physical alterations to the building envelope following the audits. These included: the addition of insulation in the ceiling to close the gaps detected by the thermal imaging camera (Publication III); the installation of removable shading devices to protect exposed windows; the installation of a flow restrictor on all internal taps; the installation of a roof vent; the replacement of lightbulbs; the installation of a second rainwater tank; and the installation of a timer on the solar hot water system to make its use more efficient.

Figure 4.4 summarises the changes made by participants during the second year as a result of the behaviour change program. These have been classified in terms of the three elements of practice; alterations in technology being the most popular change amongst households.

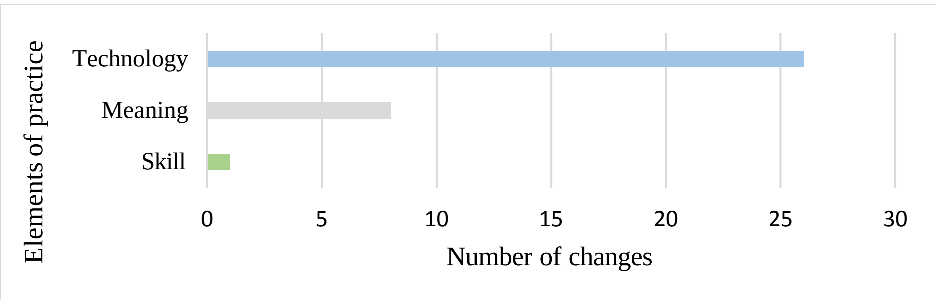

Figure 4.4. Changes made to the HSOP according to elements of practice.

4.3.4 Participant insight

Changing recurrent practices, routines and habits was perceived by participants as inconvenient and having a negative impact on comfort and lifestyle. Changing technologies, on the other hand, were perceived as easy one-off solutions which did not require constant effort. Participants acted on changes that were cheap, easily achievable and had immediate effects.

Not all homes consciously acted towards reducing their resource use in the second year; however, they reported having thought about it more frequently as energy and water use became more tangible through the audits and monthly reports.

The on-line feedback system, however, was not a popular tool. While the information displayed on the website was perceived to be interesting, it was seldom accessed. Only one home reported to have used it regularly by making it part of their Monday morning routine. Others favoured the monthly reports, which were received by email and were therefore part of the daily practice of checking emails.

4.3.5 Conclusions

Seventy four percent of the changes made in the second year were modifications in the technology element of practice (Figure 4.3), either in the building system or in the form of automation. Meanings and skills, on the other hand, are more challenging to change as they impact directly on needs and perceptions of comfort. The changes that affected the meaning element of the practice (*e.g.* personal showers) had minimal impact.

Practices meet needs and are an integral part of user's routines. Automation can enable this change to happen by allowing the alignment of practices with the house technology (*e.g.* PV panels) and occur independently of home occupants, consequently reducing perceived hassle.

Current persuasive behaviour change solutions do not consider the home system as a whole and do not take user needs and interlocked practices into account. These need further understanding for the design of enabling systems.

4.4 The home as a system of practice and its implications for energy and water metabolism

This section responds to the following research question:

Is there a home system of practice and if so, can it be influenced to enable the reduction of resource consumption?

The answer to this question was divided into three parts. Firstly, the practices of personal showering, irrigation and thermal conditioning were investigated in isolation; that is, the elements (*i.e.* meaning, skill and technology) affecting these practices were analysed. Secondly, emphasis was placed on how these practices interact with the rest of the system and how they fit into established everyday routines. Finally, a consideration was made of how practices can be influenced to enable lasting change in the home was considered. Results were based on merging quantitative and qualitative data.

4.4.1 Everyday practice

Personal showering and garden hand watering

Histograms representing the distribution of personal shower length as well as volume of water used for garden hand watering were plotted for eight homes. Then, frequency curves were fitted to the histograms and their properties used to describe the practices.

The results revealed that both practices followed lognormal distribution curves (Figure 4.5). This means that the practices are executed the same way on every occasion. In the case of personal showers, the right skewness of the curve suggests that personal showers do not or cannot become significantly shorter than they currently are. Since the practice of personal showering is mainly driven by meaning (Publication V), the shape of the curve also represents variations in meaning. The lower the standard deviation (σ) of the frequency curve, the higher the degree of habituality associated with the practice. Interviews revealed that curves with a high σ are related to individuals whose shower practices are less habitual; for instance, their practice meaning can alter between freshening up (resulting in a short shower) and relaxation (resulting in a longer shower). Results also indicated that early morning showers are usually shorter than later showers possibly as they hold different meanings; for instance, getting ready for work versus relaxation at the end of a busy day.

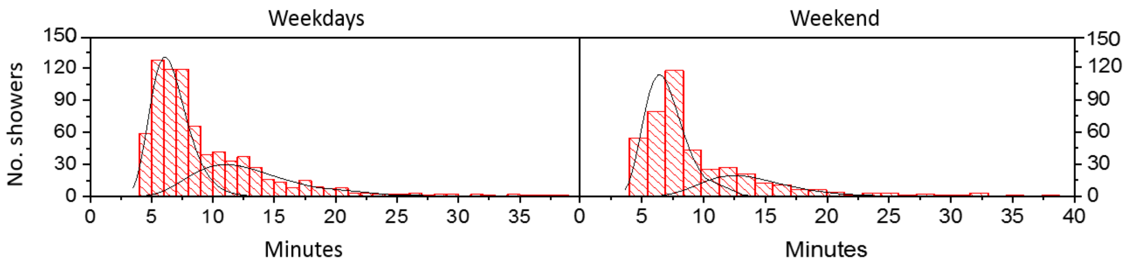

Figure 4.5. Example of lognormal shower length distributions for weekdays and the weekend. The multimodal histograms represent the showering practice of different occupants (adapted from Publication VI).

The similarity in shower length found between weekdays and weekends points to the assumption that a personal shower routine of a regular length of time is followed each day to achieve a specific meaning. Accordingly, significantly shorter showers are unlikely to occur unless the skill or technology elements of the practice are modified. Moreover, practices with a high degree of habituality may be even more challenging to affect.

The practice of hand watering, unlike showering, is influenced by meaning but also technology and skills as these are more flexible (Publication V). Nonetheless, the right skewness of the curve indicates that the practice is still carried out in a habitual manner to achieve a specific purpose.

Heating

As seen in section 4.2 (Publication IV), the practice of heating can also be carried out for different purposes, including warmth, comfort or as a habit. The use of the heater is not necessarily related to the internal house temperature, but to individual needs and daily routines.

4.4.2 The HSOP

Histograms depicting the distribution of shower and hand watering times follow Gaussian curves, which means that the practices occur at a similar time, each day, according to the home routine. Distribution curves with a high σ depict higher variations in showering time, which is a consequence of flexible schedules and routines. Conversely, low σ represent a more interlocked routine constrained by other scheduled daily activities. The σ of morning shower times, for instance, tend to be smaller than the σ of evening or afternoon shower times. Similarly, showering times were statistically significantly different during weekdays and weekends. Weekend showers occur later than weekday showers and their distribution curves have a much wider σ (Figure 4.6). Some homes also have multimodal showering time distributions on the weekends, revealing that no specific routine is followed. This shows that routines and practices can be realigned when there is a change in context.

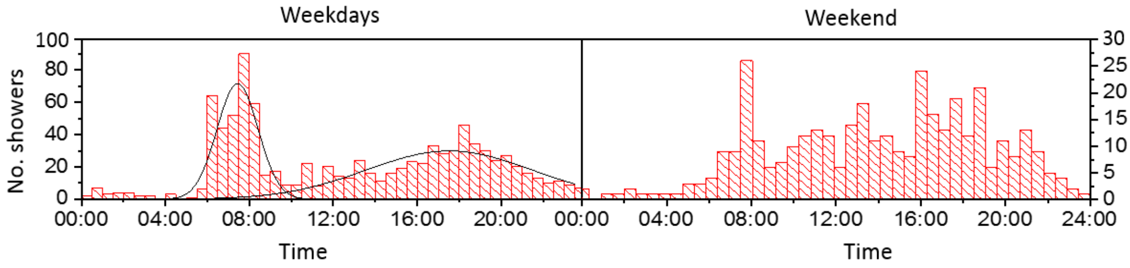

Figure 4.6. Example of distribution of shower times for weekdays and weekend in the same home. Weekday showers are more defined than weekend showers, which in this case, are multimodal (adapted from Publication VI).

Practices are defined by meaning, skills and technology, but they are also part of the HSOP. The time when practices occur is dependent on, or interlocked to, other practices in a daily routine. For instance, the practices of personal showering, irrigation or thermal conditioning are constrained by the practices of eating breakfast, going to work and cooking. When a new practice is introduced or modified, interlocked practices in the system need to be adjusted. For instance, when an individual decides to start cultivating a vegetable garden, the practice of irrigation needs to be reviewed. Moreover, individual practices also interact with the practices and routines of other home occupants (interlocked routines) (Figure 4.7). For instance, one of the participants revealed the need to water the lawn on a daily basis to clean dog waste. This means that the dog practice needs to be addressed before the watering practice can be affected. In other words, persuading the home occupant to change may not work unless the whole HSOP in understood and accounted for.

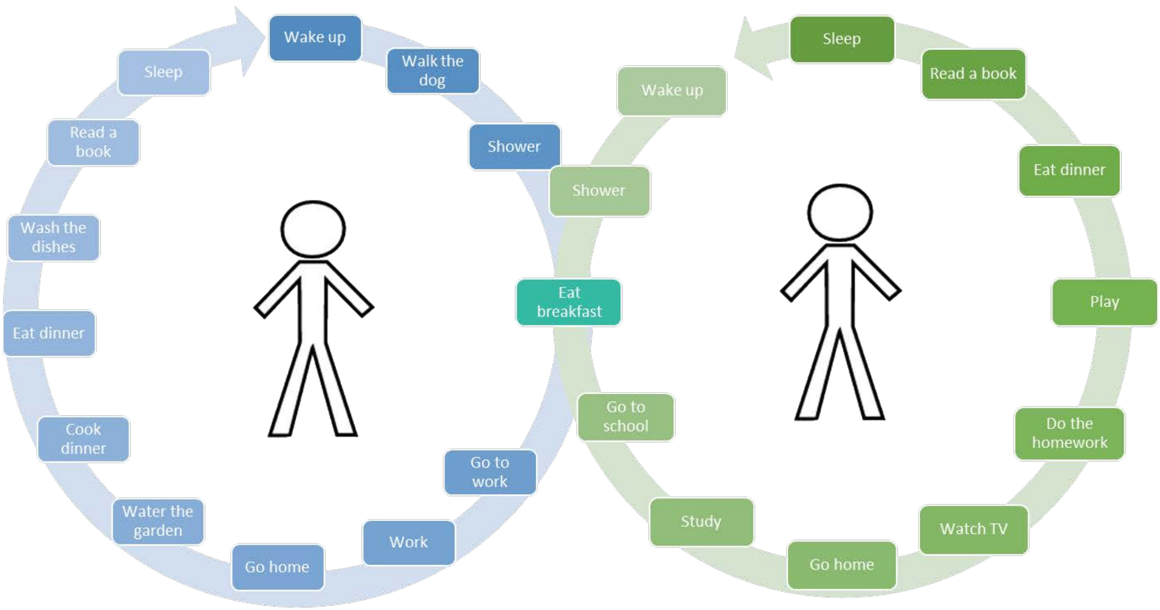

Figure 4.7. Interlocked practices and routines in a HSOP.

4.4.3 Enabling change in the HSOP

Changing everyday practices is challenging as they are part of an established routine which interact with other occupant routines as well as house technologies, meaning and skills. This research has shown, however, that when used correctly, automated systems (*e.g.* irrigation, pool cleaning and dishwashing) can operate independently of the user, minimizing hassle while enabling change (Publication V). For instance, PV electricity generation can be better utilized during the day even though the occupants might not be at home. Automation therefore enables dis-interlocking (*i.e.* disconnecting or isolating) practices from the HSOP without the need to affect individual behaviours and routines.

4.4.4 Conclusions

The concepts discussed in this section might seem intuitive as we all experience the SOP in our daily lives; however, the mixed methods approach applied to analyse the results described how multifaceted the HSOP is and reveals approaches to affecting resource use in the home. Informative persuasive approaches often fail as they do not consider the home system as a whole. Approaches need to address interlocked practices and interlocked routines as well as the three practice elements. Dis-interlocking practices from an established routine through automation may be more efficient to enable lasting reductions in energy, water and resource use in the home while ensuring that occupant needs are met.

Chapter 5 Discussion

This chapter brings the results of all publications together to answer the overarching research question:

Can we explain the behaviour, practices and routines of home occupants in terms of practice theory, and if so, can this be defined as a system of practice?

The chapter starts with a discussion of the home system and progresses to explain, based on the research results, how the physical and social systems function and integrate in the home, affecting GHG emissions and resource use. This discussion is then followed by the development of hypotheses and conceptual ideas to be further developed and tested.

5.1 The home system

The home can be conceptualised as three layers; the physical, the metabolic and the social systems (Figure 5.1). The physical layer includes the structural components and technologies of the building, such as walls, roofs, taps, appliances, water pipes and electrical cables. The metabolic system consists of the energy, water and material flows through the physical system (Rodgers, 1997, Girardet, 2010). These enter and leave the house through pipes and cables, being internally processed and transformed through the operation of appliances. The social system includes the house occupants who are responsible for the decision-making and operation of the building technologies through their everyday practices (Publication II). Occupant practice in turn is influenced by wider society as well as their own behaviours and the behaviours and practices of other home occupants (Publication II). The physical and the social systems interact to affect the house metabolic flows (Publication VI). Optimal house performance from an energy and water efficiency perspective depends therefore not only on the efficiency of the building structure and individual technologies, but also on how they are operated on a day-to-day basis.

A holistic understanding of the home system is essential for the development of solutions that enable resource savings leading to a reduction of residential carbon emissions. However, the social system is not yet fully understood. This research adopted a holistic approach to the home by analysing both the physical and social systems, with an emphasis on the latter to unveil and describe some of its complexities through a combination of socio-psychology and practice theories (Publications IV, V and VI).

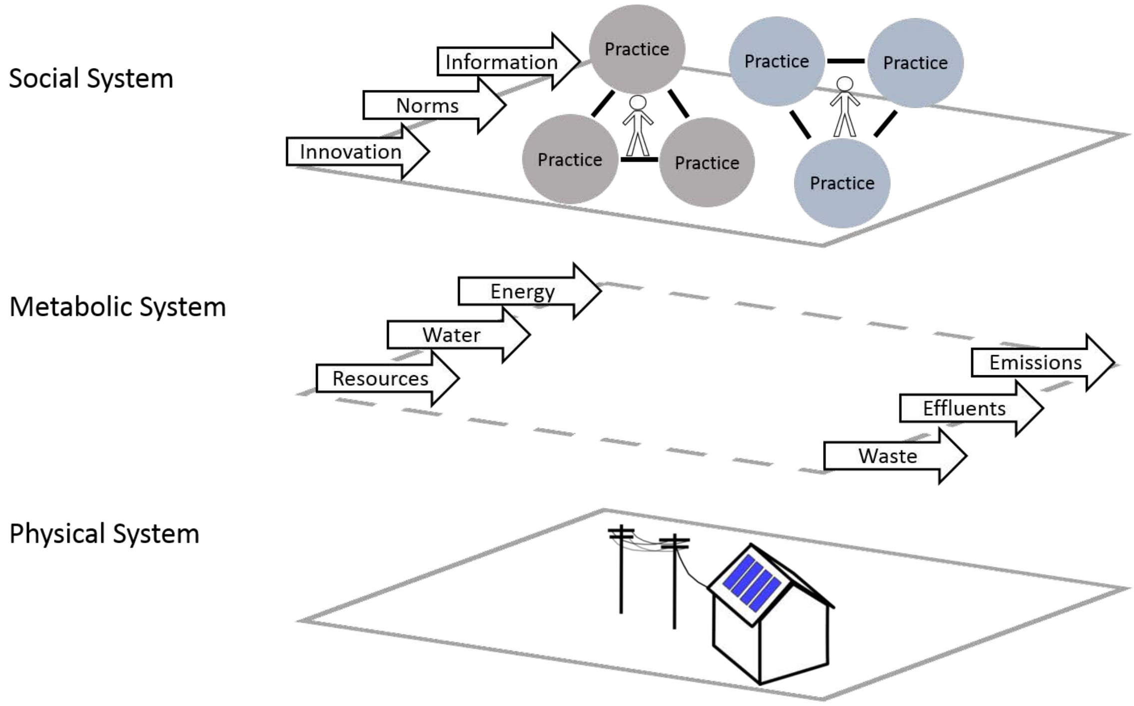

Figure 5.1. The physical, metabolic and social layers making up the home (Publication VI).

5.2 The home social system

5.2.1 The multiple facets of the social system

The building envelope and the presence of specific appliances and technologies can significantly impact on residential carbon emissions and resource use. For instance, the 10 house Living Lab demonstrated that the houses, which were designed with energy efficient characteristics, perform operationally better than the average WA dwelling; with the highest energy user in this research consuming 1,896 kWh (electricity and gas) per year less than the average home (Publication IV). The Fremantle homes also followed similar seasonal energy use patterns according to the ownership of cooling and heating devices (Publication IV).

Despite the annual and seasonal similarities between the homes, the daily use of thermal conditioning technologies was aligned with specific household routines, lifestyles and family structure; and did not necessarily relate to the house temperature or thermal comfort (Publication IV). For instance, individuals who are at home during the day tend to make use of the heater and/or AC during the day and may align its use with electricity generation from the PV system; while occupants who are economically active use cooling and heating only outside business hours.

Further inter and intra-home differences in practice emerged. Some occupants keep the heater on for continuous periods of time, while others turn it on and off regularly and others operate it only occasionally, reserving its use for extreme weather conditions (Publication IV). These variations in practice reflected conflicting attitudes toward energy savings, divergent perceptions about contribution to overall GHG emissions, differing opinions of social norms, differing perceptions of comfort and different levels of awareness about the building technology (Publication IV). The daily intra-home patterns of cooling and heating also revealed different meanings for the use of thermal conditioning, which supports findings from previous research (Shove, 2003, Gram-Hanssen, 2010). The implication of these intra-home behaviours and practices is that one individual may negate the efforts of another individual, resulting in a reduction in overall house performance.

Homes are often considered as a single unit when in fact they comprise several individuals who have different attitudes, lifestyles, routines, perspectives and practices, which in turn are influenced by meaning, skill and technology. Moreover, these individuals interact and influence one another, adding a supplementary layer of complexity to the social system of the home. It follows that in order to promote domestic resource reduction, all these variables need to be fully understood and adequately addressed.

5.2.2 Affecting behaviours and practices in the home

The persuasive behaviour change program carried out in this research (Publication V) applied best practice socio-psychology based methods to promote energy and water reduction in the participant homes. The effects of the intervention were analysed to provide insight into the home system, including challenges and opportunities for change. The provision of feedback through an online platform had the objective not only to increase awareness and inform individuals of their daily resource use, but also to assist in the identification of defective house equipment and appliances.

The results indicated, however, that individual behaviours were mostly unaffected and the use of the feedback system did not become a regular practice and did not prevent equipment failure from occurring. Attitudes, values and perceptions remained unaltered despite an increase in general awareness. The alteration of practices, on the other hand, was more easily achieved. Nonetheless, not all practice elements were equally affected and the majority of changes consisted of the modification of technology (Publication V). Modification of the practice skill also occurred but this was rarer and changes affecting meaning generated insignificant savings.

Changes in meaning could be harder to achieve as meaning is the reason behind the execution of a practice (Shove et al., 2012); that is, meaning relates to a need that an individual wants to fulfil. The participants in this research value comfort above economic or environmental benefits. Consequently, the modification of practices impacting on meanings relating to the notions of comfort or relaxation were not carried out. In fact, most participants rejected the suggestion of having shorter showers or reducing the use of the cooling or heating devices with the concern that these would negatively impact on their lifestyle. In contrast, small adjustments to the technology elements of the practice were welcomed as these usually consisted of simple one-off changes that did not largely impact on established comfort or habits (Publication V). These conclusions are supported by other research which suggest that consumers are favourable to efficient technologies but perceive convenience, practicality and cost as barriers to action (Dolnicar and Hurlimann, 2010).

Changes to the physical building system were also popular, especially ones having an immediate and noticeable positive effect on thermal comfort, such as the installation of shading devices to prevent the house from overheating in summer. Similar to the changes made to the technology element of the practice, these were relatively easy to achieve and did not require repetitive effort or changes to intrinsic needs (Publication V).

Whilst changing individual behaviours and perceptions is essential for holistic home sustainability, it is posited that they cannot be significantly affected in the long term by a short term intervention (Publication II). Previous research has shown that behaviours end up reverting to what they originally were after the behaviour change intervention is interrupted (Brynjarsdottir et al., 2012). Behaviours are influenced by close relationships as well as wider society and culture (Stephenson et al., 2010, Shove et al., 2015). Changing behaviours would therefore also entail a societal transition. Likewise, the skill of a practice is learned through the observation of other practitioners over the years, being society and culture dependent (Gram-Hanssen, 2010, Scott et al., 2012). For instance, the practice of washing dishes can vary significantly between regions and countries even when technologies are similar. In some cases, dishes are washed in a full sink, while in others, running water is used instead and the notion of submerging dishes in greasy water is culturally inconceivable. Meanings may be even harder to affect as previously discussed, as they consist of genuine human needs.

Figure 5.2 schematically illustrates the notions discussed above. The outer layers represent elements of practice or behaviours that are more easily affected and the inner layers represent elements that are unlikely to be changed. Technology, belonging to the physical system of the home, is more transient and flexible. Skills and norms are society and culture dependent and may transition with time although not in the short term. Meaning, values, attitudes and perceptions, on the other hand, are part of individual identity and although they may be influenced, they are unlikely to be entirely modified.

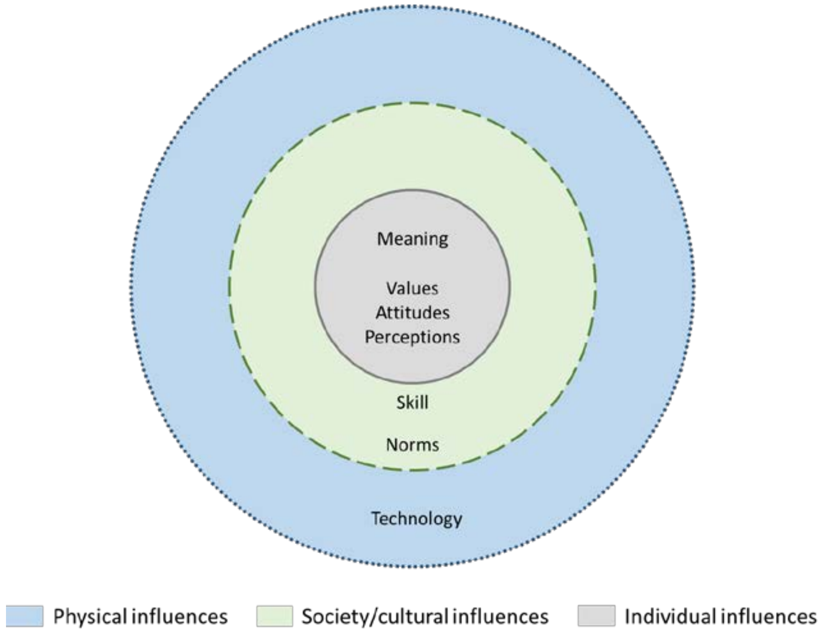

Figure 5.2. The elements influencing the social system of the home.

Scott et al. (2012) proposes that the first step in promoting change in practice consists of understanding practice meaning and challenging the *status quo* in a co-creation process with the users. Rather than affecting the meaning itself, the process would encourage the development of alternative technologies capable of meeting the same need through a more efficient use of resources. Publication V supports the view that long term change can be more easily achieved through modifying the technology element of practices; however, these require a broad understanding of occupant needs as well as the HSOP for them to become embedded in occupant routines.

5.2.3 The home system of practice

The HSOP is a network of the practices (defined by meaning, skill and technology) conducted by home occupants on a daily basis as part of a routine (Publication VI). These routines, composed of practices which are reproduced in a sequential manner, overlap and interlock with one another (Publication VI), creating a home equilibrium (Kashima Y., 2017, pers. comm., 19 Sept) (Figure 5.3 a). The introduction of new practices (*e.g.* checking a feedback website) or a change in context require established routines to become destabilised (Figure 5.3 b) and find a new equilibrium (Figure 5.3 c). Unless a realignment of everyday practices occur, new practices cannot become embedded in the HSOP and fulfil a specific role. Consequently, they might not be adopted by the home occupant.

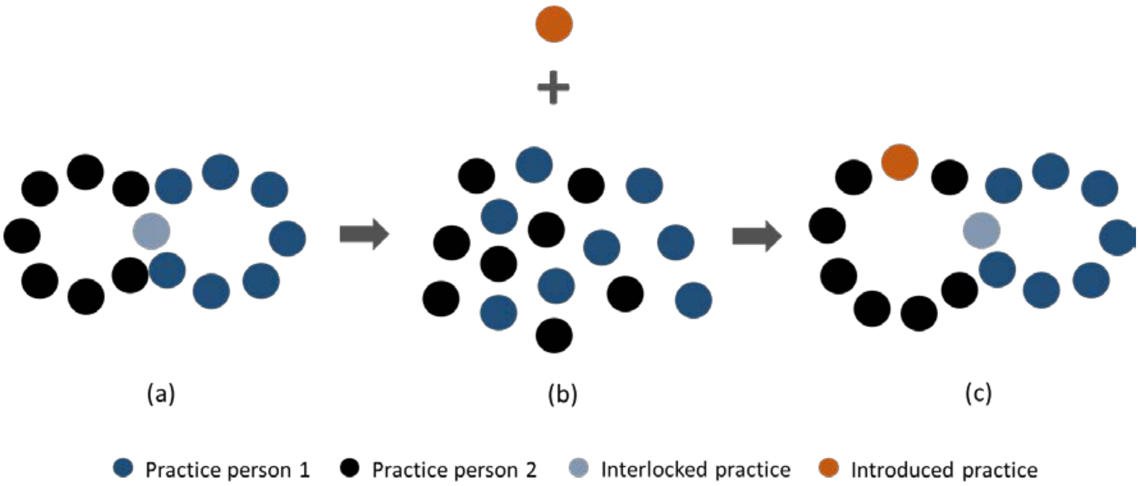

Figure 5.3. Equilibrium of practices in the home. (a) Original home equilibrium; (b) Destabilisation of the home equilibrium through the introduction of a new practice; (c) Realignment of practices and establishment of a new home equilibrium.

It is posited that practices that have a high degree of interlocking (*i.e.* their frequency curves have small standard deviations) are also more strongly bound in the home equilibrium and harder to change (Publication VI). For instance, the time of morning personal showers is highly interlocked with the practice of work, which means that a modification of the timing of morning personal showers may not be feasible without a modification of the timing of the work practice. The same applies for the interlocked practices of two different home occupants. In this research, the dog practice of relieving itself on the lawn is interlocked with the daily practice of the home owner watering the lawn; and the watering practice cannot be modified without a change in the dog practice (Publication VI). Conversely, flexible practices with lower degrees of interlocking (*e.g.* evening personal showers) may realign more easily.

A practice realignment, however, does not necessarily mean that the practice itself is affected. While the timing of practices may realign and reach a new equilibrium in the home system, the meanings, skills and technologies of the practices may remain the same; that is, the manner in which occupants perform specific practices follows a common pattern according to the meanings of the practices (unless other elements of the practice are also affected) (Publication VI). For instance, showers that are taken with a specific purpose have similar lengths every time, which indicates that a specific habitual washing routine is carried out.

Practices that have more than one meaning (*e.g.* personal showering for relaxation, cleanliness or social expectation) and therefore a lower degree of habituality may be more flexible and easier to affect than practices that are conducted with the same purpose at each instance (Publication VI). Individuals who have personal showers with one sole meaning may not be willing or may not have the skills to reduce the length. In contrast, individuals who attribute multiple meanings to one practice may be able to make a conscious decision to only adopt one of its meanings and associated practice habits.

It is posited that practitioners that perform habitual and highly interlocked practices are unlikely to change them unless there is a major modification in context (*e.g.* a change in lifestyle, family structure or to the technology element of the practice) causing practices to realign (Publication VI). A significant change in context is likely to drive a conscious decision-making process that is driven by individual values and attitudes (Kashima Y., 2017, pers. comm., 19 Sept). Once a new home equilibrium is established, however, everyday practices and interlocking routines realign to drive the operation of the HSOP.

5.2.4 Emerging hypothesis

If practices are bound in time, being reproduced sequentially as part of an established daily routine (Publication VI) then it is probable that practices are also bound in space given that they are dependent on the local context, the technologies present in a certain location (Shove et al., 2015) and other people's practices and routines (Publication IV).

The reproduction of practices in space was not explored in this research; however, it is posited that the interlocking and bundling of practices and routines in the HSOP is dependent on both space and time. Moreover, the proximity of practices in space and/or time would determine their degree of interlocking. Consecutive practices that are part of a daily sequential personal routine are highly interlocked. For instance, morning weekday personal showers are highly interlocked with the practice of breakfast, which is in turn highly interlocked with the practice of transport to work.

This logic is likely to also be applicable to practices performed by two or more different individuals and the interlocking degree would depend on whether the practices are performed in the same or a different place and at the same time or at different times (Figure 5.4). It is posited that practices are highly interlocked when they occur at a similar time and at the same place. For instance, person 1 (P1) having a personal shower in bathroom 1 will influence person 2 (P2)'s shower in bathroom 1 if it is carried out at a similar time because P1 and P2's showers are limited by P1 and P2's own interlocked routines. Practices that occur at different times and in different places may not show the same degree of interlocking. Practices may be lightly or indirectly interlocked if they occur at the same time but in different places. For instance, the water heating technology may not work if P1 and P2 have personal showers at the same time but in two separate bathrooms, indirectly interlocking the two showering practices. Conversely, practices that occur at the same place but at different times may also indirectly affect each other.

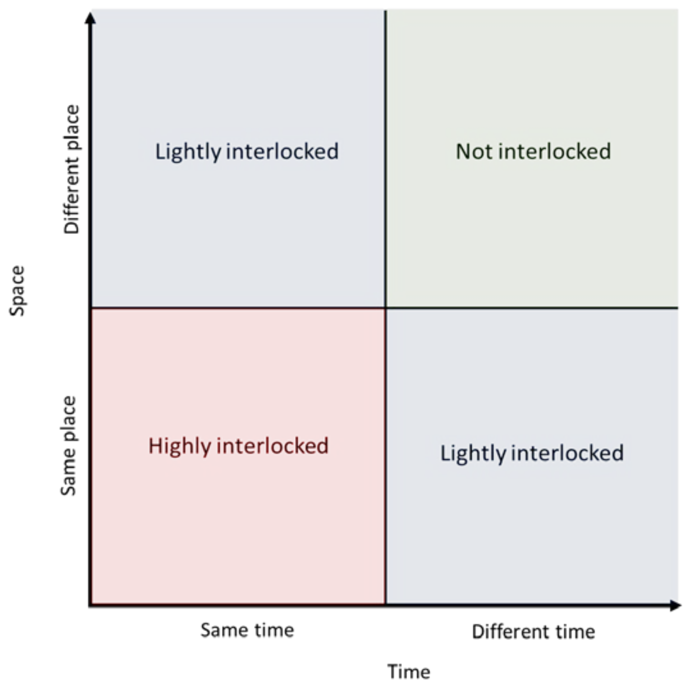

Figure 5.4. Interlocking degree of practices according to their reproduction in time and space.

Figure 5.5 represents the conceptualisation of the reproduction of practices in space and time as part of individual routines in the home system. Individual practices are interlocked within a daily sequential routine (Publication VI), while the practice of different occupants (P1 and P2) highly interlock when they are reproduced closely in space and time.

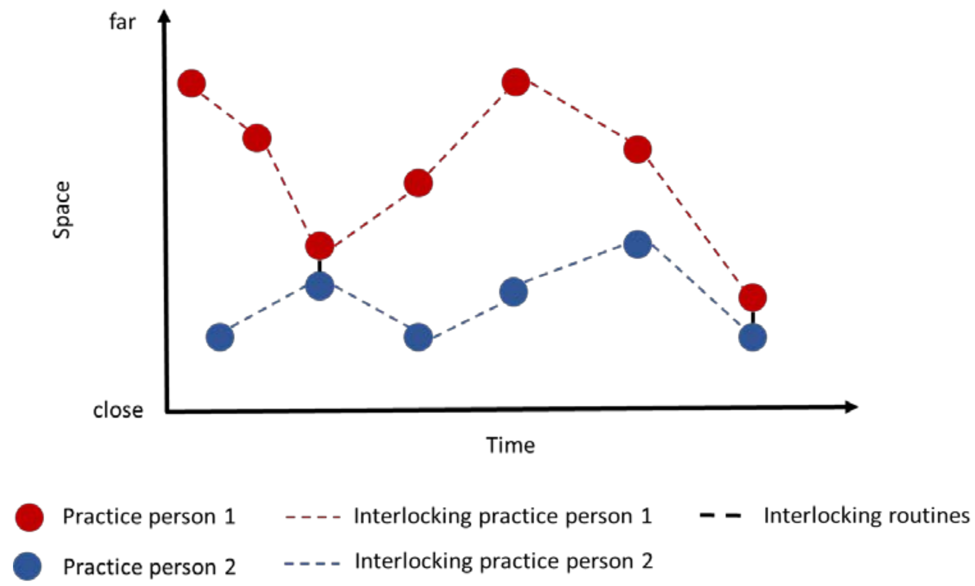

Figure 5.5. Reproduction of home occupant practices and routines in time and space.

5.3 Enabling change in the home system

This research shows that the metabolic flows in the home are affected by house design, appliances, occupant lifestyle, family structure, the degree of occupancy of the house, the HSOP and occupant behaviours (Publications IV and VI). The major metabolic patterns are driven by lifestyle, family structure, house occupancy, house design and appliances, which form the basis of the pyramid of Figure 5.6. The network of practices (HSOP) is responsible for the everyday operation of the home which is automatic when the home is in a state of equilibrium. Occupant behaviour also affects the home system and the initial decision-making processes that inform the establishment of the HSOP. However, behaviours are not considered on a regular basis; only when provoked. Occupant behaviours are a small component of the social system of the home and, as previously discussed, cannot be easily influenced.

Influencing lifestyle, family structure, home occupancy and behaviours are not as straightforward as many decision makers intuitively believe. The introduction of new technologies and upgrading of house design and appliances may improve overall house performance if they are embedded in user routines and are well understood by occupants without the risk of generating potential rebound effects. Affecting everyday practices is only accepted or effective when it includes a modification of the technology element of the practice. However, this requires the technology to be properly adopted and embedded into established and aligned interlocking routines.

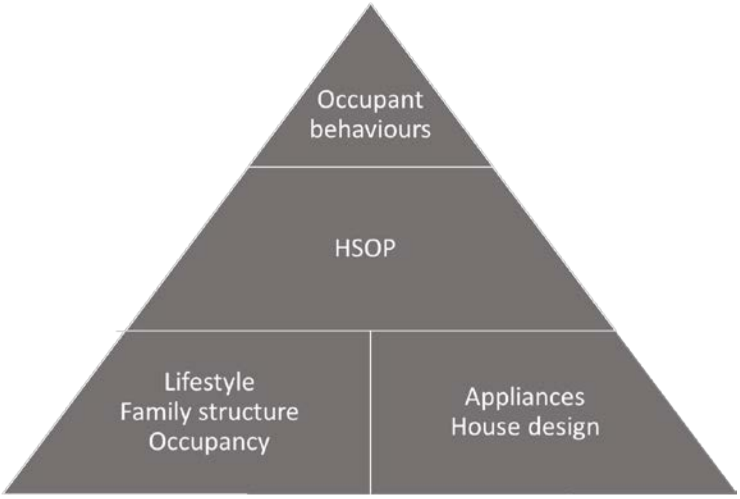

Figure 5.6. The home system influencing metabolism.

Given the complexity of the home system, the results presented in this thesis suggest that rather than disestablishing, realigning and recreating interlocked connections and practices in the HSOP, automated technologies could enable improved resource efficiency through acting completely independently of the HSOP. Manual practices are bound in space and time in a rigid routine, while automated practices are bound only in space in the sense that they can function at flexible times and operate only in conformity with the house technologies. Yet, they are still required to meet occupant needs and skills to be able to work effectively.

Chapter 6 Conclusions and recommendations for future research

Residential homes are usually analysed either in terms of their physical and/or metabolic attributes or in terms of occupant behaviour. However, the way these layers interact is less well documented. A detailed understanding of home dynamics is essential to enable effective resource reduction in residential houses, especially since low energy buildings often do not perform to their full potential.

This thesis has combined concepts from socio-psychology (Ajzen, 1991, Cialdini, 2007, Festinger, 1957), practice theory (Schatzki, 1996), urban ecology (Rodgers, 1997, Harder et al., 2014) and lifecycle assessment to provide a holistic understanding of the home. The latter was considered as a SOP, that is, a network of practices that are bound together in a specific context. While this concept has previously been applied to the study of larger societal systems (Watson, 2012), here SOP is applied to provide a deeper understanding of the home. This thesis also tested notions posited by practice theory with a real life and rich dataset. Quantitative methods were used to describe and verify concepts that are usually studied through qualitative methods alone.

The results and discussion were based on a two year longitudinal study of ten embedded living laboratories (Eon and Morrison, 2017) consisting of Australian homes. A mixed method approach (Creswell and Plano, 2011) with detailed monitoring data and qualitative data from semi-structured interviews and audits was utilised to analyse features of the ten homes, including operational building performance, occupant behaviours, everyday practices in isolation and finally, the HSOP.

The results presented in this thesis demonstrated that the ten houses designed with energy efficient features perform better than the average Australian dwelling. However, it also confirmed results from previous research; that is, that low energy houses do not necessarily operate to their full potential (Publications III and IV) and that houses with similar designs and occupancies can perform very differently to one another (Publication IV). From a building perspective, performance can be attributed to construction quality, maintenance and technology (Publications III and V). From an occupancy point of view performance is explained by lifestyle, family structure, occupancy, inter and intra-home behaviours and practices (Publications IV, V and VI).

Change through persuasion is commonly attempted to modify occupant behaviours and practice for increased house performance, often through information provision and feedback. This research has shown, however, that behaviours, skills and meanings are unlikely to be affected and may only generate limited resource savings (Publications V and VI). The introduction of the practice of feedback visualisation is also not usually integrated into occupant routines. The technology element of practices, on the other hand, is more flexible and more frequently acted upon. Technology changes (automated technologies in particular) that do not impact on meaning, interlocked routines or lifestyle have a higher probability of acceptance by occupants and result in long term reductions in resource use (Publication V).

Practices are performed in a sequential temporal spectrum (Publication VI) that may also be bound in space. They are interlocked not only to individual practices but also to other occupants of the home, resulting in a home equilibrium. Highly interlocked practices are more strongly bound in the equilibrium and less changeable than practices that have a lower degree of interlocking. It follows that affecting practices or introducing new practices into an established interlocked routine requires their realignment, which may be challenging. Interventions aimed at affecting specific practices may ignore the underlying reasons for these practices to be occurring (*e.g.* occupant meanings or highly interlocked practices in the system) and their position and role in the overall system. The effective modification of occupant behaviours and everyday practices requires a holistic understanding of the home and the HSOP. The home system includes: house technologies, household composition and structure, occupant lifestyle, occupant behaviours and the HSOP. The latter includes occupant practices, routines, interlocking practices and interlocking routines.

While homes may have similar yearly or seasonal energy and water use patterns (Publication IV), their HSOP may vary significantly, which means that the holistic understanding of the HSOP mentioned above may not be possible at a large scale. Another solution is to dis-interlock practices from the system through the use of automated technology that can be operated independently of users while making the most of the home physical system.

The idea of utilising automation for improved house performance is not new; however, this thesis shows how this concept integrates in the larger home picture to enable the dis-interlocking of otherwise highly interlocked practices, from the HSOP. However, if automation is to reduce resource use then occupant meanings and skills should be understood. LLs should be employed to co-create, develop and test, together with users, innovative automated technologies to enable low energy or ZEH to perform to their full potential.

6.1 Recommendations for future research

This research has contributed to the advancement of the understanding of the home, including occupant everyday practices and the relationship between occupants and the physical system. However, given the multidimensionality of the home system, several questions remain unanswered and several others have arisen from this research, requiring further investigation. The results reported here need to be validated given the methodological constraints identified in section 2.5 and the lessons learnt from the investigation process need to be considered in future studies. This section discusses recommendations for future research.

6.1.1 Research arising from this thesis

- Development of automated technologies in a living laboratory to enable resource reduction in the home. This research constituted the first step in a LL (insight research), which aimed to collect baseline data about user practices and needs in order to inform the development of technical or social innovations. Further LL stages include ideation, co-creation with users and testing of the innovation in the LL. It is recommended that future research follows up from the findings of this thesis to develop innovative automated solutions together with users and test them in real-life places. User collaboration is essential to ensure that the innovation becomes part of the system of practice and that it is effectively and skilfully adopted to enable change in the home.

- Understanding of how practices are bound in space in addition to time. One of the main findings in this thesis is that practices are reproduced in a temporal sequence. However, practices may also be bound in space. This should be further researched; potentially through the installation of motion sensors in home LLs to provide an extra dimension to the understanding of practices.

- Understanding of the degree of interlocking practices in space and time. It was posited that the degree of interlocking of practices and routines vary according to their reproduction distance in space and time. This concept needs to be further developed and tested in LLs. This could be done, for instance, through monitoring the daily practices of individual home occupants with the use of diaries, motion sensors or through mobile device tracking. These would be able to register time and location of the practice, relating individual routines and practices.

- Development of a house typology classification based on home occupancy, family structure and house technologies. Homes are usually classified according to their design. This thesis also proposed a home typology based on the ownership of cooling and heating devices, which drive major annual energy trends. However, none of these classifications account for occupant behaviours and practices. Although these are variable, this research indicates that there may be a correlation between occupant lifestyle and family structure, house appliances and resource use. For instance, certain types of families that also own specific appliances may follow similar routines and everyday practices. A typology that takes occupancy into consideration may be useful to predict residential energy use and inform behaviour or practice change interventions.

- Understanding of the relationship between the occupant perception of home and everyday practices. This research has shown that there is a connection between occupant behaviour and everyday practice. Moreover, meanings affecting the way practices are carried out are difficult to change. An investigation into how the perception of home drives practices would be interesting. For instance, if an individual definition of the home is a thermally comfortable environment, one may be more inclined to excessive use of the heater or AC systems on a daily basis.

- Understanding of the HSOP within a precinct. This thesis has analysed practices and interlocked practices and routines within individual homes without necessarily considering the larger societal context. A systems approach that includes the understanding of how the practices and routines of a community interlock might provide the basis for the development of not only ZEH, but zero emission or regenerative precincts.

6.1.2 Research validation

- Installation of meters and sensors in separate circuits to measure specific practices more accurately. The number of monitoring meters and sensors in this research project was limited by budget constraints. Although algorithms were employed to detect specific water and energy practices in the home, they may not have captured uncommon practices using unusually low or high amounts of energy or water. It is recommended that these are monitored separately to verify the practices and interlocking practices discussed in this research.

- Use of methods such as diaries to capture practices as they happen, including user perception. The qualitative data in this thesis was collected at three different instances through semi-structured interviews. These reflected on past practices and relied on occupants recalling their previous actions which may or may not be accurate. Requesting participants to keep a daily journal or to register their practice as they happen (*e.g.* through photographs) may result in a more precise description of the practice.

- Reproduction of the research with a larger number of participants. Given the small sample of homes analysed in this research, the generalisation of some of the findings is not possible. It is recommended that a larger sample of residential homes is selected for further evaluation of: 1) the embodied energy of new and old Australian houses (Publication III); 2) the evaluation of PV performance (Publication III); 3) the perception of thermal comfort (Publication IV), 4) the effects of the intervention in terms of practice change (Publication V); and 5) the understanding of interlocked practices (Publication VI).

- Reproduction of the research with homes of lower socio-economic backgrounds. The research participants were all from an affluent socio-economic background and generally valued comfort over economic savings. This could have reduced the impact of the behaviour change program as the participants were not necessarily motivated to make lifestyle changes.

- Reproduction of the research with a more accurate representation of the average Australian dwelling. The houses in this research were selected specifically for their energy and water efficient design attributes. However, this may have negatively impacted the results of the behaviour change program. For instance, some of the participants articulated that they could not make further changes to their house design or lifestyle given that they already lived in a low energy house and were already aware of energy and water saving measures. The average Australian home occupant may react differently to the feedback and information delivered through the audits.

6.2 Final remarks

The home is a complex, dynamic and ever evolving environment, making its comprehension both problematic and captivating. This thesis has attempted to better explain the different layers influencing the home and their effects on resource use.

Occupant behaviour, practices and routines were explained through more traditional socio-psychology theories as well as the emerging practice theory. The definition of homes as a system of practice was useful to describe the concealed interactions between different individuals as well as between occupants and their surroundings.

While many questions still remain unanswered, the results presented in this thesis should help to inform more effective solutions to enable the attainment of truly low energy or ZEHs.

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4. Methods to enable residential building sustainability: integrating and evaluating energy, water, materials and liveability

Christine Eon and Josh Byrne

INTRODUCTION

Buildings are responsible for 32 per cent of the global energy use and generate 19 per cent of energy related greenhouse gas (GHG) emissions (Lucon et al., 2014). Most emissions generated by buildings are produced during their operation, mainly through electricity usage. It has been estimated that if business as usual continues, the energy use in buildings will likely double or triple by 2050 (Lucon et al., 2014). Although commercial buildings will see their energy consumption rise over the next 35 years, the main rise is expected to occur in the residential sector, which currently consumes nearly three times as much as the commercial sector (Lucon et al., 2014).

The scale of this may seem daunting, however the residential sector is considered as presenting the most cost-effective opportunities to reduce GHG emissions (Ren et al., 2011). Design and technology responses used to achieve low carbon and 'zero emission homes' (ZEHs) are proven and accessible. Studies have also demonstrated that ZEHs are affordable and can be adopted as a minimum standard (Harvey, 2013; Uihlein & Eder, 2010). Indeed, policies towards ZEHs have already been implemented in several jurisdictions, including the European Union and the state of California (USA). Other OECD countries such as Canada, Japan and Australia are also making efforts towards lowering residential emissions through minimum energy efficiency requirements in their building codes.

Post-occupancy monitoring studies have confirmed that houses designed to be low emission perform better than conventional houses (Berry et al., 2014; Hamada et al., 2003). However, it has also been demonstrated that they do not reach their full potential, often presenting discrepancies between their design and operational energy consumption (Ambrose et al., 2013; Majcen et al., 2013). Barriers impeding the optimal performance of low-carbon houses are present at all levels, from design and evaluation (Lowe & Oreszczyn, 2008), to construction and verification (IEA, 2008), and house day-to-day operation (Bond, 2011).

Energy efficiency is clearly a key component in reducing household carbon emissions, but we need to go further. Life-Cycle Assessments (LCAs) which account for the carbon footprint across the life of the building should also be considered. Water usage also needs to be addressed, as well as affordability, accessibility to services and commerce, biodiversity and adaptability, which are all important in the context of lowering the impact of residential buildings, and improving occupant well-being.

The objective of this chapter is to present methods to evaluate and monitor the sustainability of residential dwellings, from design to operation. The discussion focuses on the Australian setting with some international examples provided for comparison. To begin with, mandatory housing energy assessment tools and their regulatory context are outlined, followed by the discussion of two emerging 'beyond compliance' tools that address LCAs, as well as broader sustainability outcomes. Attention is then turned to ways to verify and evaluate actual performance by describing verification methods for testing the thermal efficiency of a building, and methods for monitoring the performance of houses during the occupation period.

ASSESSMENT TOOLS

There exists a range of tools around the world used to determine the sustainability and energy performance of residential buildings. Most countries have their own set of rating tools, which can be voluntary or mandatory. Some examples include CASBEE (Japan), HQE (France), Energy Star (USA), R-2000 (Canada), BREEAM (UK) and LEED (USA).

In Australia, two tools are used for the assessment of energy efficiency in residential buildings at the design stage. The Nationwide House Energy Rating Scheme (NatHERS) is mandatory in five out of six Australian states. The Building Sustainability Index (BASIX) replaces NatHERS in New South Wales (NSW) and the Australian Capital Territory (ACT). There are also a number of voluntary or beyond compliance tools that can be used at the design stage to assist with best practice sustainability outcomes, including GreenStar and EnviroDevelopment, used for large-scale residential developments. Other emerging tools are eToolLCD and Living Key which can be used for both single and multi-residential properties.

Rating tools are usually classified into three categories: performance-based design; life-cycle assessment systems; and sustainable building rating and certification systems (Bragança et al., 2010). This section will focus on Australian tools for single residential dwellings: NatHERS (performance-based design), eToolLCD (life-cycle assessment system) and Living Key (property sustainability assessment and rating system), in order to exemplify the three categories of rating tools cited above.

NatHERS

In 2003, NatHERS was formally introduced into the Australian National Construction Code (NCC) as a means of establishing a minimum energy efficiency requirement to maintain thermal comfort in dwellings. It is based on a simulated thermal performance of the building design and incorporates factors such as climate zone, building area, orientation, insulation, building materials, thermal mass and glazing type.

Rating scores are given on a scale of zero to ten, with the higher the star rating, the less the energy required to make a house thermally comfortable. Theoretically a 10-Star house should require very little or no artificial heating or cooling to be comfortable year round. Since 2012 all new houses or renovations are required to meet a minimum of 6-Stars.

Three different pieces of software are accepted by NatHERS for calculation of the thermal energy load in residential buildings, including Accurate Sustainability, BERS Professional and FirstRate 5. Although these software products have been developed by different organizations and present different user interfaces, they all use the same calculation engine, developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO). In NSW and the ACT only accredited assessors who have undertaken recognized training through the Association of Building Sustainability Assessors are able to provide certification to meet compliance under the NCC. In other states, this accreditation is not compulsory and has resulted in rating errors and less than optimal house designs (DSD, 2014). Compliance inspections during the construction phase are also not mandated by the NCC, and poor construction practices, in particular related to the installation of insulation, have resulted in buildings that divert from their original accredited design (DSD, 2014, 2015).

Another major limitation of NatHERS is that it does not provide an indication of the overall energy efficiency of a home, nor other measures of sustainability, in spite of the software having the capability of undertaking a more comprehensive assessment. Heating and cooling are typically responsible for 40 per cent of the residential energy demand (DEWHA, 2008), but other major energy uses such as water heating, appliances and lighting are not considered. Likewise, other resource efficiency factors that have significant environmental and carbon footprint implications such as the use of renewable energy, water efficiency, embodied energy and occupancy scenarios are not considered.

Although NatHERS is the only framework recognized by the NCC in most Australian states, numerous other house assessment tools have been developed with the aim of delivering a more comprehensive house sustainability evaluation. Two more are discussed below.

eToolLCD

The open-use web-based software tool eToolLCD is applied to conduct life-cycle assessment (LCA) of new buildings and all associated infrastructure. It calculates the embodied energy of materials and predicts the energy and water that will be consumed over the building lifespan as well as operational costs. The following is taken into consideration when calculating the embodied energy of a building: the embodied energy of construction materials; the energy for the transport of materials to the construction site; the energy required for earthworks, onsite assembly and installations; and recurring embodied energy from maintenance and fit-outs.

Users are required to provide information in eToolLCD about the type of materials used and quantities required. Embodied energy is then modelled based on existing international LCA databases (Haynes, 2010). Transportation method, distance travelled, machinery and hours of equipment used can also be inputted by the user. Materials which require maintenance or replacement during the lifetime of the building, such as wall painting and carpets, are also modelled by the software. Both embodied energy and transportation of these recurring materials are calculated in the model. Operational energy is estimated based on the occupancy, appliances, carbon intensity of energy supply, mains water supply and sewerage treatment.

Since its development in 2010, eToolLCD has been used for over 200 building LCAs and has reached countries such as the UK, Germany and Brazil. It is currently used for the conduction of EN15978[1] LCA compliant studies and is also adopted as a component of other building assessments, including GreenStar and EnviroDevelopment. While eToolLCD has been very successful in modelling GHG emissions of buildings around the world, the many variables and assumptions made by the software make it difficult to predict the performance of a building accurately, although examples of post-occupancy monitoring studies show that buildings modelled by eToolLCD are achieving expected outcomes (Byrne, 2014).

Living Key

Living Key (previously known as ARCActive) is an emerging sustainability tool and consists of a multi-criteria assessment designed to evaluate the overall sustainability of a property. This tool takes into consideration the building envelope and its usage, but also the adaptability of the dwelling, its location, its connectivity and the quality of life that it provides to its inhabitants. The following categories are analysed: energy, water, liveability, resources, nature, community and transport.

Unlike the tools presented beforehand, Living Key does not predict GHG emissions or forecast water and energy consumption in a building. Instead, it attributes points for sustainable initiatives, design and community integration, making it an easy to understand holistic rating system. In relation to energy, points are given for houses with a high NatHERS rating and/or quality of climate sensitive design. It also takes into consideration renewable energy generation, water heating, method for climate conditioning and fit-outs. The water category assesses sourcing and reuse, in-house fixtures and irrigation methods. Liveability addresses quality of life, assessing features such as universal access, low allergen features and gardens. The objective of the resource category is to evaluate building adaptability, longevity and embodied energy. Points are also allocated to the usage of recycled or reused materials. The nature category promotes native vegetation as well as biodiversity, both in the property and in the vicinity. The objective of the community category is to assess services and amenities available at reasonable distance to the property in order to foster walkability and community interaction. Finally the transport category checks the quality and proximity to public transport.

Although Living Key is a new rating system, it has assessed some of the leading high performance homes around Australia. Examples include NatHERS 10-Star Josh's House, NatHERS 8-Star CSIRO Australian ZEH and NatHERS 8-Star CSR House.

BUILT VERIFICATION PROCESSES

The previous section identified tools for assessing and determining the sustainability of residential houses, enabling an informed decision-making process at the design stage. This section discusses the two most common methods for the verification of houses 'as built', consisting of fan pressure testing, most commonly known as blower-door test, and thermal imaging. These methods are used to identify and measure air leakages and infiltration in buildings, which are responsible for increasing the demand for artificial heating and cooling between 20 and 50 per cent (Fernández-Agüera et al., 2011). Air infiltration can also cause health problems associated with the formation of mould and condensation, in addition to damaging the building fabric and reducing the longevity of materials. It has been shown that upgrades in the building envelope could reduce infiltrations by 52 per cent, saving 7 per cent energy in heating and cooling of houses (Ren & Chen, 2014). Measuring, locating and fixing air infiltrations can be key to achieving high energy performance in buildings.

Blower-Door Test

A blower-door test is used to verify the airtightness of a building and determine whether unwanted infiltration is occurring. A blower door comprises a fan mounted in an adjustable panel set up temporarily in an external doorway. The variable-speed fan blows air out or into the house while a pressure gauge measures the difference in pressure between the building's interior and exterior.

Before conducting the blower-door test, all windows and external doors must be closed, while keeping internal doors open. All heating and cooling sources must be turned off, including wood stoves, fireplaces and clothes dryers. Exhaust fans should also be switched off.

Once the house has been prepared and the blower door set up, the fan can be switched on for depressurization. The pressure difference between the inside and outside of the house is typically set at 50 pascals (Pa). Infiltration is identified by the airflow necessary to maintain the house at the constant pressure of 50 Pa. The higher the required airflow, the 'leakier' is the house. Pressurization tests can also be carried out in addition to depressurization and the building airtightness is calculated as an average. Airtightness can be expressed in different units: air changes per hour at 50 Pa (ACH50) and airflow by the surface area of the building ($l/s.m^2$ or $m^3/h.m^2$).

Few countries include an airtightness requirement in their building codes. However, in Europe and North America, airtightness standards are becoming mandatory in several jurisdictions. A list (non-exhaustive) of airtightness requirements for new residential buildings is given in Table 4.1.

A recent study revealed that the airtightness of new Australian homes averages 15.4 ACH50 with half the houses tested being above 15 ACH50, which is the airtightness assumed by NatHERS (Ambrose & Syme, 2015). These results are much higher than international best practice and considered leaky by Bassett (2001). Blower-door tests must be carried out by an accredited professional and comply with standards, such as BS EN 13829, CIBSE TM23 and ISO/NP 16956.

Table 4.1 Airtightness requirement for new residential buildings

Country	Standard	Compliance	Airtightness			Source
			ACH50	$m^3/h.m^2$	$l/s.m^2$	
Denmark	Danish Building Regulations BR10	Mandatory			1.5	(Kunkel et al., 2015)
	Building Class 2020	Voluntary			0.5	(Kunkel et al., 2015)
Sweden	BFS 2011	Mandatory			0.6	(Kunkel et al., 2015)
USA	IECC 2012	Mandatory	3–5			(DOE, 2011)
	Energy Star	Voluntary	3–6			(EPA, 2011)
Canada	R-2000	Voluntary	1.5			(Natural Resources Canada, 2012)
Germany	DIN 4108-7	Mandatory	3			(Kunkel et al., 2015)
	Passivhaus	Voluntary	0.6			(McLeod et al., 2012)
UK	Building Regulations 2000 Part L1A	Mandatory		10		(Office of the Deputy Prime Minister, 2006)
France	Thermal Regulation RT 2012	Mandatory		0.6 (4 Pa)		(Kunkel et al., 2015)
	BBC – Effinergie	Voluntary		0.6 (4 Pa)		(Effinergie, 2008)

Thermal Imaging

Once the airtightness of a dwelling is measured, specific leaks might need to be identified. Several methods can be employed for detecting air infiltration while the house is still being depressurized between 20 and 30 Pa. Larger leaks can be felt with the back of the hands while air is rushing through gaps due to the pressure difference. To identify smaller gaps, thermal imaging is the best method, as it enables the visualization of the leaks.

Thermal imaging cameras measure the infrared radiation being emitted by a surface, translating it into a gradient colour image, where hot surfaces are displayed as bright colours and cooler areas in darker colours. In order to detect air leakages, a difference in temperature of 3 °C is needed between the inside and the outside of the building. Typically, 35 per cent of leaks occur in joints between wall, floor and ceiling, 15 per cent occur around windows and doors, 12 per cent occur in the chimney, 18 per cent in ventilation systems and 18 per cent in the ceiling (Alfano et al., 2012). By pointing the thermal imaging camera in these key locations, energy losses should be easily identified.

A thermal imaging camera can also be used to identify insulation gaps. This is done by comparing the thermal pattern of the location where insulation should be with the thermal pattern of a reference point (Eads et al., 2000). In order to improve accuracy, a difference of at least 10 °C between the inside and outside air temperatures is needed. It is a good practice to execute the assessment at a period of the year when air conditioning is needed in order to obtain the temperature difference required.

While thermal imaging cameras are relatively easy to operate, identifying patterns and interpreting images require experience and knowledge about the construction being analysed. Accredited assessors can be found through the International Association of Certified Thermographer (IACT) website (iactthermography.org), where standards and guidelines are also available for support.

PERFORMANCE MONITORING

Studies have suggested that occupant behaviour can have as much impact on the performance of houses as the building envelope (Gram-Hanssen, 2012; Lopes et al., 2012). The post-occupancy monitoring of identical low-energy houses in the UK demonstrated that occupant behaviour can account for 51 per cent and 37 per cent of the variance in heat and electricity consumption, respectively, between dwellings (Gill et al., 2010, p. 491). The variability of occupant behaviour makes it difficult to model by building assessment software at the design stage. However, Ehrhardt-Martinez, Donnelly and Laitner (2010) suggest that as much as 18 per cent energy savings can be achieved through raised awareness, with the use of in-house energy feedback displays. The use of residential energy management systems enables occupants to change behaviour following a period of targeted information. This behaviour change can be achieved through the following strategies (Yew et al., 2012):

- automating energy use data collection;
- monitoring and controlling household appliances;
- providing feedback;
- informing users.

Post-occupancy monitoring can therefore be viewed as important to not only evaluate real-life performance, but also to raise consumption awareness through user feedback. This section discusses house monitoring systems and presents a detailed case study on the system that has been installed at Josh's House in Perth, Western Australia.

Review of Monitoring Systems

Monitoring systems consist of four main components: meters, sensors, data logger or Programmable Logic Controller (PLC) and management software. Meters measuring electricity, water or gas need to be coupled to a sensor, which transmits a signal relative to the volume of water/gas or watts used. The sensors in turn are connected to a data logger or PLC, which is the central component of the monitoring system. It is responsible for recording and storing data from multiple sensors and transmitting it to a computer for analysis by specialist software. PLCs differ from data loggers in that they can be programmed for automation and load management, such as switching appliances on or off in accordance to the peak electricity demand. Data loggers and PLCs can range in complexity depending on their design purpose.

Factors influencing the selection of a suitable data logger or PLC include the number of channels required (correlating to the number of meters/sensors to be used and whether these produce an analogue and digital signal), its storage capacity, the method of data transfer (Ethernet or Wi-Fi), data format (CSV files or web browser), the complexity of the system and available user interface. Data logger manufacturers usually provide a compatible user interface that can be used for real-time data visualization, data analysis, the generation of reports and load management; however, the useability and presentation value of these can vary greatly. This interface is usually web based and can be accessed remotely on any device connected to the internet.

There are numerous data logger brands and models available in the market. Table 4.2 provides an overview of the system that is currently installed at Josh's House.

JOSH'S HOUSE

Josh's House (JH) is a NatHERS 10-Star family home built in the suburb of Hilton, Perth, Western Australia in 2013. The project aims to demonstrate that highly energy efficient homes can be built with conventional materials for a comparable cost to other regular similar-sized dwellings. What differentiates this project from other 10-Star houses is that it has also an exemplar across other sustainability indicators, achieving an 'Exceptional'

Table 4.2 Monitoring system at Josh's House, Perth, Western Australia

Monitoring system application			Hardware		
Parameters monitored	*Meters and Sensors*	*User Interface*	*Data logger*	*Features*	*Communication*
Electricity – including oven, lighting, appliance circuits and pumps, plus solar photovoltaics (PVs), battery and grid supply	Latronics kWh	dEX Software: Web-based user interface. Real-time monitoring data shown in dynamic tables and graphs. Data can be accessed remotely over the internet. Additional custom visualization of selected data channels via a third party server-based program for open use display on project website.	Datataker DT80	Inputs: 12 digital channels and 15 analog channels Expansion modules for additional inputs Data storage: 128Mb (10 million data points) Built-in LCD display	Integrated communication interface: USB, Ethernet, data ports (RS-232/ RS-422/RS-485) and Modbus Data export: CSV files sent via email, web browser and FTP server
Gas	Ampy 750 and pulse kit				
Temperature – living areas and bedrooms, plus slab, mass walls, ceiling, roof cavity and roof surface	TCKPP1 20AWG thermocouple wire				
Internal relative humidity and CO_2	Vaisala GMW95R Temp, Humidity, and CO_2 sensor				
Weather – rain, wind speed and direction, solar radiation, external temperature and relative humidity	Vaisala WXT520 weather station				
Mains water	20 mm Elster V100 and MEB7454 'T' probe				
Rainwater	20 mm Elster V100 and MEB7454 'T' probe				
Hot water	20 mm Kent S130				
Groundwater	40 mm MT-EX				
Greywater	20 mm Elster V100 and MEB7454 'T' probe				
Rainwater tank level	Mercoid Series SBLT2 submersible level transmitters				
Soil moisture	Decagon 10HS capacitance soil moisture probes				

Living Key rating and an eTool Gold certification. Josh's House was designed to be zero net energy and water highly efficient (incorporating rainwater harvesting and greywater use), but it also addresses other aspects of sustainable living that are often overlooked. These other factors include good indoor air quality, universal access, as well as productive, biodiverse gardens incorporating intensive food production and engaging outdoor play spaces for children.

Josh's House is used as a Living Laboratory to demonstrate the day-to-day operational performance of a sustainable house and to verify that it fulfils its intended design while being occupied. Monitoring equipment as described in Table 4.2 has been installed and is currently collecting real-time data from a multitude of instruments. The project has already gone through one year of data collection, verifying that the sustainable 10-Star house is performing as designed, using 92 per cent less mains water than the Perth average and exporting net surplus electricity to the grid (Byrne, 2014). Further information on the project can be found at www.joshshouse.com.au.

CONCLUSION

Improving the energy and water efficiency of residential dwellings is the subject of research and policy work in many countries around the world. The potential for this to contribute to a reduction in anthropogenic GHG emissions and improved resource management more broadly is significant.

There are a number of obstacles preventing the uptake of high-performance, sustainable housing, including the limitations of assessment tools, inadequate regulatory controls, poor building construction and occupant behaviour. This chapter provided an overview of existing methods employed to predict, verify and monitor parameters affecting thermal comfort, energy and water consumption, and the related carbon emissions in residential buildings in Australia and elsewhere. Current methods are not comprehensive and present opportunities for continued innovation.

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NOTE

1. BS EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method.

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Integrating theories of practice and behaviour into home settings through living laboratories

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Integrating theories of practice and behaviour into home settings through living laboratories

Abstract

Household metabolism is an emergent area of research that focuses on reducing the flows of resources through the home. While house design is known to affect these flows the heterogeneity of practice and behaviour of the occupants is not fully understood. Persuasive and enabling sustainability are distinct, social theory based, schools of thought which are employed to affect occupant actions. Persuasive sustainability aims to affect behaviour and attitudes through modifying norms or providing prompts and information. Enabling sustainability aims to affect everyday practices through insight-based design in the home. This article unites the schools of thought and links them to research in Living Laboratories, which provide a place for insight into user-based practice and behaviour, as well as prototyping social and technical innovations. This unified tripartite approach provides a more explicit understanding of how resource flows in the home environment can be affected.

Keywords

Living Labs, practice theory, behaviour change, resource consumption, enabling change

1. Introduction

The reduction of resource consumption in households is considered by many as a cost effective step toward urban sustainability. Improved building envelope design and technology are known to significantly reduce energy and other resource demands in households, however they are not the only influencing factor. Individuals are a key player making everyday decisions and influencing usage through their behaviours and practices, which in turn are influenced by place, technologies, interpersonal relationships, society and information. As such, the implementation of strategies based on behaviour change has been a key approach to promoting resource efficiency in residential buildings and finding optimal behaviour change methods, in particular targeting energy conservation, has been the focus of research since the 1970s (Delmas, Fischlein, & Asensio, 2013).

The ideas behind changed behaviour for environmental sustainability have generally been based on social theories such as those developed by Ajzen (1991), Festinger (1957) and Cialdini, Kallgren, and Reno (1991). Typically, socio-psychology approaches consider cognitive dissonance, social norms, information provision and feedback to instigate change (Abrahamse, Steg, Vlek, & Rothengatter, 2005). Since human-computer interactions became accessible, scientists have started deploying them on a regular basis for the delivery of eco-feedback and information; Brynjarsdottir et al. (2012) refer to this as persuasive sustainability.

Practice theory also originates in social theory but offers an alternative approach to promoting a reduction in resources consumed. Practice theory scholars argue that resource consumption depends largely on the practice, or technology used to carry out certain activities (Shove & Walker, 2014). For example, standby consumption can be avoided if appliances do not have standby options in the first place. While on the one hand social norms, habits and awareness influence change, on the other hand products and technologies can facilitate or hinder change. The innovation of a product or procedure can therefore act as an enabler of sustainability, especially when designed in conjunction with users. This is referred to by Brynjarsdottir et al. (2012) as non-persuasive sustainability, although we prefer the term enabling sustainability.

The two schools of thought mentioned above (i.e. socio-psychological and practice theories) are seldom aligned and reported research tends to be founded in one of the two schools. A systemic approach that persuades as well as enables may help to uncover layers of complexity in everyday practice and behaviour to provide a more elegant understanding of how resource flows through households can be affected.

This article discusses the adoption of Living Laboratories (Living Labs) as a place for aligning persuasion techniques and enabling consumers as a means to encouraging resource reduction in and through real life environments. Firstly, we will describe the approaches commonly used to reduce resources in residential settings. Next, we will discuss social psychology and practice theories, which are the basis of persuasive behaviour change methodologies and enabling approaches, respectively. We then introduce the concept of Living Labs followed by a discussion of insights and interventions that are applied to promote sustainability in Living Labs. We finish with a discussion about the complexity of the layers that influence change, which we define as the triangle of Practice and Behaviour Change. The latter concept considers the integration of learnings from both social psychology literature and practice theory literature, bridging some of the persuasive limitations referred to by Brynjarsdottir et al. (2012).

2. Influences on resource usage in the home environment

Resource flows and transformation processes within urban environments have been described using the concept of urban metabolism, which compares an urban system to a living being, consuming resources, transforming them internally and generating waste as a byproduct (Zhang, 2013). Household metabolism (Figure 1) evolved from urban metabolism and describes the flows of water, energy and resources and their use and change within residential places (Harder et al., 2014). A common approach to reduce household resource consumption consists in minimizing the inputs into the system, improving the efficiency of processes within the system and reducing the outputs (Rodgers, 1997). The systemic view provided by the household metabolism approach offers an understanding of the household from a systems perspective, but it overlooks the more complex processes happening within homes, where humans are the main players.

Reducing energy, water and resource consumption in households, culminating in lower waste levels, depends therefore not only on the available infrastructure and technology, but also on the user's attitude and practices. Indeed, it has been defined that building emissions (CO_2) are a factor (equation 1) of the carbon intensity (CI) of energy sources, the technology energy intensity (TEI) of energy-using devices, the structural energy intensity (SEI) of the building envelope and critically, the human activity (A) within the building (Lucon et al., 2014).

$$CO_2 = CI \cdot TEI \cdot SEI \cdot A \qquad \text{(Equation 1)}$$

Whilst technologies such as renewable energy, efficient appliances and good building design are well understood and can be implemented relatively easily, the complexities of human behaviour and practices are still not well understood.

3. Practice and behaviour through social theory

Social theories can be used to explain practice and behavior relating to resource flows in everyday settings. Resource reduction can be promoted either by changing the context in which decisions are made or by encouraging voluntary change (Abrahamse et al., 2005). Changes in context can consist of the enforcement of regulations or structural modifications that facilitate desired behaviours or make habitual behaviours less attractive; one example of change in context would be reducing the number of car parks in urban environments (Steg & Vlek, 2009). Voluntary change implies individual changes in attitude and may consist of a one-off behaviour, such as buying an energy efficient appliance or it might be a change in routine, also known as curtailment behaviour. The latter involves the repetition of tasks, requiring individuals not only to engage in a certain behaviour, but to maintain it in the longer term (Abrahamse et al., 2005).

Policies to reduce energy, water and resource consumption often focus on promoting one-off behaviours. Although these changes can lead to successful outcomes, they can also cause rebound effects, increasing overall resource consumption (Sorrell, Dimitropoulos, & Sommerville, 2009). Behaviour change interventions that focus on modifying attitudes, values and perceptions might be encouraged alongside innovative technology and design strategies.

The design of successful voluntary behaviour change interventions relies on understanding the underlying factors influencing people's decisions. Several disciplines including behavioural economics, sociology, psychology and practice theory have attempted to uncover elements that influence behaviour. It has been argued that these disciplines offer different perspectives of the same subject and their lessons should be integrated to form a comprehensive behaviour change intervention strategy (Wilson & Dowlatabadi, 2007). The following section provides an overview of the two schools of thought commonly used to inform interventions and evaluate their success or failure.

3.1. Social Psychology Theories

Social psychology is the study of people's interactions with wider society and studies how individual behaviours, thoughts and attitudes are influenced by others, either consciously or subconsciously through social and cultural norms. Several social psychology theories have been developed since the 1920's to explain individual behaviour and are frequently used for the development of pro-environmental behaviour change programs. These theories include planned behaviour, cognitive dissonance, social norms and habitual behaviour.

The theory of planned behaviour predicts that a behaviour is preceded by the attitude towards the behaviour (i.e. beliefs and evaluation of the outcomes), subjective norms (i.e. the perception of the behaviour by others) and perceived behaviour control (Ajzen, 1991). This means that an individual who is concerned about carbon emissions, for example, might not act to reduce these due to a lack of perceived personal impacts.

On the other hand, the likelihood of engagement leading to behaviour change may increase if an individual is consciously supportive of the cause or if the individual simply agrees to take action (Sparks & Shepherd, 1992). This is in accordance with the theory of cognitive dissonance which posits that people are uncomfortable to find themselves in a situation in which their attitude and behaviour are inconsistent and will therefore make changes towards correcting this discrepancy (Festinger, 1957). These adjustments can be made through changing behaviour, changing beliefs or creating new cognitive elements aligned with behaviour (Festinger, 1957). This need for consistency is recognised as an opportunity to encourage behaviour change through triggering individuals' values and self-concepts, effectively making them aware of potential dissonances (Verplanken & Holland, 2002).

Whilst personal values and beliefs affect people's behaviours, individual conduct is also influenced by the behaviours and judgment of the wider society. These unspoken social rules are referred to as social norms, which are of two kinds: descriptive and injunctive (Cialdini et al., 1991). Descriptive norms define what the customary behaviour is in a given situation. Injunctive norms on the other hand, prescribe how one should behave either by approving or disapproving of the behaviour. For example, a study on littering showed that people are more inclined to drop litter in littered locations. In contrast, clean environments tend to remain unlittered for longer periods of time (Cialdini et al., 1991). Social norms are even more effective when encouraged by a peer in the form of a social intervention (Hopper & Nielsen, 1991).

The theories of planned behaviour and cognitive dissonance consider individuals as purely rational evaluating outcomes as well as the costs and benefits of certain decisions, however, daily habits can prevent change (Steg & Vlek, 2009). Habits are prompted to meet a specific goal and if the goal is met in a satisfactory manner, the tendency is that one will repeat the same behaviour on the following occasion when the same goal is being sought (Aarts, Verplanken, & van Knippenberg, 1998). Repetition requires less mental effort, which can lead to an unintentional habit and once habits are established, future actions are likely to be guided by them, regardless of values, attitudes or norms. Due to the unconscious nature of habits, habitual behaviours are only reviewed when provoked or in the event of a change in context (Steg & Vlek, 2009)This change in context for modifying behaviours is what practice theory advocates.

3.2. Practice Theory

People do not use resources such as water or energy directly, but rather with the objective of achieving a desired social outcome; an everyday practice such as cleaning, shopping or dining. In order to understand energy or water usage, it is therefore important to comprehend the practices involved in achieving daily objectives (Hargreaves, 2011) Practice theory attributes practice to daily routines, neither being necessarily linked to attitudes. Gram-Hanssen (2014) outlines the four elements that influence practices: embodied habits, institutionalised knowledge, engagements and technologies. Embodied habits are those we regularly undertake in an unconscious mechanical manner such as showering. Institutionalised knowledge refers to the way we learn about a certain practice, through information provision or through watching others perform it. Engagement refers to the reason for executing the practice, where there is a reward at the end of the practice, such as feeling clean. The technological element encompasses the technology or infrastructure that is used in or influences the undertaking of the practice, such as a showerhead. Another model (Scott, Bakker, & Quist, 2012) describes practices as a combination of matter (stuff), images and skills, where matter refers to materials that facilitate the practice such as technologies; images refer to what is to be achieved; and skills refer to the competence needed for the execution of the practice. As practice theory is still an emerging field, there is a lack of a unifying model of assessment (Hargreaves, 2011).

Practice theory is based on how people’s identity, preferences and individual interests are fluid depending on the context and the relations within that context. Everyday practices have a dynamic nature because as technologies and infrastructures change over time, existing social practices become obsolete and new practices become embedded in new routines (E. Shove, Watson, & Spurling, 2015). Modern technology may dictate the way an action should be performed. For example, capsule based coffee machines imply that consumers buy the manufactured coffee capsules for the coffee making practice. Encouraging resource reduction and efficiency can help to promote sustainability, but this encouragement assumes that practices and preferences are static over time and are the result of conscious customer decisions and available technology (Shove & Walker, 2014).

4. Living Laboratories

Specific behaviours and practices occur in specific places and are reliant on the elements that make up the place, including people, technology and external influences. Reducing resources in residential settings is therefore dependent on individuals’ home characteristics. Hence, research evaluating the impact of persuasion and enabling strategies on resource consumption needs to be undertaken in a real life setting such as a living laboratory.

The ideas behind the development of Living Labs vary depending on purpose (Dell'Era & Landoni, 2014). Burbridge et al. (2016) have modified the definition of Dell'Era and Landoni (2014) to reveal the Living Lab as a place (Femenías & Hagbert, 2013) rather than a methodology, while including the three key features of Living Labs; co-creation, user awareness and real-life settings (Leminen, Nyström, & Westerlund, 2015). The following definition also encompasses knowledge, social and technical innovations.

> *A Living Lab is a real-life place for user co-creation of innovations in knowledge, products, services and infrastructures* (Burbridge et al., 2016).

The similar definition presented by Bergvall-Kåreborn, Ihlström Eriksson, and Ståhlbröst (2015) suggests that the current discourse is converging to a unified meaning of the term Living Lab. Bergvall-Kåreborn et al. (2015) also propose that different types of places and spaces can facilitate or hinder innovation. The attributes of local knowledge and user influence affect the nature of innovation in a place and space. It is therefore important to capture the heterogeneous nature and manifestation of social and technical innovation for real-life Living Labs in different settings (Franz, 2015).

The heterogeneity of innovation in Living Labs may be revealed through scaling effects which are due to different interpretations of the physical boundaries of a Living Lab. A typology of Living Labs might include three scales; urban, dedicated and embedded.

The urban Living Lab has a boundary ranging from the city district to whole metropolitan area and is seen as an approach to dealing with challenges such as the low carbon city, blue/green infrastructures and social uplift (Rosado, Hagy, Kalmykova, Morrison, & Ostermeyer, 2015). At the district level this approach had been proposed as a means to design a new university campus where the user focus is business, society and academia (Evans, Jones, Karvonen, Millard, & Wendler, 2015). Dedicated Living Labs are place specific, usually a dedicated building, and are used for prototyping products and services (Elfstrand, Morrison, Toups, & Hagy, 2016). Embedded Living Labs are existing residences or workplaces that are studied to provide insight into user practice (Liedtke, Baedeker, Hasselkuß, Rohn, & Grinewitschus, 2015).

There is a consonance between the evolved definition of Living Labs, and their heterogeneous character, and the consolidation of the theoretical scientific basis behind Living Labs (Rosado et al., 2015). The theoretical basis for a sustainable Living Lab draws on three contiguous interdisciplinary areas. Firstly, systems and engineering where simulations, smart automation and engineering for optimal performance enable eco-visualisation, which can be integrated into home designs (J. Rodgers, Bartram, & Woodbury, 2011). Secondly, design and behavioural science where the Living Lab facilitates change through a user-centred, co-creation approach (Scott et al., 2012). Thirdly, sustainability science which is an inclusive super-discipline with a clear foundation in the study of human, social and ecological systems (Bettencourt & Kaur, 2011; Spangenberg, 2011). Figure 2 illustrates the three disciplines that provide the basis for a Living Lab as described.

A further theoretical basis for the Living Lab concerns the process of the co-creation of innovations in knowledge, products, services and infrastructures. The co-creation process is essentially transdisciplinary in character where the knowledge is generated in patterns across relevant disciplines and discourses (Pohl, 2008). Co-creation is a stringent process in the Living Lab where integral thinking between users leads to innovation (Franz, 2015).

4.1. Insights and Interventions in Living Labs

Social theories provide an explanation for people's behaviours and attitudes and inform real-life behaviour change interventions and insights. Several strategies are employed by researchers when attempting to change people's behaviours in real-life settings such as Living Labs. As discussed in Section 3, Brynjarsdottir et al. (2012) categorize interventions into persuasive and enabling. Persuasive methods include information provision, commitment, goal setting, feedback, prompts and rewards and are prevalent in the socio-psychological literature. Enabling methods are designed to modify the practice context, targeting habits, knowledge, engagement and technology as favoured by practice theorists. This section will describe the methods that are adopted in Living Labs to persuade or enable change.

Persuasive Methods

Information campaigns are the most commonly utilised persuasive method with the intent of promoting behaviour change. It assumes that if people have a better understanding of an issue, they will act accordingly. Although mass information campaigns lead to increased levels of awareness, they are often an ineffective means to alter behaviour (McKenzie-Mohr, 2011). The lack of information, however, may represent a barrier (P. W. Schultz, 2002). Tailored information, on the other hand, has proven to be effective to change behaviour leading to lower energy usage (Abrahamse et al., 2005). Home audits are a successful example of tailored information as they reveal specific and personal household issues while also activating individual values to minimize dissonance. A variation of energy reduction results have been found in the literature, including savings of 4% (Hirst & Grady, 1982), 10% (McMakin, Malone, & Lundgren, 2002) and 21% (Winett, Love, & Kidd, 1982).

Commitment strategies are another commonly sought behaviour change method based on the need that individuals have to behave consistently. For example when one makes a promise or simply agrees to something, one is likely to behave accordingly, no matter how much time has elapsed between the commitment and the behaviour (McKenzie-Mohr, 2011). Behavioural practitioners make use of commitment techniques, either verbally or in written form, to promote a desired behaviour. Both are effective, although written commitments appear to have a more lasting effect (Pardini & Katzev, 1983-84). Commitments can also be made public, having the potential to lead to 20% savings in electricity and 15% savings in natural gas (Pallak, Cook, & Sullivan, 1980). However, very strong public commitments can have the opposite effect and discourage participants if consecutive failures emerge (Shippee & Gregory, 1982). A review by McKenzie-Mohr (2011), demonstrated that commitment is higher when households are invited to voluntarily participate, for example, in a house audit.

Goal setting is often used in combination with commitment and feedback as it enables setting a measurable target that can be monitored over time. Feedback strategies have the objective of providing households with information about their energy or water consumption on a regular basis and when used in combination with goal setting enables tracking goals against real usage. This provides a better understanding of behaviour outcomes and promotes cognitive dissonance (Darby, 2006). Feedback can be direct or indirect. Direct feedback can be provided through meter readings or via a monitor or in-home-display (IHD), which reports real-time consumption data. Indirect feedback refers to data that has been processed before reaching the household, such as bills, which often include historical data or comparisons against other households. Research shows that direct feedback results in higher energy savings compared to indirect feedback: 5-15% and 0-10% respectively (Darby, 2006). Additionally, the more regular the feedback, the more efficient the reduction in energy consumption. The inclusion of both descriptive and injunctive norms to the feedback process assists high consumers in reducing their energy usage towards the average while retaining low consumers (Abrahamse et al., 2005; Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007).

Prompts can be used to break habits and remind households about taking a certain action. They can be in the form of a sticker next to the light switch (Tetlow, Beaman, Elmualim, & Couling, 2014), for example, or in the form of an alarm triggered by an IHD whenever energy consumption reaches a certain level (Alahmad, Wheeler, Schwer, Eiden, & Brumbaugh, 2012).

Finally, financial incentives in the form of monetary rewards and tax credits have been used to promote energy savings in households. Although they produce good immediate results, Abrahamse et al. (2005) suggest that the effects of rewards are short-lived, stopping as soon as they are interrupted.

Whilst the interventions described in this section are commonly used the means to deploy them are diverse. Table 1 shows a summary of the theories, interventions and techniques employed to deliver these interventions. Most interventions fall into three categories, referred to here as social, technological and knowledge-based interventions. Social interventions involve some form of social interaction, such as face-to-face meetings, audits or workshops. Technological interventions are methods that rely on technology and do not involve any kind of social interaction. That is, IHDs, websites and automatic messages deliver feedback, norms, prompts and goal setting. IHDs can break down energy usage by appliance and show energy consumption in different formats, catering for different audiences while providing real-time and long-term feedback. Some researchers argue that this method enables the interaction of households with the data and therefore higher engagement (Fischer, 2008) and appliance control (Yew, Molla, & Cooper, 2012), leading to a significant reduction of electricity consumption (Faruqui, Sergici, & Sharif, 2010). However, arguments against the deployment of IHD's focus on the fact that displays are designed by researchers and do not necessarily correspond to what the user wants to see, reverting to the background situation after a novelty period (Brynjarsdottir et al., 2012). Brynjarsdottir et al (2012) argue that this technology is trying to persuade the user to change rather than providing solutions to change. In addition, the deployment of IHDs to influence behaviour change assumes that the user has previous knowledge of interaction with this technology and that the user makes this part of everyday practice. Unilateral impersonal communication such as letters, emails, bills or marketing campaigns have been categorised as knowledge-based interventions.

Enabling Methods

Practice theorists argue that rather than persuading customers to modify their behaviours through norms, prompts or information, change should be enabled through influence on the elements of practice: embodied habits, institutionalised knowledge, engagements and technologies (Gram-Hanssen, 2014). This includes modifying technologies or infrastructure in a way that results in a desirable outcome but also facilitates resource reduction. It has been shown that the introduction of energy efficient technologies often results in rebound effects (Sorrell et al., 2009), which is where practice-oriented design has the opportunity to provide innovative solutions. Practice-oriented design begins with understanding how practices are influenced by embodied habits, institutionalised knowledge and learning, anticipated outcomes or the reason a practice is being undertaken, and the technology used. Practice-oriented design involves users in the design of a new technology in a process of co-creation and testing in a Living Lab (Scott et al., 2012). This process enables the users to challenge the *status quo* and identify innovative solutions that meet their needs as well as reduce resource consumption and avoid potential rebound effects. Practice-oriented design includes a number of different methods(Table 2).

Each method attempts to identify the embodied habits, institutionalised knowledge, reason for the action and technologies used in everyday practices. The first eight methods are used to gather deeper insights into the socio-psychological aspects of daily practices, and how these manifest in and influence practices, as well as tracking the types of resources used by households. In a practice-oriented design exercise, the user, or the practitioner, is central to the innovation, and can therefore become more engaged in finding solutions and testing them in collaboration with researchers and businesses (Liedtke et al., 2015). The final three methods (co-creation, prototypes and in-situ tasks) reflect this by putting the users and occupants of the Living Lab at the forefront of designing and testing new products, services and systems, as well as investigating how these influence evolving behaviours and practices.

Table 3 summarises how the common methods of practice theory (Table 2) can be used to study the elements that influence practices, as Table 1 outlined for the socio-psychology theories. These methods are used to address overarching questions on electricity, water and resource use. These methods are grouped into social, technological and knowledge based insights that are gained from their use to allow comparison with the socio-psychological methods reviewed in Table 1. Many methods target multiple elements and insights, providing holistic results.

4.2. Temporal implication of persuasive and enabling methods

The long-term effect of behaviour change programs is often not measured and emphasises the need to carry out longitudinal studies in Living Labs. The duration of behaviour change or practice-based interventions is also limited to a very specific timeframe. This makes it difficult to assert the long-term effectiveness of insights and interventions and especially the means employed to deliver these interventions. In spite of the limited data, the few existing longitudinal behaviour change studies suggest that some persuasive methods have longer lasting effects than others (Abrahamse et al., 2005). Information campaigns, for example, might be effective for a short-term solution, such as saving water in summer. IHD can be a good tool while it is a novelty, but if it does not meet consumer needs, the technology quickly becomes idle and its effectiveness might only last a few months. Other interventions such as team work (Staats, Harland, & Wilke, 2004) and audits, which demand a higher level of personal engagement, might last a few years. In fact, there is no evidence that persuasive methods can be effective for more than a few years after the end of an intervention. The replacement of current technology with technology that enables change through everyday practice, on the other hand, can have a long-term effect on resource reduction. Rather than requesting that households turn off their standby appliances manually, for example, appliances without a standby mode could be provided instead. The success of innovative technology is dependent on user knowledge and can be hindered by rebound effects; however, the implementation of practice-based design and co-creation in Living Labs is a contemporary approach which ensures that users not only take part in the design of a technology that is needed in the long-term, but also understand its function. Figure 3 estimates the duration of insights and interventions according to the existing literature.

5. Towards lasting change in the home

People's practices and behaviours influencing resource consumption inside the home, are shaped by a multitude of psychological, social and technical factors. People act in agreement with their values and perceptions, which are influenced by a series of other factors such as close family and friends, social rules and norms established by the community and the wider society, information provided by media campaigns or newspapers, the practices carried out in order to achieve daily life goals, and finally by technology that facilitates or even dictates certain practices. Figure 4 illustrates the complexities of the layers influencing human behaviour. Figure 4a represents some of the external factors affecting users' perceptions and behaviour in households; these are information, social norms, social and technical innovation and influence from family and friends. Figure 4b represents the influences on users inside their own homes. In a house with multiple inhabitants, knowledge and practices are learnt from one another, although each occupant has their own behaviours and attitudes. For example, one individual might be environmentally conscious and make an effort to turn off lights, while another might not think it is important and end up hindering the efforts of the first. Additionally, the type of appliances present in the house might also dictate a certain practice and in some cases influence behaviour. For instance, when used correctly, an IHD might influence behaviour through the provision of feedback and social norms. However, IHDs are only useful if the occupant has prior knowledge and significant interest. Energy conservation within a house is therefore not straightforward and depends on the collective behaviour and practices from distinct individuals who influence each other. In other words, people's behaviours and practices are influenced by who they are, where they are, and whom and what they are exposed to.

As discussed in this paper, social psychology theories have traditionally informed resource reduction in households from a user point of view. Their aim has been to modify behaviour by changing existing attitudes, knowledge and values without necessarily understanding the reasons behind existing behaviours, but rather focusing on the use of persuasion to promote change. It is imperative that consumers understand the implications of their actions and adopt a positive attitude towards resource consumption; but changing behaviour may involve perceived lifestyle impacts or change of embodied habits that require high levels of commitment which may, or may not, be feasible in everyday life. Studies testing the long- term effects of social psychology interventions suggest that the effects of most persuasive behaviour change methods last only between a few days and a few years, stopping as soon as making changes becomes too difficult, disruptive or loses the novelty effect.

Practice theory offers a different approach to close some of the gaps found in persuasive interventions through investigating what drives people's practices and the reason for certain behaviours; that is, what and who is influencing the user in question. As highlighted by practice theory researchers, people do not consume resources as such, but resources are used as a means to achieve a goal. Technologies used to achieve these goals are therefore a key part of the practice and have a direct impact on resource use. This allowed the focus to be on understanding user's underlying needs and habits so that new technologies can assist users to make permanent changes rather than just convince them that change is necessary. However, practice theory has also been criticized by transition theorists due to the narrow user focus preventing generic patterns to be identified and the lack of analytical models developed (Geels, 2010). As practice theory is still developing, the authors believe that these patterns and models will be developed over time and do not justify the dismissal of the user learnings gathered.

Persuasion and enabling methods are usually not aligned in behaviour change studies as they are seen as two distinct methodologies. We argue that they are in fact trying to achieve the same objective, which is to reduce resource consumption in households, but approaching it through different angles. On the one hand, persuasive methods address personal energy use from a top down approach, delivering social norms and providing information; on the other hand, enabling methods are very focused on user needs and addresses consumption from a bottom up approach. Rather than being conflicting methods, the two schools of thought complement each other, filling each other’s gaps, informing and modifying attitudes while enabling long-term changes that bring value to the user.

We suggest that behaviour change strategies should address all the elements that influence the decision-making processes in the home (Figure 4). That is, successful resource reduction interventions in households should not be limited to everyday practices or behaviour, but also introduce innovative technologies within the specific place where the practices and behaviours occur. Sense of place is important as practices can change depending on where they are implemented. For example, one individual may use a washing machine to clean clothes in his/her own home but hand wash them when travelling. Studying behaviours and practices in real-life settings, Living Labs, is therefore vital to capture real motivations and needs. We conceptualise this notion through the triangle of Practice and Behaviour Change (Figure 5), where change is dependent on the sense of place for an individual or family constellation in the home, the everyday practice and behaviour of those home occupants, and social and technical innovation in the home environment. We posit that relevant social and technical innovation requires a holistic understanding of the home as a sense of place and insight into the everyday practice and behaviour of the occupants. While each can be tackled separately, as has been done in previous research, we suggest that all three elements are equally important to promote change.

The notions that have been conceptualised in this paper should be tested in real-life environments. Embodied Living Labs are the ideal place to observe and learn the practices used to complete a determined task, understand the effects of behaviour and relationships on resource consumption, co-create innovative solutions to problems and test innovative technologies or approaches. Previous studies have found that the traditional methods employed to understand practices and behaviour, including diaries, surveys and interviews, have not captured the nuances of daily practices and if not integrated with quantitative data, fail to provide sound explanations for practices (Romero, Al Mahmud, Beella, & Keyson, 2013). Living Labs enable researchers to measure the effect of different interventions upon resource usage both quantitatively and qualitatively. Through constant interactions between researchers and users, better insight is obtained about lifestyles, needs and attitudes and tailored solutions can be developed in conjunction with the user. This co-creation process enables the development of innovation that is truly useful, bridging some of the limitations found in efficient design or technologies. Living Labs can help to overcome a limitation of many research studies which tend to see homes as a single unit instead of a place with specific objects and multiple people interacting with one another.

Table 1. Theories, strategies and tools for socio-psychological behaviour change interventions

Theory		Insights & Interventions	Social interventions	Technological interventions	Knowledge based interventions
Socio-Psychological Theories	Theory of Social Norm	Descriptive norm	Social interaction	In-home-display, website	Letters, marketing campaign
		Injunctive norm			
	Theory of Planned Behaviour	Descriptive norm	Social interaction	In-home-display, website	Letters, marketing campaign
		Injunctive norm			
		Information provision	Audit, coaching	Website	Mass campaign, letters, emails, information material
		Feedback	-	Website, SMS, in-home display	Bills, letters, email, direct meter readings
	Theory of Cognitive Dissonance	Feedback	-	Web-based, SMS, in-home display	Bills, letters, email, direct meter readings
		Commitment & goal setting	Verbal or written	Website, in-home-display	-
		Value activation	Coaching, audit, peer interaction	-	Survey
	Habitual Behaviour	Prompts	-	SMS, email, in-home-display, website	Stickers, written reminders

Table 2. Common methods used in practice-oriented design in Living Labs and their purpose (from Greene, Bowden, & Gheerawo, 2013)

Method	**Purpose**
Diary	Self-reported daily practices and actions to examine the relationship between these thoughts and actions.
Experience Sampling Method (ESM)	Participants respond to prompts and probes about their daily practices, which allows for the connection of behaviours and practices with self-reported data on their feelings, emotions and moods regarding the practices and contexts.
Probes	A communication with participants asking them to respond with some information. This gathers insights into behaviours, practices, motivation and habits of energy, water and resource use.
Interview	Used to gain self-reported insight into behaviour and practices, and the motivations, routines and context behind these, as well as how they change over time.
Social Network Analysis (SNA)	Participants map their social network in relation to specific practices or resource usage. This tracks the importance of the social network on daily practices and how this changes over time or context.
User Re-enactment	Observe, review and question the participant’s interpretation of their behaviour, practices and routines, not just relying on self-reporting of processes after the fact.
Orientation to the Living Lab	Orientation is given before participants move in to a specially designed Living Lab to track how they learn to use and understand products, services or systems in the Living Lab and how this alters over time.
Material Input per Service Unit (MIPS)	A whole life cycle analysis of products and services used to estimate their environmental impact, and identify key behaviours and practices that influence their use.
Co-creation	Participants and researchers design products, services and systems that will change how they undertake daily practices and the associated energy, water and resource use.
Prototypes	Working models of a product, service or system are built to be tested in a Living Lab to understand how people behave and respond to them.
In-situ tasks	Explore how different participants respond and use the prototype, along with the associated habits, motivations and energy, water and resources consumed.

Table 3. The common methods used in practice-orientated design to study the elements that influence daily practices

Theory	Element targeted	Social insights	Technological insights	Knowledge based insights
Practice Theory	Embodied habits	User re-enactment In-situ tasks ESM	User re-enactment Probes	Interview Diary
	Institutionalised knowledge/learning	User re-enactment SNA In-situ tasks	User re-enactment In-situ tasks Prototypes	Questionnaire Interview Diary
	Engagement/reasoning	Probes In-situ tasks ESM	Probes ESM	Interview Diary
	Technology used	User re-enactment In-situ tasks	Co-creation MIPS Prototypes	Questionnaire Interview Diary Orientation to the Lab

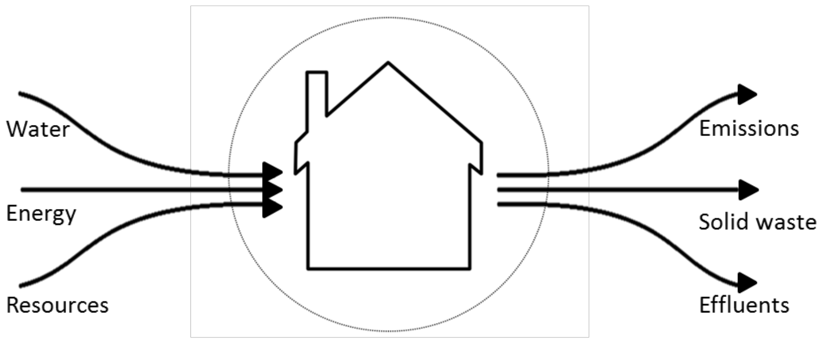


Figure 1. Household metabolism (adapted from Rodgers, 1997) considers water, energy and resource streams as an input into the home and waste streams as an output out of the home

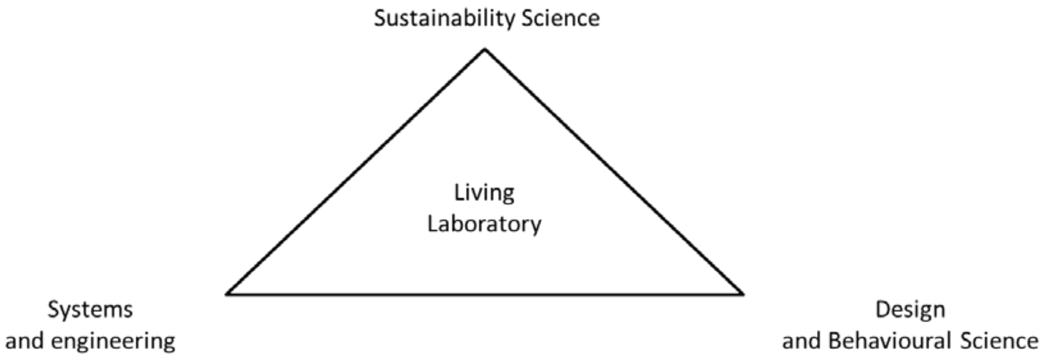


Figure 2. Three interdisciplinary disciplines provide the scientific basis for a Living Lab with a focus on innovations in sustainability (adapted from Rosado et al., 2015)

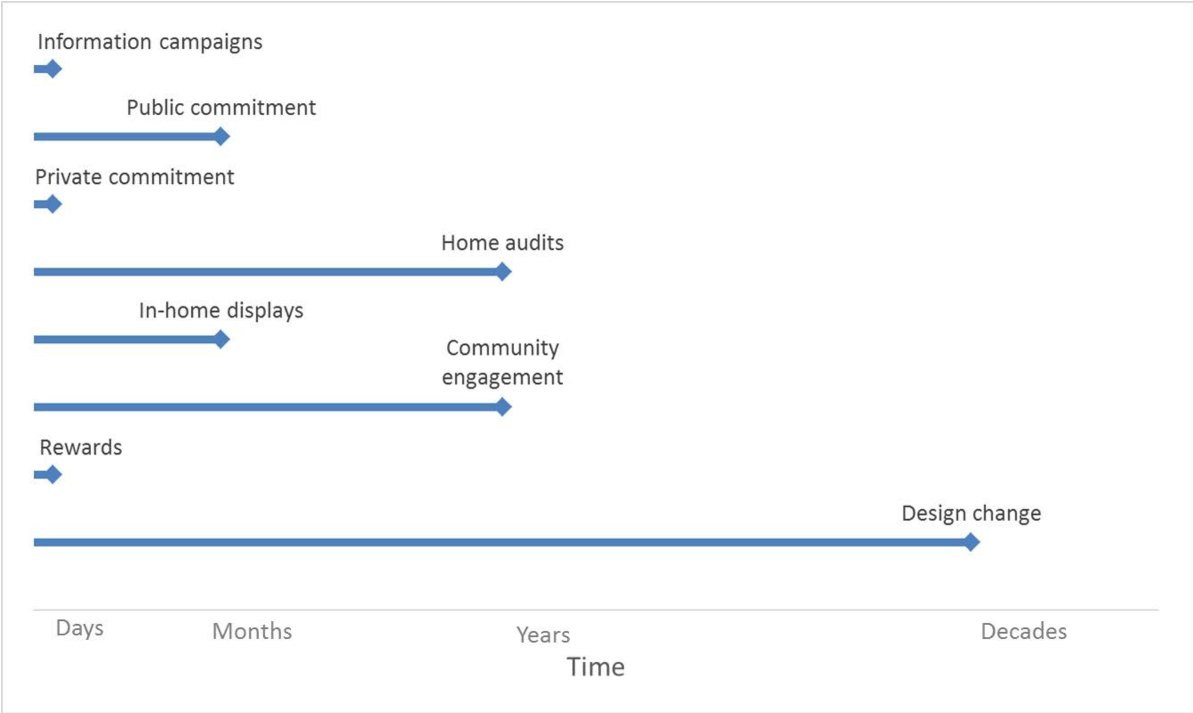
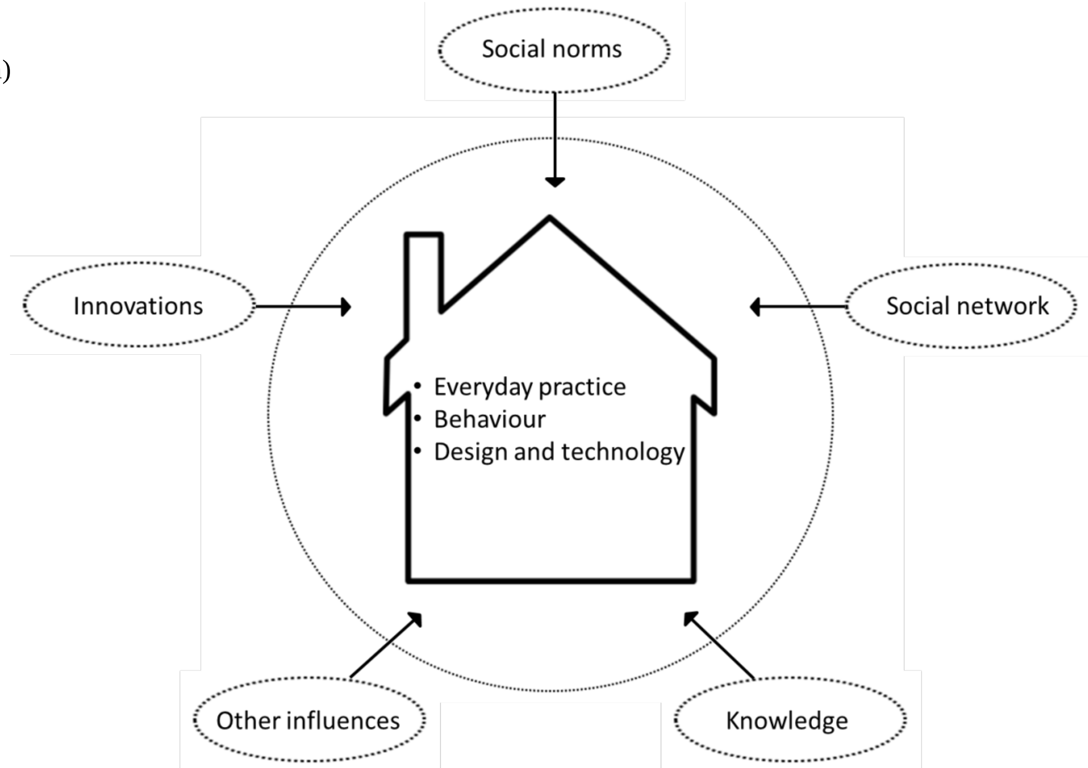


Figure 3. Schematic of estimated time duration of insights and interventions for the home environment

(a)



(b)

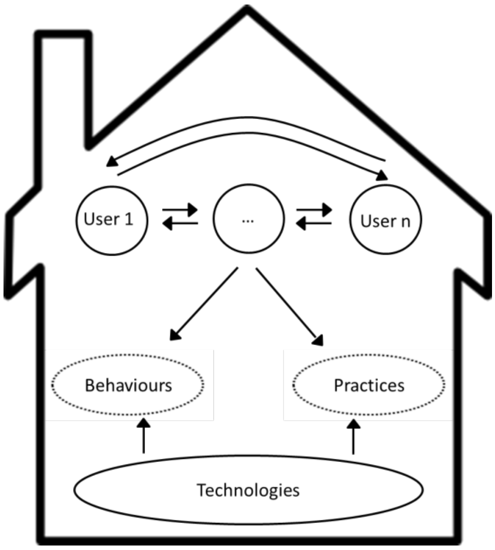


Figure 4. Influences on user's practices and behaviour within homes. (a) Wider influences on homes. (b) Interpersonal and technology influences within homes.

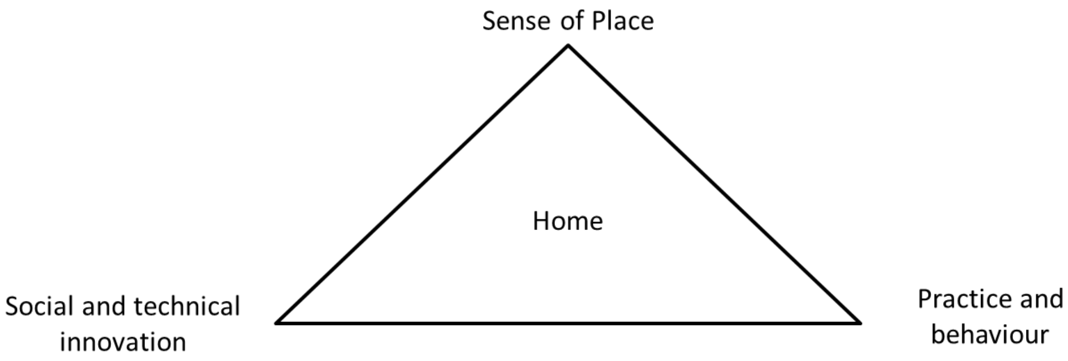


Figure 5. The triangle of Practice and Behaviour Change links the three important elements to achieve change in the home.

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RESEARCH ARTICLE

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Verification of an emerging LCA design tool through real life performance monitoring

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Abstract. Recent research has demonstrated that low-emission houses often underperform, consuming more energy than predicted by their designs. Life cycle assessments (LCA) have been employed to complement mandatory energy assessments, as they offer a more comprehensive evaluation of greenhouse gas (GHG) emissions over the building lifespan. This research monitored ten energy efficient Australian houses and recorded data about energy use and photovoltaic generation over 1 year. The houses were assessed with a relatively new LCA tool in addition to the Australian mandatory house energy assessment Nationwide House Energy Rating Scheme (NatHERS). The objective of this study was twofold: first, to evaluate the results of the assessment tools compared to actual house energy requirements and second, to understand how design, renewable energy, and occupancy can impact the overall GHG emissions of the houses. The results show that energy use is positively related to NatHERS ratings, but some of the high performance houses perform poorly and there was significant variation in energy use between houses with the same ratings. The LCA revealed that modern houses have higher embodied energy than older houses, while solar panels are not always used to their full potential. This paper attributes some of the variations between theoretical and actual energy use to construction issues and occupant practices.

1 Introduction

Recent research has shown that low energy buildings may not perform as intended due to barriers related to the inaccuracy of energy assessments [1], poor construction and verification processes [2,3] and occupant behaviour [4,5]. These issues have raised concerns about the reliability of energy assessments and their sufficiency to effectively reduce greenhouse gas (GHG) emissions in the building sector. Current building regulations have also been criticized due to their narrow scope and focus on operational energy alone [6]. The mandatory Australian residential energy assessment (Nationwide House Energy Rating Scheme – NatHERS) is even more limited, as it is restricted to reducing the energy demand for space heating and cooling. These are the largest energy consumers in residential dwellings, representing 40% of the total energy use, but the contribution of water heating and appliances, for instance, is also high and cannot be neglected [7]. Compliance inspections during the construction phase are also not mandated by NatHERS and poor construction practices, in particular related to the installation of insulation, have resulted in buildings that divert from their original accredited design [3,8,9].

As countries strive to achieve low energy buildings, the contribution of embodied energy in materials becomes more important in relative terms [10,11]. Over the last decades the number of people per household has declined while the number of households has increased [12], creating a higher demand of resources per capita and increasing the carbon footprint due to additional appliances and infrastructure. This problem is more accentuated in low density countries such as Australia, where houses are also becoming larger [13]. Life cycle assessments (LCA) are increasingly being deployed to complement mandatory energy assessments, as they offer a more comprehensive evaluation of GHG emissions over the whole building lifespan. LCAs are still voluntary, but they are now part of leading international building sustainability assessments, such as BREEAM, LEED and Green Star. Despite the comprehensive nature of LCAs, few studies have verified actual energy use compared to LCA predictions.

This research evaluates the energy performance and carbon footprint of ten Australian single detached houses considered to be above standards from a national regulation point of view. These houses were assessed with the LCA software eToolLCD in addition to the compulsory energy efficiency assessment mandated by the Australian National Construction Code (NCC). The ten studied houses have had their energy use and photovoltaic (PV)

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Table 1. Monitoring equipment installed in the ten houses.

Parameters monitored	Meters and sensors	Data logger
Gas	Ampy 750 & pulse kit for 750 meter	
Grid electricity	Schneider Electric iEM3110	Schneider Electric COM'X 200
Photovoltaic generation	Latronics kWh	

generation monitored for 1 year while occupied, enabling the comparison between predicted and actual house performance from the perspective of the two distinct rating tools (NatHERS and eToolLCD). House inspections and interviews with house occupants allowed us to obtain a complete picture of the impacts that design, renewable energy, and occupancy have on the overall GHG emissions of the houses.

2 Methodology

2.1 Profile of the ten houses

The houses selected for this research are located in the City of Fremantle, in Western Australia. The houses have mixed occupancy and designs (Appendix A), however, they all possess technologies or design components that make them more energy efficient than the average Australian home. Four of the houses have been built to meet the Australian building code requirements, which oblige all homes built since 2012 to achieve a rating of at least 6-Star NatHERS.[1] One house is classified as deemed-to-satisfy (DTS), that is, it has not been rated, but it follows prescribed designs specified by the NCC. Three houses are considered to be high performance homes, that is, their rating is above 7 Star. And finally, two houses are older homes which have been retrofitted to include insulation, PV systems and solar hot water. Nine of the houses possess a PV system and eight possess a solar hot water system.

2.2 Quantitative data collection

Monitoring equipment (Tab. 1) was installed in the ten participant houses in order to measure total grid electricity use, gas consumption and photovoltaic electricity generation in the houses that possess solar panels. The monitoring equipment consists of multiple sensors that are coupled to existing meters and transmit electric pulses to a data logger. The data logger collects the data at 15 min intervals and transmits csv files to the researchers remotely through a 2G wireless internet connection.

2.3 Life cycle assessment

The eToolLCD software was used to determine the energy and carbon emissions associated with the houses during their whole lifespan. Whilst software such as Envest, LCADesign, Gabi, and Simapro, for instance, are more internationally renowned than eToolLCD, the latter was chosen for this study as it was developed in Australia and is tailored to the local market, taking the local building construction practices into consideration. The LCA accounts for processes involved during material manufacture, transportation, assembly, maintenance, house operation, demolition and disposal. The embodied energy is calculated according to the design entered in the software by the user and modelled based on existing international LCA databases as well as local industry practices [14]. The software also considers renewable energy, fixtures, appliances and water use.

The lifespan of each home was estimated by the software based on the design quality of the building, the ownership type, the local density, the house typology (i.e. strata complex, single detached house, apartment) and the suburb redevelopment potential. Houses B, C, D and J are heritage listed which implies that their facades must be preserved; however, they all have undergone a major recent renovation and their lifespans were based on these.

Two scenarios were simulated for each house. Scenario 1 predicted energy use and embodied energy per year, calculating a predicted carbon footprint based on the average Australian household energy use and appliances, building area and NatHERS rating. For this purpose, the retrofitted and DTS houses were assumed to be the equivalent of a 6-Star NatHERS rating. Scenario 2 used inputs from real data monitoring to determine total yearly energy use. The embodied energy determined in Scenario 1 was adjusted in Scenario 2 to take the household appliances into consideration, rather than averages.

House design information was obtained through plans supplied by the house owners. House visits were also undertaken at the start of the project to collect appliance information and any other missing data not included in the plans. Missing specifications that could not be verified onsite were assumed based on industry common practices (Appendix B).

2.4 House inspections

At the end of 12 months of data collection house inspections were conducted to identify possible missing insulation and air infiltrations. A thermal imaging camera Testo 870 was employed for verification of the insulation in walls and ceilings. Other sources of heat gain were also visually detected through thermography [3].

Previous research has shown that occupant behaviour is often a cause of discrepancy between theoretical and actual energy use in the home, differences varying up to 37% [5]. Whilst occupant behaviour is not the focus of this research, semi-structured interviews were conducted at the end of

[1] Rating scores are given on a scale of 0–10, with the higher the star rating, the less the energy per square meter required to make a house thermally comfortable. Theoretically a 10-Star house should require very little or no artificial heating or cooling to be comfortable year round.

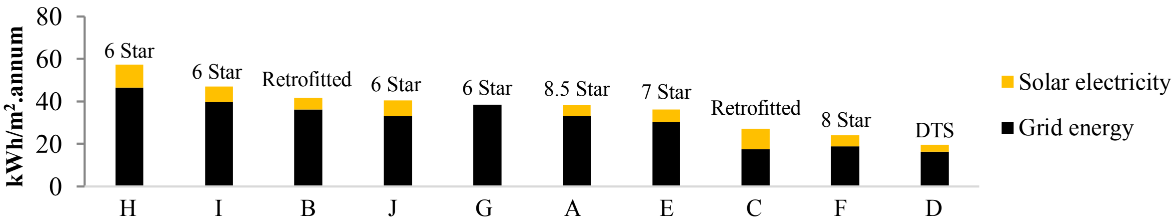

Fig. 1. Total energy use per square meter in the ten participant homes in 2015.

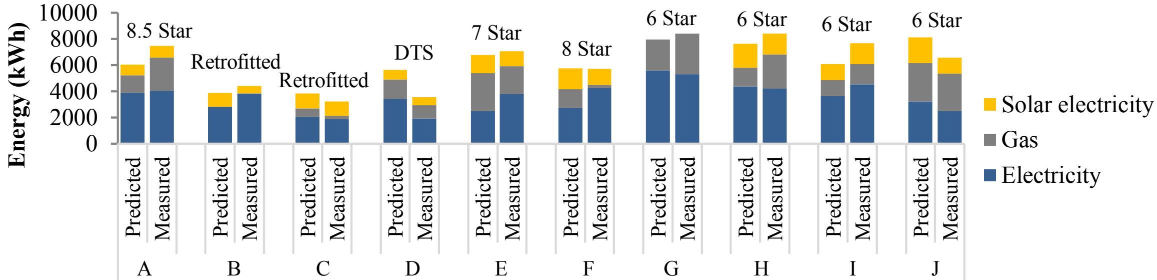

Fig. 2. Total energy prediction per year using eToolLCD compared to the total measured operational energy used in participant households during 2015.

the monitoring period to identify whether occupant practices could be affecting the LCA and NatHERS predictions.

3 Results

3.1 NatHERS

Mechanical heating and cooling are typically the highest energy consumers in Australian houses, responsible for 40% of the total energy use [7]. Hence, it is expected that higher NatHERS Star-rated houses, which in theory require less heating and cooling loads per square meter, consume less energy per area than lower NatHERS Star-rated houses. Figure 1 shows the total energy use per square meter in each of the participant houses. Results show that in general, the higher the Star rating, the lower the energy consumption per square meter. However, some surprising results were found: the 8.5-Star house used significantly more energy than the 8-Star house, the 7-Star house, the retrofitted House C and the DTS house. There is also a 33% variance between the total energy consumption of 6-Star houses with similar designs.

3.2 eToolLCD

3.2.1 Operational energy use

The eToolLCD operational energy estimates are based mostly on the heating and cooling loads required throughout the year. However, additional elements such as lighting, hot water systems and appliances are also factored into the equation. Figure 2 shows the results of the total energy prediction per year (Scenario 1) compared to the total measured operational energy used (Scenario 2) in participant households during 2015. Differences between predicted and measured energy use ranged between 1% (House F) and 58% (House D), the average variation being 17%.

3.2.2 Carbon footprint

3.2.2.1 Embodied carbon emissions

The embodied carbon of the ten houses include emissions generated from material production, transportation, construction, maintenance (recurring), building demolition and debris disposal. Recurring emissions are closely related to the buildings lifespans, which were estimated as 40 years for all the houses except for House E, which was estimated to have a lifespan of 80 years. This difference is due to House E being the only house that is part of a strata complex, sharing walls with two other dwellings. Additionally, this house was architecturally designed, allowing for flexible use of space. The other houses are all located on larger individual blocks with single ownership and lower density.

Figure 3 shows the total embodied energy as well as the embodied energy per square meter of the ten houses averaged per year. Emissions generated from material production account for 41% of the total building embodied carbon, followed by recurring maintenance over the building life cycle (26%), demolition and disposal (17%), transportation (13%) and construction (3%) (Fig. 3). The building structure is the main contributor to embodied carbon [15]. Accordingly, the floor area and the choice of structural materials are influential factors driving the overall building embodied emissions. House C has the highest embodied carbon per square meter out of the ten houses (Fig. 3), mostly due to the use of limestone (17%) for the construction of walls. Other houses presenting high embodied carbon per square meter include modern houses built within the last 10 years (Houses H, I, A, G and F). These houses' structures are mostly made of brick, concrete and steel, which possess high embodied carbon, producing, respectively, 13%, 12% and 9% of the total house embodied emissions. On the other hand, three out of the four houses possessing the lowest embodied carbon per square meter

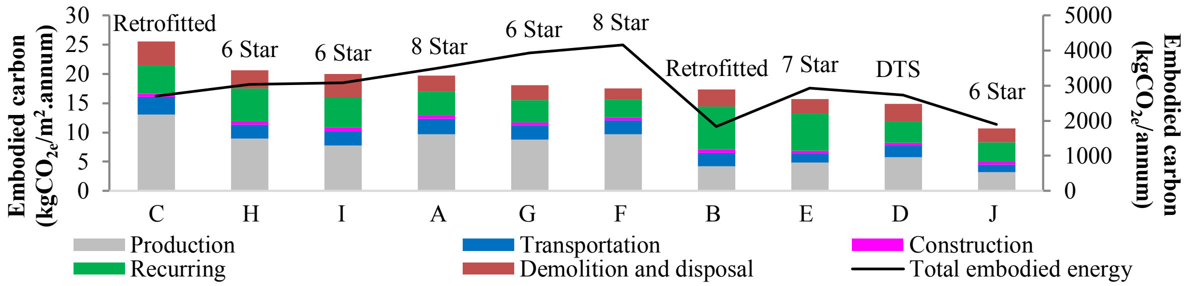

Fig. 3. Yearly embodied carbon per square meter categorised into the five building life cycle stages and total yearly embodied energy for each house.

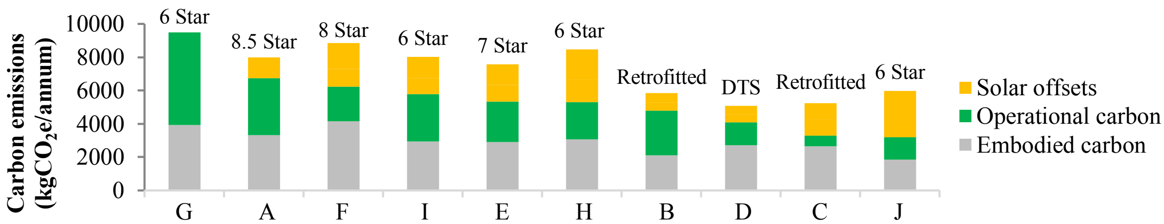

Fig. 4. Yearly carbon footprint and solar offsets.

(Houses B, D and J) were built in the first half of the 1900s and their structure is mainly timber. These houses generate relatively low (31%) carbon emissions during the material production stage and the highest percentages of emissions are related to maintenance. Despite the high proportions of concrete and steel in its structure, House E presents a low yearly embodied carbon per area due to its high lifespan. Embodied emissions in this house are mostly due to maintenance, including the use of refrigerants and replacement of solar panels, causing, respectively, 15% and 7% of yearly embodied carbon emissions.

For the total yearly embodied carbon of each house, the houses with the highest embodied energy are all modern 6–8.5-Star houses (F, G, A, I, H) (Fig. 3). Not only were they built with high embodied carbon materials, but they also have large floor plans in comparison to older houses in the same region and similar socio-economics. The average area of new homes (built after 2006) in this sample is 186 m^2, while old houses average 130 m^2. House F (8 Star), for instance, has 238 m^2 of habitable area in addition to a brick double garage, a brick fence and cement driveways. In contrast, House B's habitable area is 106 m^2 and the house structure is timber. Its total yearly embodied carbon emissions are 2.3 times less than House F.

3.2.2.2 Total carbon emissions

Solar panels offset on average 51% of the houses yearly operational carbon emissions (Fig. 4). Without these offsets, operational emissions would represent 58% of the total emissions over the building lifetime. However, renewable energy reduces this proportion to 41% and building materials become the main contributor to GHG emissions. As a result, modern houses have higher total carbon footprints as compared to older homes due to larger floor plans and structural materials, as previously discussed.

It has been shown, however, that 51.8% of PV systems in Australia do not perform to capacity [16]. This research has found that four of the houses possessing PV systems do not operate optimally. House J's system, for instance, was installed on a South facing roof and according to the eTool model, it is generating 6% less electricity than predicted. House D's PV system is shaded by a neighbouring tree, generating 15.7% less electricity than expected. Finally, the PV system on House B is generating 34.6% less electricity than expected. This is likely due to dust accumulated on the panels surface, as the owners revealed that the panels had never been cleaned. Monitoring data also revealed that the PV circuit breaker of House F tripped after wet weather events and stopped generating electricity for 3 weeks as the failure was not immediately detected by the house occupants.

3.3 House inspections

Thermography revealed that all the houses presented insulation gaps in the ceiling and walls mostly around the corners (Fig. 5a). Missing insulation was also commonly found above attic hatch doors and around downlights (Fig. 5b). The efficiency of water heaters in some cases was compromised due to the lack of insulation around outlet pipes (Fig. 5c). The inspections also revealed that some houses did not possess shading devices on West and East facing windows, becoming very hot in summer. These design flaws could be affecting the operational component of the LCA results.

Occupant practices were also considered as a potential contributor to the variations found between predicted and actual energy use. Whilst these behaviours and practices were not explored in depth in this study, they could explain, for instance, the difference of 1200 kWh between predicted and measured grid electricity for House D (Fig. 2). Interviews

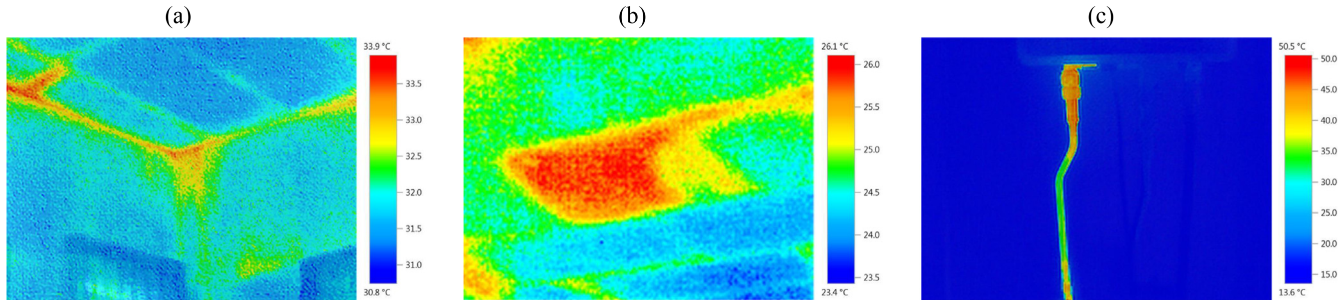

Fig. 5. Thermal images of (a) ceiling corners; (b) down lights and (c) hot water system outlet pipe.

with the house occupants revealed that while they possess a reverse cycle air conditioner unit, they prefer to use a fireplace to heat the house in winter and they rarely use the cooling system in summer. House H, on the other hand, uses significantly more gas than expected (Fig. 2). According to the house owner, her children enjoy having long showers. Unexpected behaviours are not considered by either NatHERS or eToolLCD but can significantly affect the results and should be further explored.

4 Conclusion

Ten houses were monitored over 1 year and energy use was compared with NatHERS and LCA estimates. While high performance houses used less energy per square meter than 6-Star houses, there was significant energy variation between houses with the same rating. eToolLCD predictions also differed up to 58% from actual energy use. Reasons for these variations included issues associated with construction and maintenance. Insulation gaps were found in all houses and are believed to be impacting on thermal comfort. It was also revealed that PV systems are underperforming due to wrong placement, lack of maintenance and system failure. Interviews with households also revealed that occupant practices vary considerably between houses, ultimately affecting dwelling performance. As houses become more energy efficient, the contribution of embodied energy becomes higher as a proportion of total life cycle emissions. This study shows that embodied energy contributes 59% of total emissions in houses that possess renewable energy. It was also revealed that the modern houses in this study generate higher life cycle emissions compared to older houses due to the use of high embodied energy materials in their construction as well as possessing larger floor plans. While current policies target the reduction of residential GHG emissions through energy efficiency measures, this research shows that embodied energy should be addressed. Moreover, maintenance, PV performance monitoring and occupant awareness should also be considered. It is recommended that further research is conducted to offer a better understanding about patterns of occupant practices and their relationship to energy use at a home level.

5 Implications and influences

The research findings have implications for policy makers who currently focus on reducing residential greenhouse gas emissions through simulations of operational energy use. The findings from this research show that a more holistic approach needs to be taken, considering all stages of the building lifecycle.

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Appendices

Appendix A. Dwelling characteristics and occupancy.

House	Year built	Typology	Floor area (m^2)	Design	Technologies	NatHERS/ description
A	2009	Detached house	177	Double brick walls; concrete slab; R3 ceiling insulation; R1.5 roof insulation; North orientation.	1.2 kW PV system; solar hot water with gas booster	8.5 Star
B	1950	Detached house	106	Timber frame walls with R2 insulation; R2.5 ceiling insulation; suspended timber floor with R1.5 insulation; North orientation.	1.5 kW PV system; solar hot water with electricity booster	Retrofitted
C	1899	Detached house	106	Limestone and double brick walls; suspended timber floor and concrete slab; R3.5 ceiling insulation; R1.5 roof insulation; South-East orientation.	1.68 kW PV system; solar hot water with electric booster	Retrofitted
D	1920	Detached house	183	Double brick and timber frame walls with R3.5 insulation; concrete and suspended timber floor; R3 ceiling insulation; R1.5 roof insulation; North orientation.	1.1 kW PV system; solar hot water with gas booster	Deemed-to-satisfy
E	2011	Strata complex	186	Rammed earth and insulated panel walls with R2.5 insulation; concrete slab; R3 ceiling insulation; R2.5 ceiling insulation; North orientation.	2 kW PV system; instantaneous gas water heater	7 Star
F	2011	Detached house	238	Rammed earth and double brick walls with R2.5 insulation; concrete slab; R3 ceiling insulation; R2.5 roof insulation; North orientation.	2.28 kW PV system; solar hot water with electric booster	8 Star
G	2013	Detached house	218	Double brick walls; concrete slab; R4 ceiling insulation; West orientation.	Solar hot water; with electric booster	6 Star
H	2013	Detached house	147	Double brick walls; concrete slab; R3 ceiling insulation; North orientation.	2.66 kW PV system; solar hot water with gas booster	6 Star
I	2013	Detached house	154	Double brick walls; concrete slab; R4 ceiling insulation; North orientation.	1.8 kW PV system; solar hot water with gas booster	6 Star
J	1901	Detached house	177	Timber frame walls with R2 insulation; concrete and suspended timber floor; R4.5 roof insulation; South orientation with North facing clerestory.	3.5 kW PV system; instantaneous gas water heater	6 Star

Appendix B. Major missing specification assumptions for the LCA modelling.

Component	Assumption	Justification
Material quantity for the roof structure	An eToolLCD template for the roof structure was used. It calculates the material quantity based on the roof area and pitch.	The template is based on common construction practices.
Ceiling insulation	For houses with ceiling insulation but no specification, an R-value of 2.5 was assumed.	This is a common R-value used in the ceiling.
Construction materials in the heritage part of House C	Limestone walls and suspended timber floors.	These were common building materials used in the early 1900s in the City of Fremantle.
Staircases	An eToolLCD template for timber staircases was used.	The template is based on common construction practices.
Suspended floor structure	An eToolLCD template for elevated wooden stilts was used when specific details about the underfloor structure were not available.	The template is based on common construction practices.
Ducted air conditioner duct length	An eToolLCD template for duct air conditioner was used. The length of the duct was estimated based on the house habitable area.	The template is based on common construction practices.
Tiled areas	The tiled area of bathrooms, kitchens and laundries was estimated.	0.5 mm thick tiles have a relatively small embodied energy compared to a brick wall. This estimation does not have a significant impact in the overall embodied energy of the house.

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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.

Keywords Living Labs · Everyday practice · Behaviour · Design · Thermal comfort · Renewable energy

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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

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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

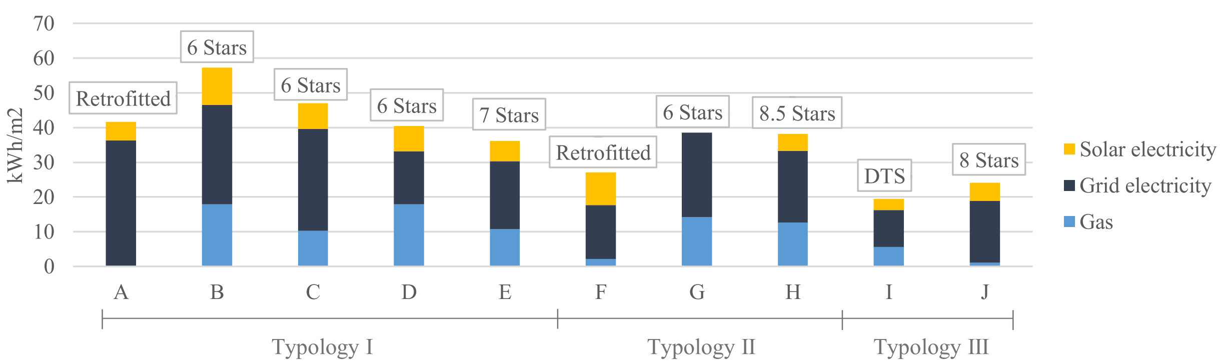

Fig. 1 Energy use per square metre in the ten homes in 2015 grouped by house typology. Typology I includes houses that possess mechanical heating and cooling; typology II are houses that only possess mechanical heating; and typology III are houses that do not possess or do not use mechanical heating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

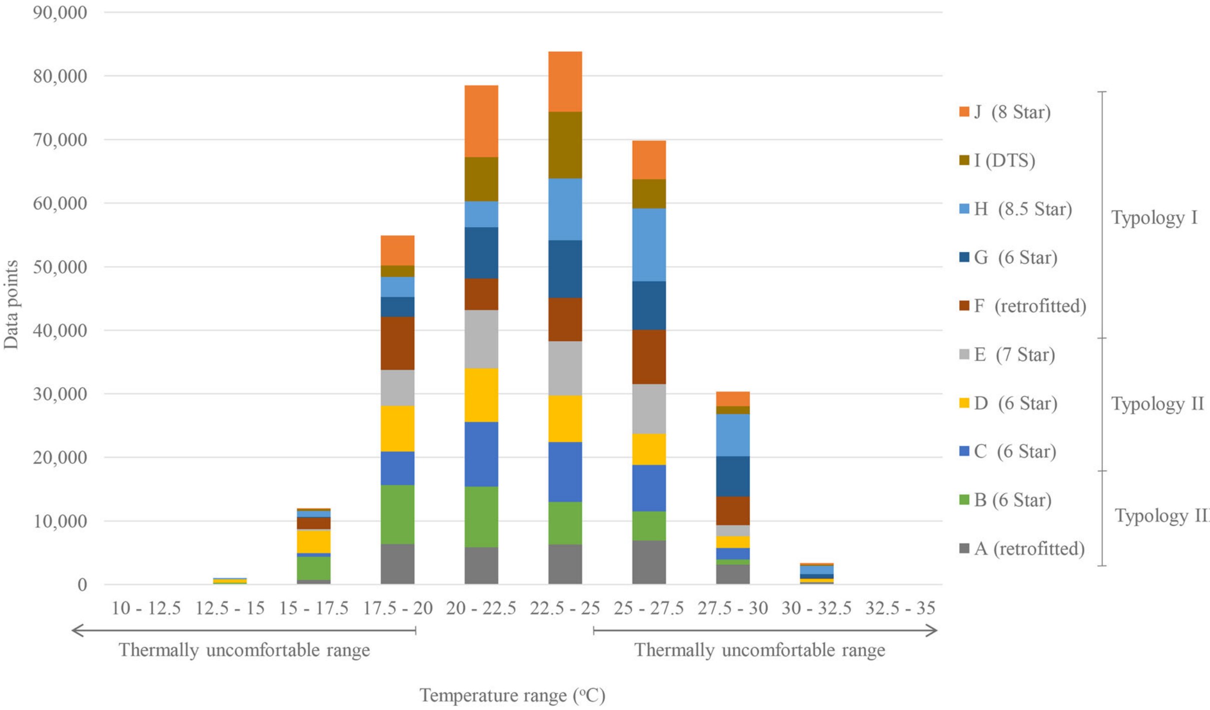

Fig. 2 Temperature distribution in the different houses throughout the year of 2015 (n = 35,040 per house). The higher the temperature distribution range, the higher the household occupants' discomfort in winter and summer

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).

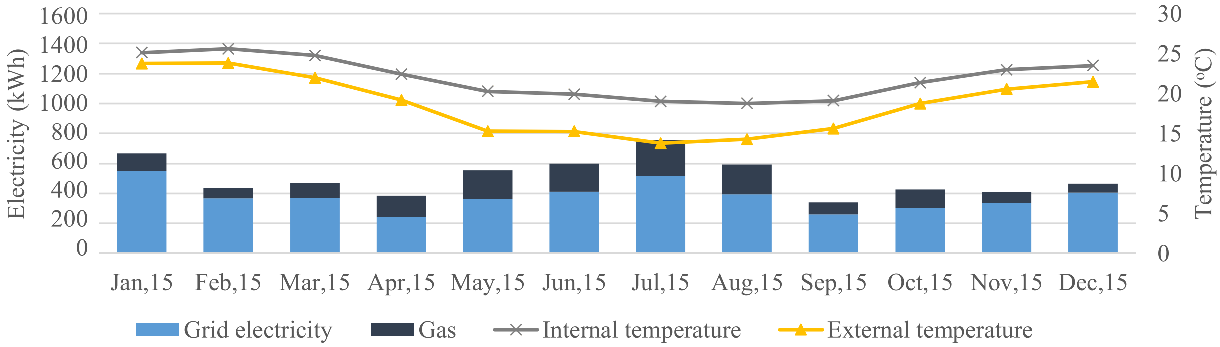

Fig. 3 House C is an example of typology I, which consists of houses that possess mechanical heating and cooling. Their annual energy profiles comprised two peaks, one during the Australian summer (December to March) and one in winter (June to September). The house shown in this example has a ducted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

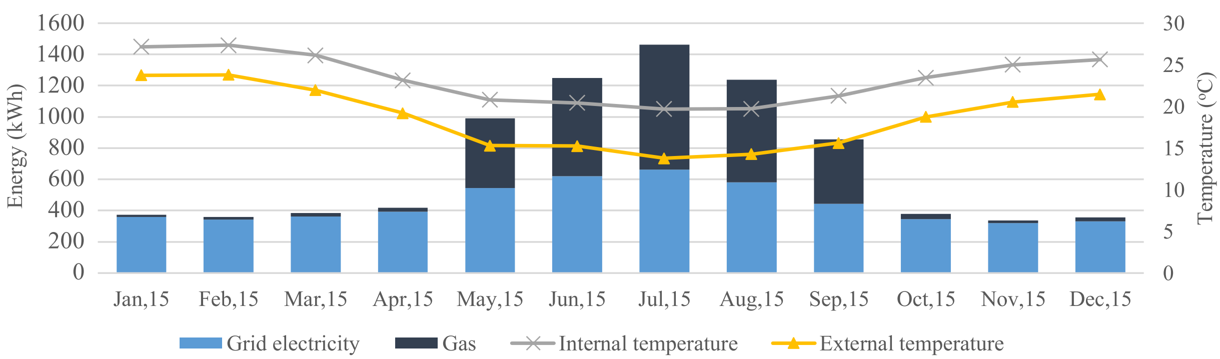

Fig. 4 House G is an example of typology II, which consists of houses that possess mechanical heating only. Their annual energy profiles comprise of one energy peak in the Australian winter (June to September). The house shown in this example has a portable gas heater which is used in winter

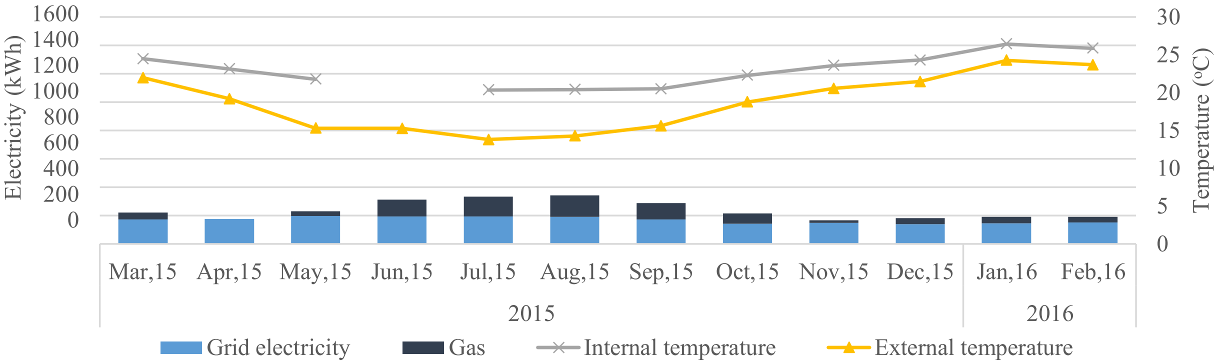

Fig. 5 House I is an example of typology III, which consists of houses that have very limited or no mechanical heating or cooling, keeping a fairly constant energy profile through the year. The slight increase in gas use in winter is due to water heating

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

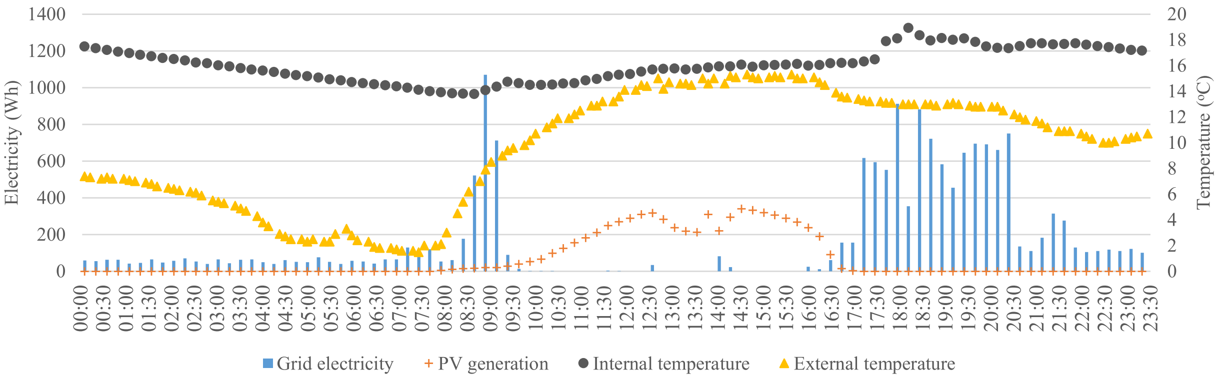

Fig. 6 Diurnal electricity profile of house B on the 9th of July, coldest day of 2015. The minimum temperature in this house was 13.8 °C at 08.45. This house has a ducted air conditioner for heating. The noticeable increase in internal temperature alongside a high electricity consumption indicates the 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.

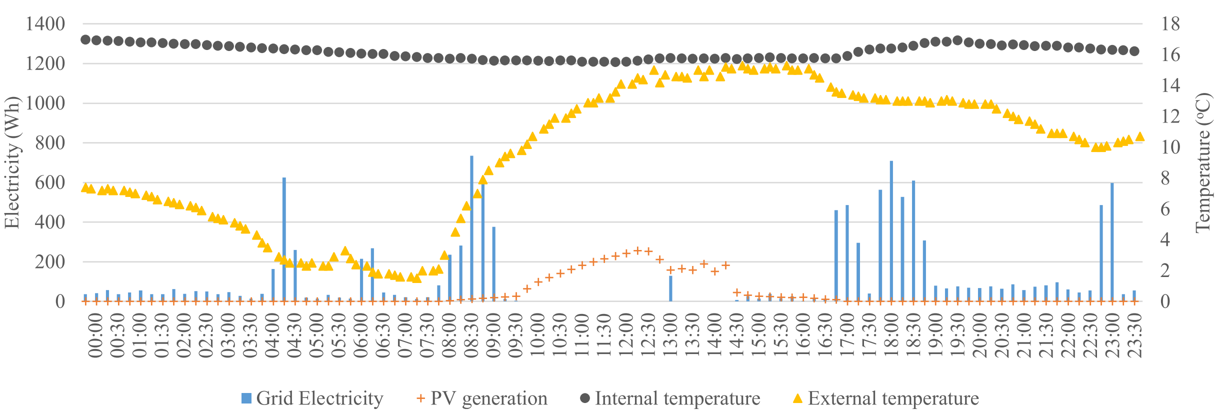

Fig. 7 Diurnal profile of house F on the 9th of July, coldest day of 2015. The minimum temperature inside the house reached 15.7 °C at 07.30. This house has a portable oil heater powered by electricity. Electricity use is higher in the morning and evening, but the temperature increase in the house only 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

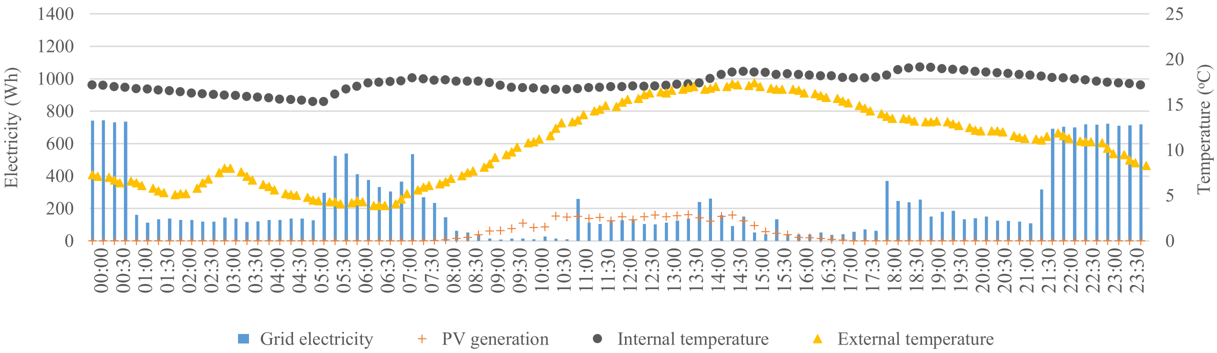

Fig. 8 Diurnal profile of house A on the 13th of July, second coldest day of 2015. This date was chosen here as this house experienced data loss on the 9th of July. This house reached a minimum internal temperature of 15.3 °C at 05.00. This house has a reverse cycle air conditioner for heating. An increase 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).

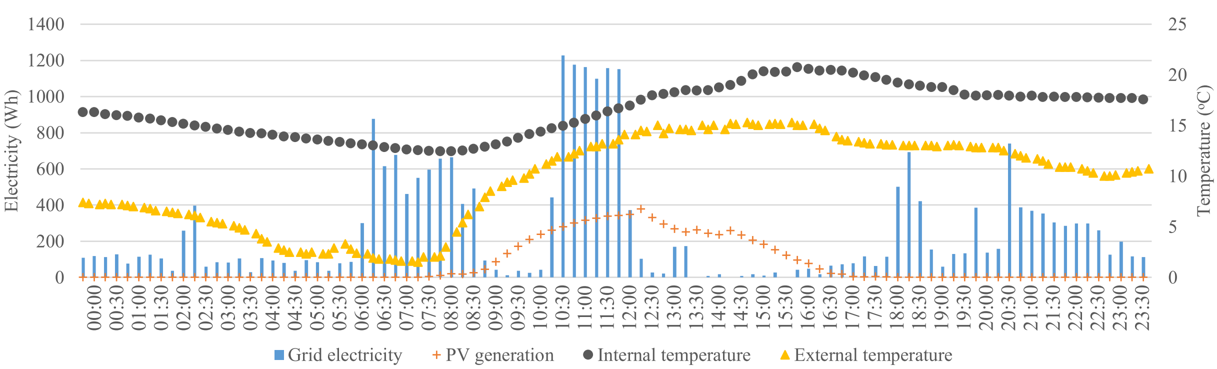

Fig. 9 Diurnal profile of house D on the 9th of July, coldest day of 2015. The minimum temperature in the house was 12.4 °C at 08.30. This house has an electric floor heater in the living area. It is assumed that the use of the heater is associated with an increase in internal temperature alongside an 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

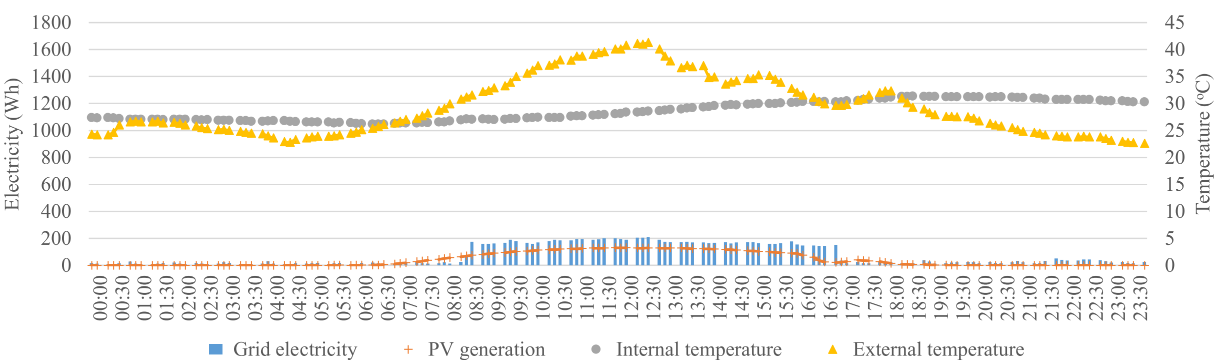

Fig. 10 Diurnal profile of house A on the 5th of January, hottest day of 2015. The air conditioner was on during the hottest hours of the day and was turned off as the external temperature started to drop

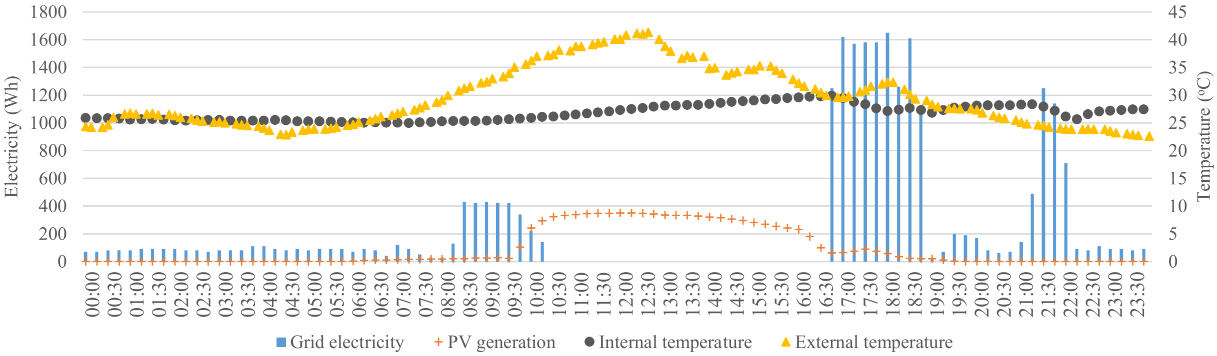

Fig. 11 Diurnal profile of house C on the 5th of January, hottest day of 2015. The air conditioner is turned on in the evening a few hours at a time

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

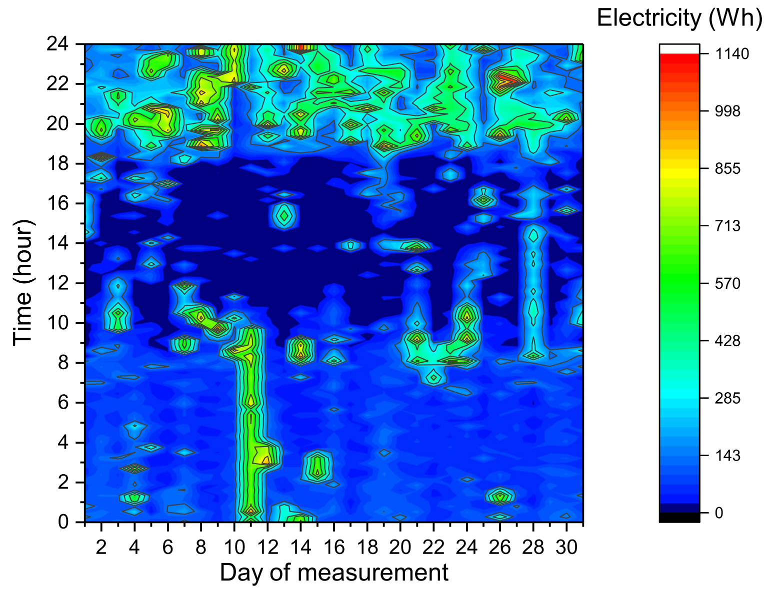

Fig. 12 Grid electricity contour plot of house B in July 2015 at 15-min intervals. Five hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by the photovoltaic panels, which reduce the need for grid electricity. 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

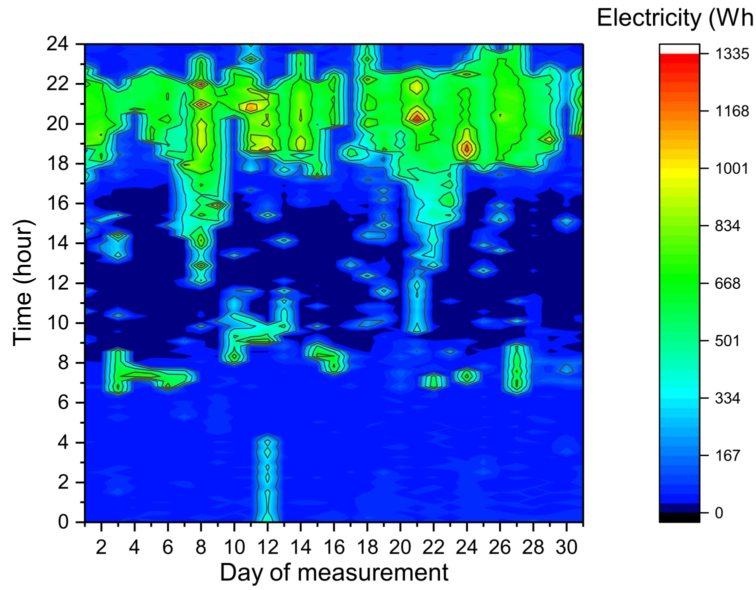

Fig. 13 Grid electricity contour plot of house E from the 10th of July to the 9th of August 2015 at 15-min intervals. Five hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by photovoltaic panels, which 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:

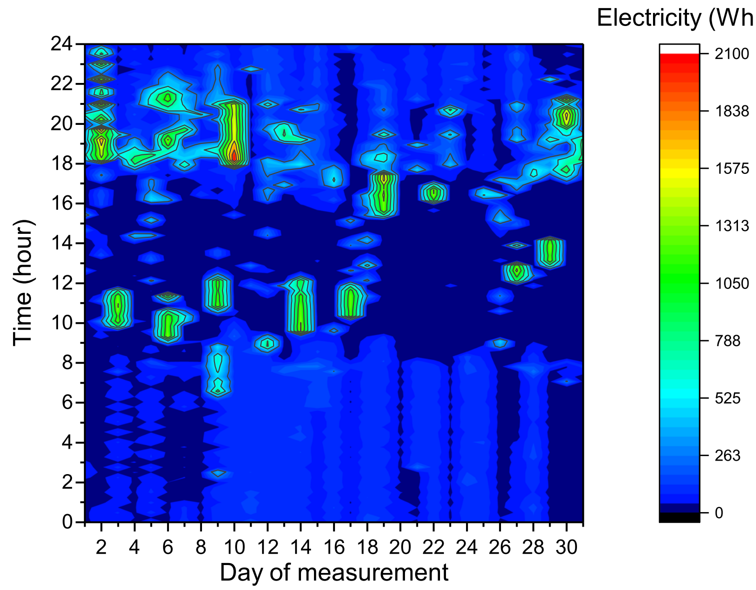

Fig. 14 Grid electricity contour plot of house D from the 3rd of July to the 2nd of August 2015 at 15-min intervals. Seven hundred watt-hours or higher electricity use (green shades) can be attributed to the use of the heater. The navy band during daylight hours is caused by photovoltaic panels, which 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.

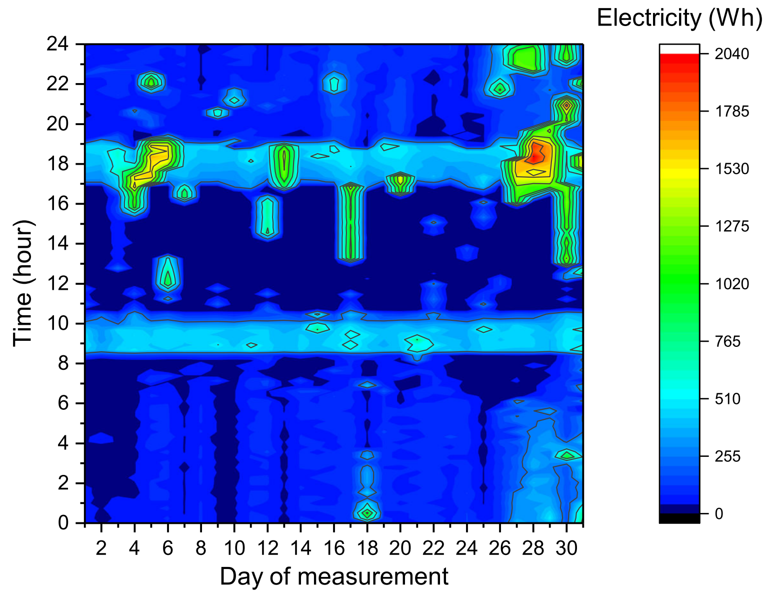

Fig. 15 Grid electricity contour plot of house C in January 2015 at 15-min intervals. The navy band during day hours shows the impact of the photovoltaic panels on grid electricity consumption. The PV system covers small electricity needs, but higher loads such as ambient cooling requires additional 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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Influencing energy and water use within a home system of practice

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A B S T R A C T

Approaches that attempt to influence resource use in the home often consider the building system alone, without due consideration of occupants and their practices. However, occupants interact with technology and ultimately affect energy and water metabolism in the home. This research used an explanatory design mixed method approach to investigate the energy and water use in eight homes over a two-year period, before and after an intervention based on persuasive behaviour change. Each home was considered as a system of practice and results were analysed in terms of overall resource reduction, changes in practice and changes made to the building systems. It was revealed that five of the homes succeeded in reducing their resource use through the two years. Most changes were achieved through affecting technology as an element of practice. Automation was shown to enable the dis-interlocking of practices from aligned and interlocked routines and can be considered an effective solution to influence resource use in the home.

1. Introduction

Minimizing the negative effect of occupant behaviour on the energy and water metabolism of homes has been the subject of recent research. Approaches based on socio-psychology theories [1–3] that place the individual at the center of the analysis have been extensively discussed in the literature [4–6]. These typically involve methods to persuade change [7], such as information campaigns and feedback, and are delivered through information and communication technologies (ICT) [4,8]. However, this approach ignores the interaction of occupants with the physical infrastructure of the home. As buildings become more energy and water efficient and incorporate technologies such as solar photovoltaic panels (PV) and smart systems, it is expected that the resource use in the home should be reduced. Nevertheless, rebound effects often occur [9,10] and the technologies are forgotten if they do not meet occupant needs or do not become an integral part of user routines [11–13].

Practice theory [14,15] posits that rather than focusing on values, attitudes and social norms, the emphasis should be on influencing the elements that constitute daily practices, which are defined as meaning, skill and technology [16,17]. Meaning is the reason for a practice to be undertaken, which is influenced by personal emotions, perceptions and values [14]. Skill refers to the knowledge of the practice and understanding of its implementation [16]. Technology denotes the physical elements that are involved in the execution of the practice [18]. The three elements of practice are bound together and a modification in any of them affects the performance of the practice and ultimately the use of resources that support it. The continual reproduction of everyday practices forms a routine, where each practice and practices are interdependent. This mutual dependency between everyday practices is termed interlocking [19,20].

Occupants of the same home may have distinct driving-factors for water and energy use [21], different interlocking practices and distinct practice-as-entities; that is, they ascribe different connotations to the elements of practice [22] thus diverging in the manner they perform it [23]. Individuals may also vary their own practices in accordance with the meaning they attribute to them. For instance, the meaning for personal showering can be cleanliness, warmth or relaxation and it follows that the duration of personal showering varies [16,24–26]. A shower that is motivated by the need for cleanliness, would likely be shorter than a shower that is motivated by the need for relaxation, which might be driven by sensorial feelings [27]. Practices also vary according to place and context and the relationships within this context [28]. For instance, the timing of practices usually varies between weekdays and weekend due to realignment of routines and interlocking practices [29]. It is presumed that a change in place, hence a variation in infrastructure, would also affect the performance of individual practices

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[28]. It has been proposed that the latter are combined in bundles through space and time [20], which suggests that the understanding of resource and technology use in the home requires the home itself to be viewed as a system of practice (SOP).

Due to the complexities associated with the home SOP, influencing practices can be challenging without a more complete understanding of the home system. Our hypothesis is that resource reduction in homes can be realised through one-off changes in the physical infrastructure of the building or technological innovation rather than through affecting everyday practices. However, automation could enable the dis-interlocking of specific resource intensive practices from the system.

This research is a longitudinal investigation of variations in energy and water use as well as resource intensive practices in eight homes for two years, the year before and the year after an intervention designed for persuasive behaviour change. This research contributes to the understanding of the home SOP and the interactions between occupants and technologies.

2. Methodology

The dynamics of change are followed through an explanatory design mixed method approach, consisting of detailed quantitative and qualitative data collected over the two-year period.

2.1. Project participants

Eight homes located in the City of Fremantle, Australia, were selected as part of this research. The selection process was conducted through a media advertisement in the local newspapers and a mail drop. Interested households were further scrutinized to provide a variety of home demographics (Table 1). The selected homes possess energy and/or water efficient design elements that distinguish them from the average Australian household (Appendix A). These homes also follow principles of passive solar design to varying degrees [30], that is, they are oriented North and use direct sunlight as well as thermal mass for warmth in winter. In summer, the use of shading devices as well as natural breezes can prevent these homes from becoming too hot. Operating such a home can be challenging as it requires occupants to understand the design principles and to actively open and close windows and curtains at the right times of the day to maintain comfortable internal temperatures.

2.2. Research design

The homes were converted into Living Laboratories (LLs) to provide home insight [31] for a period of two years, from December 2014 to December 2016. LLs are real-life places where innovative technologies are co-created by multiple stakeholders, with prototyping and testing in the real life context [32–35]. The LLs in this research generated insight into the everyday practices of households as well as their interaction with technologies. The first year of research established a baseline and an understanding of user practices. Participants were not disturbed during this period. At the beginning of the second year, homes were subjected to a targeted persuasive behaviour change intervention [7] that remained until the end of the project.

This research focuses on understanding barriers to change as well as resource intensive practices in the home, such as garden irrigation, personal showering, the use of ambient cooling and heating as well as the use of a pool pump. An explanatory design mixed method approach [36] was chosen to conduct data analysis, following up from previous LLs research [31,37,38]. Qualitative data from semi-structured interviews were used to interpret quantitative data from a home monitoring system. This section describes the quantitative data collection, the behaviour change program, the qualitative data collection and finally, the methodology used to analyse the data.

2.2.1. Quantitative data collection

Monitoring equipment was installed in the participant homes to measure gas, grid electricity, mains water and rainwater use as well as internal temperature in the living area and solar electricity generation over the two years (Appendix B). Sensors were connected to existing meters, transmitting pulses to a data logger (Schneider Electric COM'X 200). The latter collected the data at 15 min intervals and transmitted csv files to the researchers remotely, through a 2G wireless internet connection. At the start of the second year, data was also transmitted daily from the data logger to an online platform (Power Monitoring Expert 7.2) that was programmed to enable data visualization. Solar electricity use was not measured through the monitoring system; instead the data was obtained through electricity bills requested from the households at the end of each calendar year. However, one of the homes (home 5) chose not to provide their bills to the researchers. Detailed weather data including external temperature, rainfall, relative humidity and solar radiation was obtained from a nearby weather station (Vaisala WXT520).

2.2.2. Behaviour change intervention design

The persuasive behaviour change program was designed based on an analysis of 34 peer reviewed articles targeting energy and water reduction in the home. Best practices were analysed according to the percentage reduction of water or energy use in the homes. The most successful interventions [39–42] encompassed a combination of strategies based on established socio-psychology theories [1–3] including social interaction (e.g. coaching, audits, community courses), goal setting, prompts, comparison with other households, targeted information provision and real-time feedback delivery through ICT. The effectiveness of feedback systems to reduce long term resource use is unclear; some researchers have shown that they generate positive outcomes [43–46] while others believe them to only be relevant in the short term [7,11,12]. Nevertheless, individual response varies with approach and therefore mixing technical and social approaches may lead to improved consumer engagement enabling change [47].

The behaviour change program in the eight LLs was initiated with a home visit at the start of the second year of quantitative data collection, which corresponded to the onset of the hot months of the Australian summer (December 2015). Initially household members were shown a historical summary of their energy and water use relating to the previous year and asked to comment on reasons for using more or less energy or water in one month in comparison to others. Following this informal conversation, an energy and water audit was conducted with the objective of identifying opportunities for resource reduction during summer. The energy component of the audit focused on explaining principles of passive solar design to increase thermal comfort in summer, as well as the identification of unwanted sources of heat gain through a thermal imaging camera (Testo 870). However, other measures were also discussed, such as programming appliances to be used during daylight hours when the PVs were producing electricity, using the washing machine with full loads or reducing the temperature of the hot water system to 60 °C. Measurement of standby power use from diverse appliances was also conducted and individuals were encouraged to switch them off when not in use. The water component of the audit focused mostly on the practices of irrigation and personal showering, which are the most water intensive practices in the home [48,49]. Households were informed about the local water company guidelines, which rule that reticulated irrigation can only be switched on twice per week on specific days and

Table 1
Measurement of the grid electricity, gas and water use variation between 2015 and 2016.

Resource	Home							
	1	2	3	4	5	6	7	8
Electricity	constant	constant	decrease	constant	constant	increase	constant	increase
p-value	0.491	0.507	<0.05	0.204	0.165	<0.05	0.707	<0.05
Gas	increase	N/A	decrease	constant	constant	constant	decrease	constant
p-value	<0.05		<0.05	0.578	0.490	0.349	<0.05	0.912
Water	decrease	decrease	decrease	decrease	constant	constant	constant	constant
p-value	<0.05	<0.05	<0.05	<0.05	0.541	0.994	0.124	0.083

times [50]. A gardening specialist conducted this part of the audit to provide advice about native plants, plant health and watering requirements. Energy and water conservation factsheets as well as a resource reduction checklist were provided at the end of the audit. A written reduction target was also requested for each household with the primary objective of generating cognitive dissonance [1].

During this home visit participants were also provided access to the Power Monitoring Expert website, which showed all their data in near-real time (one day delay) or alternatively on a weekly, monthly or yearly basis. Individuals could also navigate through the website and visualize graphs comparing themselves to other project participants. This strategy was based on the assumption that resource use is reduced when occupants are aware of peer utilization [51]. All homes were coded to protect privacy and participants were given their unique codes.

In addition to this near-real time feedback, monthly reports were e-mailed to each participant to act as a prompt. These had the objective of complementing the online dashboard by providing an interpretation of results as well as tailored tips. Resource use was displayed as the equivalent of CO_2 emissions and costs. An injunctive norm [52] in the form of a word of congratulation or encouragement was also given depending on whether the set target was achieved or not for the month.

Second home visits and audits were conducted the following winter (June 2016) and focused on the use of the ambient heating and hot water system. The thermal imaging camera was used again at this point to identify heat losses through gaps in the insulation, door frames, windows and floorboards. Participants historical data was once again discussed and messages provided during the first home visit were reinforced.

2.2.3. Qualitative data collection

Three longitudinal semi-structured interviews were conducted during the second year of the project with all household members present when possible; the first interview was during the summer home visit, the second was during the winter home visit and the final was at the end of the research at decommission (six months after the second interview). Longitudinal interviews are a method used to identify changes over time and obtain an in-depth understanding of participant's perspective [53]. To minimize fatigue, questions were carefully formulated and interviews were kept short (20–30 min) and informal. The second and third interviews were framed as feedback sessions for participants to share their experience of being part of the project and comment on the quality and usability of the website and reports.

The interviews were designed to allow participants to articulate views with regards to energy and water conservation, perceived barriers and opportunities for changing resource use, usual practices involving energy and water around the home and the involvement of family members. Follow up interviews included additional questions about physical changes made to the home since the previous audit, changes to practices, use of the website and monthly reports and lessons learnt from the project. For a complete list of interview questions please refer to Appendix C.

2.3. Data analysis

2.3.1. Behaviour intervention effect

Data analysis started with a comparison of electricity, gas and water use for each home between the two years (2015 and 2016) to evaluate the effects of the behaviour change intervention. Weather (temperature, humidity, rainfall and solar radiation) varied significantly between the two periods, affecting the energy used by ambient cooling and heating systems as well as garden irrigation. To take these variations into account, an advanced data analysis model was required. The multiple regression model is one of the most common methods to analyse the relationship between energy cost, water use and environmental factors [54,55]. However, this method is limited to investigations of non-linear relationships and lacks flexibility, when high temporal resolution data is involved [56]. Machine learning methods, such as support vector machines and neural networks [57–59] have been used to overcome the limitation of the multiple regression model, as they allow the development of a wider range of simulated shapes to model energy and water use. However, these methods are less interpretable, since it is not easy to understand the relationship between each individual predictor and the response [56].

To balance flexibility and interpretability, this study applied generalized additive models (GAMs) to estimate the potential energy and water cost due to environmental variation. GAMs provide a general framework to allow non-linear features of each variable, while keeping the additivity [60]. The variables used in this study include temperature, solar radiation, relative humidity and precipitation. Different combinations were adopted depending on the energy and water use purposes.

After excluding the impact from environmental factors, the total number of residuals and intercept was viewed as a true indicator of occupant behaviour for energy and water use. The occupant behavior change in two different years was analysed through the Wilcoxon signed-rank test [61]. This is a non-parametric statistical hypothesis test used to assess the variation between two matched samples, when the samples are not normally distributed.

2.3.2. Practice analysis

This research was also planned to assess variations in practice, in particular cooling, heating, irrigation, personal showering and the use of a pool pump, which are the most resource intensive practices in Australian homes [48,49]. With a total of 70,080 data points for each meter (grid electricity, gas and water) over the two years, the first step in the analysis of home practices was the identification of the data relating to specific practices. Algorithms were developed to process the data. The practice of ambient cooling in summer was identified by a significant increase in electricity followed by a decrease in internal temperature. In winter, the practice of ambient heating was identified by a significant increase in energy (electricity or gas depending on the heating system) followed by an increase in internal temperature. The placement of the temperature sensor in the living area ensured that kitchen practices were not mistaken for the use of ambient heating. Consequently, cooling and heating practices were only observed for the primary system in the living area. Secondary heaters and air conditioners (AC) located in bedrooms, kitchens or bathrooms were not considered in this research.

Garden irrigation is responsible for the highest water use in Australian homes [49]. Accordingly, the highest water volumes (above 120 L/interval) in the data during the summer months were attributed to the practice of irrigation. The exception is home 4, where only plants in pots are watered and which has a separate water meter measuring use in the garden. Personal showering is the second most water intensive practice in households and responsible for the highest water use during winter. Water volumes for personal showering were identified in the winter months by an increase in water use alongside an increase in gas or electricity use for water heating. The water volume ranges identified for personal showers during winter months (between 50 and 120L per interval) were extrapolated to the rest of the year, when energy for water heating is reduced due to the use of solar hot water systems. Water volumes used in the dishwasher (6.15 L–6.85 L per filling cycle) and washing machine (28.5 L–43 L per filling cycle) are limited compared to the volume ranges encountered for personal showers, which means that the algorithm is correctly excluding these secondary water uses.

Practices between the two years were compared in terms of shower lengths; hand irrigation volume; cooling and heating time, length of use and temperature setting. Shower lengths were determined by dividing the volume of water used by the volumetric flow rate of the shower head. This method does not differentiate between water used for showers or baths, but the latter is a bathing practice for only 5% of the Australian population [49].

The Mann-Whitney *U*-test was used to compare practices in the homes between the two years. This statistical test was chosen as it enables the comparison of non-parametric distributions. Additionally, the populations met the test's basic assumptions: firstly, the data had one continuous dependent variable; secondly, the data had one or more independent variables; thirdly, the observations were independent [62]. A fourth assumption concerns the population distribution shapes, which affect the interpretation of results. Populations with the same distribution shape can be compared in terms of medians and populations with different distribution shapes must be compared based on mean ranks [62]. The software package SPSS Statistics was used to conduct the analysis and verify the fourth assumption for each of the calculations. The null hypothesis of the distributions being equal for both years was evaluated at a 95% confidence level (p-value = 0.05).

Changes in automated practices such as reticulated irrigation and pool cleaning with a pump were analysed visually with heatmaps and contour plots.

2.3.3. Interview analysis

The interviews were analysed thematically [63] and were used to complement the quantitative data. The insights provided by the home occupants enabled an evaluation of the effects of the behaviour change program and an interpretation of everyday practices in the home [37].

3. Results and discussion

This section evaluates the effects of the behaviour change program. First, the overall difference in resource use between the two years was analysed. Second, the focus was on understanding changes in everyday practice and building system leading to resource use reduction or increase between the two years. Finally, participant insights were discussed. These included their views on challenges and opportunities related to changing practices and their use of the feedback system.

3.1. Overall change in resource use

Fig. 1 provides an overview of the variation in total energy and water use in all homes between the two years, before and after the behaviour change intervention. However, the weather conditions vary significantly between 2015 and 2016 and it is not possible to make an objective distinction of variations caused by weather or behaviour change. For instance, in 2016 the mean daily precipitation was 46% higher and the mean daily temperature was 4% lower than 2015 (Fig. 2). GAMs were applied to separate the energy and water use caused by the weather from the total use in the eight homes.

Grid electricity, gas and water use were separated into four major components by GAMs: use caused by temporal variation, use caused by weather variation, intercept and residuals (random behavior). Fig. 3 demonstrates an example of the influence of time and weather condition on grid electricity use in home 1 between 2015 and 2016. In this Figure, the shaded grey area indicates the 95% confidence interval, and the line of points through the grey area are the residuals of each individual model. Fig. 3 shows that while the general trends between grid electricity use, time and weather conditions are very similar for the two years, compared to a smooth decreasing trend in 2015, the relationship between grid electricity use and solar radiation fluctuates in mid-2016. Although graphs for both years show grid electricity use increase as humidity rises, this effect is more apparent in 2015. Overall, the impact from weather condition on grid electricity use in 2016 is more uncertain, which is revealed by three indicators: wider confidence interval, sparser distribution of residuals errors, stronger fluctuation of the relationship between electricity use and weather condition.

In this study, the total number of intercept and residuals were viewed as true indicators for energy and water use for everyday practices in the home. A visualized comparison of grid electricity use in two different homes (1 and 8) between two years is presented in Fig. 4. The grey line in Fig. 4 represents the smooth trend of grid electricity variation after the filter function was applied. However, it is not possible to assess whether there is a behaviour change between the years from Fig. 4 alone; therefore, a Wilcoxon signed-rank test was used.

Table 1 demonstrates the statistical results from the Wilcoxon signed-rank test at the 95% confidence level (p-value = 0.05). Five of the homes achieved savings in either energy or water. However, only home 3 had significant improvements for both energy and water, while home 5 did not change significantly for either. Furthermore, the gas use in home 1 and grid electricity use in home 8 increased in 2016 compared to 2015. These results show that water savings were achieved more frequently than energy savings. This could be related to water being more visible and tangible than energy and more frequently acted upon [64]. The highest use of water in the home is irrigation (39%) [49], and a small adjustment in the irrigation technology also has the potential to influence water use significantly without affecting occupant wellbeing; while a change in energy use may potentially impact on comfort.

3.2. Changes in the home system

Table 2 provides a summary of the changes made in the homes in 2016, both in terms of everyday practice and changes made to the building system. These were classified into the three elements of practice: meaning, skills and technology. Results revealed that most

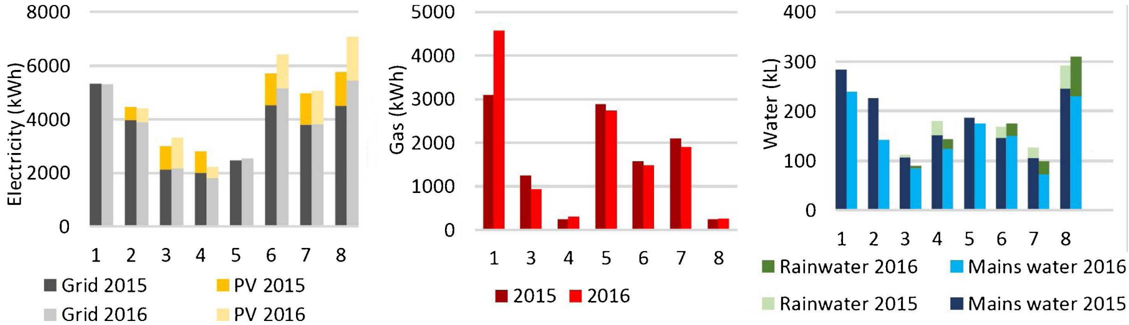

Fig. 1. Variation in total energy and water use in all homes in 2015 and 2016. Home 5 did not provide electricity bills and therefore PV electricity use was not included in the graph.

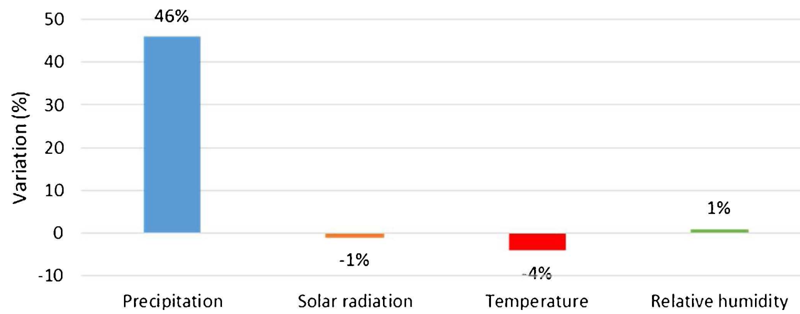

Fig. 2. Mean daily weather variation in 2016 compared to 2015.

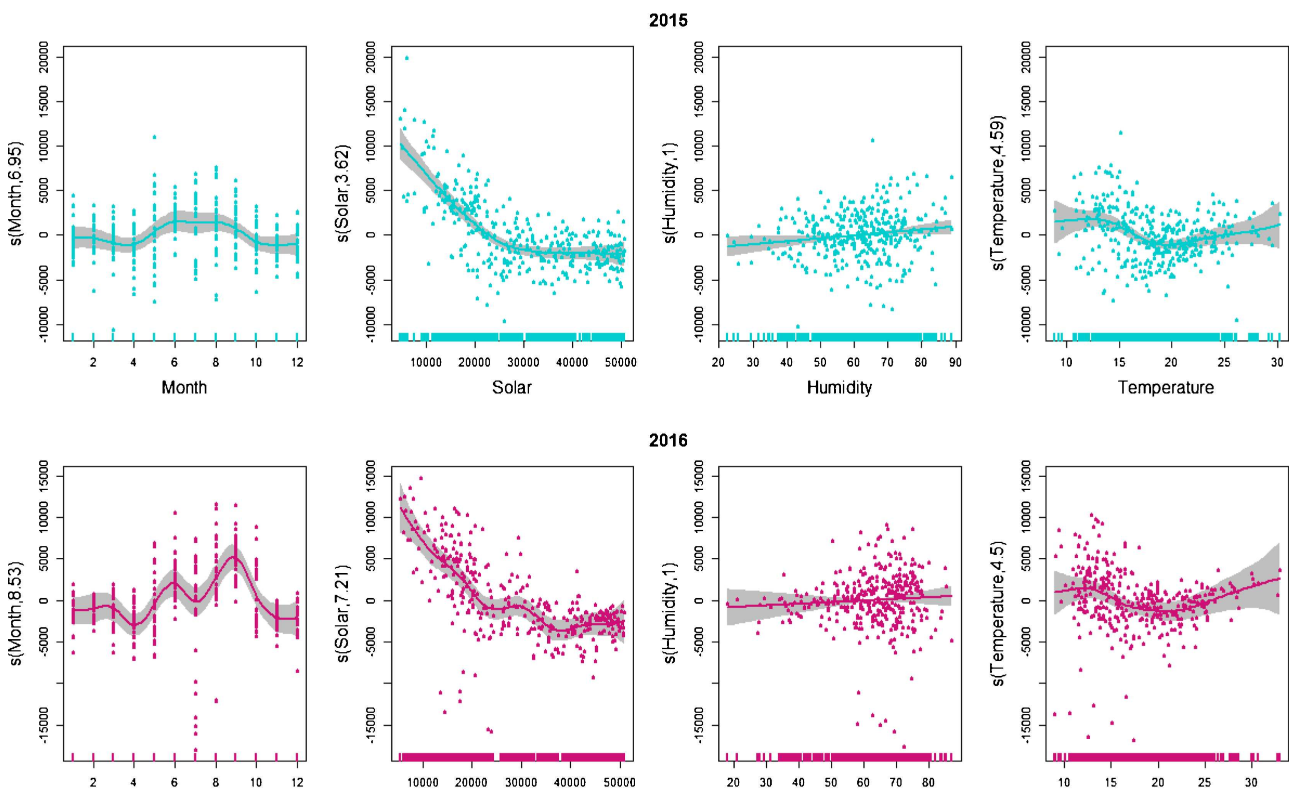

Fig. 3. Example of temporal and weather impacts on grid electricity use in home 1 between 2015 and 2016.

of the changes made during the second year of the study were technology related. Not all changes resulted in a significant alteration in resource use, however, they may have had other positive effects, such as increased occupant comfort. In some cases, improvements in one area were deterred by changes in other areas, resulting in similar resource use between the years. For instance, home 7 had shorter showers in 2016 but also started using more water in the garden (Table 2).

The rest of this section will explain and discuss the results presented in Table 2, starting with a discussion of changes in everyday

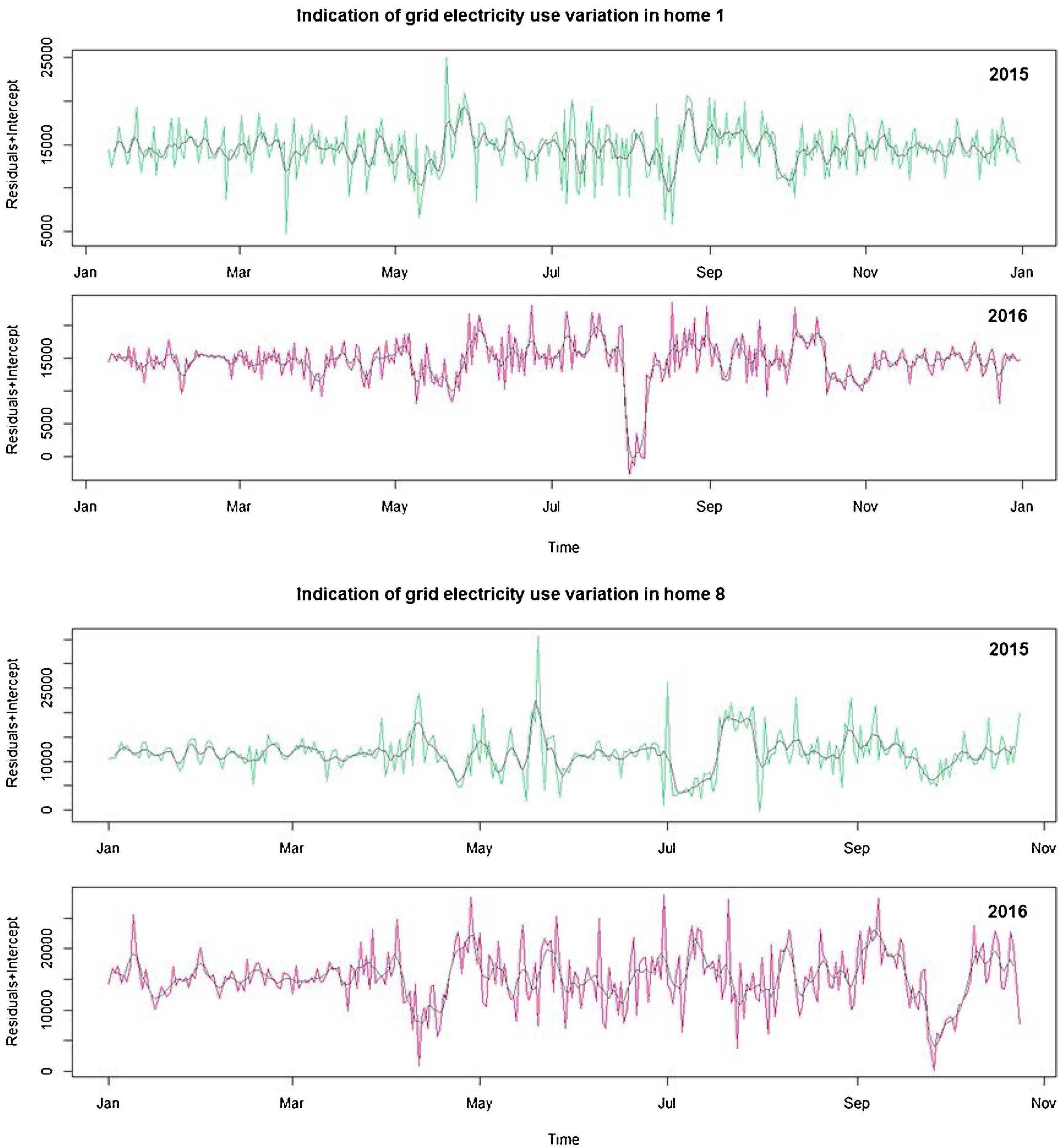

Fig. 4. Examples of energy and water use variation in home 1 and home 8 between 2015 and 2016.

practices and followed by a discussion of changes made to the building system.

3.2.1. Changes in everyday practice

Major resource use practices were analysed through mixed methods. The results are discussed through individual practice.

3.2.1.1. Personal showering practice. The first practice observed was personal showering. For the behavior change program to have succeeded with acceptance of the information provided, personal shower lengths between the first and second years should have decreased. Results revealed that half of the homes did not change their shower length (Table 3). The four homes that modified their practice reduced their personal shower median length by 59 s (Table 3). The shorter shower time belonged to home 4 who showered for a median of 5 min in 2016. This is still higher, however, than the 4-min shower length recommended by the local water authorities [65]. The implicit know-how skills and technology elements related to the practice of showering are relatively constant with time. Shower meaning, on the other hand, can vary significantly (e.g. cleanliness, relaxation or warmth), being the influential element of the practice [25]. The results show that affecting occupant meaning generates limited or statistically insignificant change (Table 2).

3.2.1.2. Irrigation practice.

Table 2
Summary of the changes made to the homes classified into the three elements of practice. Changes in resource use were taken from Table 1.

Home	Resource use	Practice change	Elements of practice			Technology Failure
			Skill	Meaning	Technology	
1	Electricity – constant				External shade cloths Roof vent LED bulbs	
	Gas – increase	Ambient heating	Recovering from sickness			
	Water – decrease	Irrigation			Established garden	
2	Electricity – constant				External shade cloth Additional insulation	
	Gas – N/A					
	Water – decrease	Irrigation	Understanding of plant needs			
		Hand washing			Flow restrictors	
3	Electricity – decrease	Ambient heating			Reduction of heater thermostat External shade cloth	
		Dishwashing			Dishwasher automation	
	Gas – decrease	Personal showers	Shorter showers			
	Water – decrease	Personal showers	Shorter showers			
		Irrigation			Mulch around plants	
4	Electricity – constant					
	Gas – constant				External shade cloth	
	Water – decrease	Personal showers	Shorter showers			
5	Electricity – constant	Dishwashing			Dishwasher automation	
	Gas – constant					
	Water – constant	Irrigation			Lawn became established	
6	Electricity – increase	Ambient cooling	Cooling length increased			
		Ambient heating			Reduction of heater thermostat	
		Pool cleaning			Pool pump timer adjusted	
		Dishwashing			Dishwasher automation	
	Gas – constant					
	Water – constant	Personal showers	Shorter showers			
		Irrigation			Less efficient sprinkler system	
					Additional planted areas	
7	Electricity – constant					
	Gas – decrease	Personal showers	Shorter showers			Water leak in 2015
	Water – constant	Personal showers	Shorter showers			
		Irrigation			Installation of an automated irrigation system	
8	Electricity – increase	Standby power			Standby automation	PV interruption
		Dishwashing			Dishwasher automation	
		Other			Installation of a timer in the solar hot water system	
	Gas – constant					
	Water – constant	Irrigation			Less efficient sprinkler system	Water leak in 2016
					New rainwater tank	
					New greywater system	

Table 3
Changes in shower length. The significance of the null hypothesis was evaluated at a 95% confidence level (p-value = 0.05). The population size represents the number of identified showers in the year. The shower length is expressed as the median in minutes.

Parameters	Year	Home							
		1	2	3	4	5	6	7	8
Energy source		Electricity	Electricity	Gas	Electricity	Gas	Gas	Gas	Electricity
Population size	2015	778	697	353	413	416	477	203	151
	2016	742	646	263	489	456	449	171	151
Shower length	2015	7.56	5.56	7.11	6.11	9.39	8.56	6.27	8.33
	2016	7.50	5.56	5.78	5.00	8.22	8.00	5.33	8.78
P-value		0.520	0.900	<0.05	<0.05	0.114	<0.05	<0.05	0.944
Significance		constant	constant	decrease	decrease	constant	decrease	decrease	constant

Table 4
Changes in hand watering volumes. The significance of the null hypothesis was evaluated at a 95% confidence level (p-value = 0.05). The population size represents the number of identified hand watering sessions in the year. The hand watering is expressed as the median (and mean rank for home 3) in litres.

Parameters	Year	Home		
		1	3	4
Population size	2015	173	28	128
	2016	93	31	129
Hand watering	2015	137.00	40.59 (mean rank)	177.50
	2016	130.00	20.44 (mean rank)	185.00
P-value		0.485	<0.05	0.906
Significance		constant	decrease	constant

3.2.1.2.1. Hand watering. Only three homes irrigate their gardens manually, with the use of a hose. The volume of water used in the garden at each irrigation session was only shortened for home 3 (mean $\text{rank}_{2015} = 40.59$, mean $\text{rank}_{2016} = 20.44$) (Table 4). However, home 1 nearly halved the hand watering frequency in 2016 ($n_1 = 173$, $n_2 = 93$) (Table 4) due to the garden being more estab-

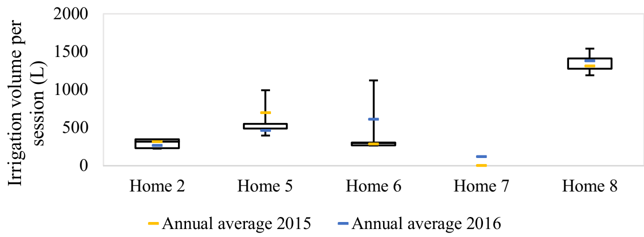

Fig. 5. Distribution of the volume of water used per garden irrigation session with an automatic reticulated system.

lished (Table 2). Unlike technologies related to personal showering, technologies related to the practice of irrigation are more variable. For instance, gardens become established, or new plants are introduced or removed.

3.2.1.2.2. Automatic irrigation. Five of the participant homes use automatic irrigation to water the garden. As a strategy to deal with drought in summer, the local water authority mandates that reticulated irrigation is only used on two allocated weekdays. Irrigation times are also restricted to early mornings (before 9.00) or evenings (after 18.00). Moreover, there is an irrigation ban between the months of June and August and homes found to be irrigating outside of the allocated months, weekdays or times are subject to fines. Mass information campaigns are also used to influence implicit skills by encouraging homes to reduce their irrigation times by 2 min, thus reducing the volume of water used in the garden at each irrigation session. Change in automatic irrigation practice was therefore measured in terms of irrigation weekdays, months, time of the day, and average volume of water used per irrigation session.

Results revealed that three of the five homes irrigated on the wrong days of the week in 2015 or more days than allowed. Two of these homes corrected their practices in 2016. The irrigation time was also corrected for two of the homes. Only one home irrigated during the banned period in 2015, but corrected it in 2016 (home 6).

Interestingly, the volume of water used for irrigation in the different homes varied significantly for some homes across the two years (Fig. 5). The water volume per irrigation session tended to be readjusted when the reticulation system was restarted after the winter ban period. Overall, two homes decreased the volume of water used for irrigation (homes 2 and 5) between 2015 and 2016 and two homes increased it (homes 6 and 8).

Interviews with the occupants of home 2 revealed that in early 2016 they stopped watering their vegetable beds, dis-interlocking the practice of irrigation from the practice of growing vegetables. They also mentioned that they closed the irrigation outlet to their established trees as a result of gaining gardening skills after the water audit (Table 2). Home 5 revealed that in 2015 a new lawn was installed, which required extra watering. The watering times, and therefore volumes, were decreased the following year. Home 6 more than tripled the amount of water used in the garden during the last trimester of 2016 due to the installation of new sprinklers and the connection of additional planted areas to the reticulated system (Table 2). Home 8 also changed the technology component of their irrigation practice between the two years. Despite the changes in irrigation volumes for homes 5, 6 and 8, these only affected a small portion of the year and did not significantly impact overall water use (Table 2).

3.2.1.3. Ambient cooling and heating practices. For ambient cooling and heating practices, changes were determined by variations in the length of cooling or heating, in internal temperature and in time of use (Table 5). Internal temperature refers to the living area temperature during the use of the system and a significant variation in internal temperature reflects a change in the temperature setting of the heater or AC system. Time of use with regards to the practice of cooling or heating is only relevant for homes that possess PV panels as these participants were encouraged to use their electric appliances during the day. In summer, participants were also encouraged to take advantage of the sea breezes in the evenings to cool the home naturally. As such, a successful change in practice involves reducing the length of ambient cooling and heating, a reduction in the internal temperature in winter, an increase in the internal temperature in summer and/or turning the heater or AC on during daylight hours.

Results revealed that homes 1, 3, 6 and 7 changed cooling or heating practices between the two years. Positive changes consisted mostly in reducing the temperature setting of the heating system. Home 6, however, also increased the length of cooling while only reducing the heater temperature setting by 0.3 °C (Table 5); this resulted in an overall increase in grid electricity use in 2016 (Table 2). Home 3, on the other hand, decreased the temperature setting of the heating system by over 2 °C (Table 5). Despite using the AC for longer periods in 2016, the practice was carried out during the day when the PVs were generating electricity and therefore limiting the impact on grid electricity use (Table 2). Home 1 started using the heater earlier in the day; however, this practice does not affect resource use as the system consists of a gas heater. In fact, heating frequency increased for this home ($n_1 = 124$, $n_2 = 176$), increasing overall gas use. Interviews with home 1 revealed that the occupants were sick during the winter of 2016, spending more time at home with the heater on (Table 2).

3.2.1.4. Pool cleaning practice. Results revealed that home 6, the only home with a swimming pool, changed the pool pump functioning times between 2015 and 2016 to make better use of the PV electric generation. This home uses the pool pump twice daily for two hours at a time. In 2016 the home occupants delayed the morning pool clean and advanced the afternoon clean by 30 min (Fig. 6). These minor alterations resulted in the decrease of grid electricity use by an average of 300Wh per day.

3.2.1.5. Reported changes in practice. Interviews revealed that one of the most popular changes made by participants in year 2 was the automation of the dishwasher to function during the day instead of the night, as this makes better use of the electricity generated by the PVs (Table 2). Home 8 also used automation to turn off the appliances that were left on standby mode when not in use. These participants installed a programmable device that switched off certain appliances at night time and during work/school hours, turning them back on when required. This was the only home that addressed standby electricity use.

While all homes were aware of their standby use, most mentioned not having the time, not remembering or simply not wanting to switch appliances off the wall manually. Other recurrent practices such as turning lights off and opening and closing windows and curtains to make better use of the passive solar design of the homes were not popular amongst households.

Whilst some participants made a conscious effort to change some of their practice-as-entity, others perceived that major changes would result in an unwanted lifestyle change. This was especially true when the meaning of practices was challenged. For instance, some attribute the meaning of comfort and relaxation to their personal showers and were not willing to give it up by decreasing the time spent in the shower. The idea of becoming too hot or too cold in summer or winter was an obstacle for many to even attempt a change in cooling and heating practice. This is in accordance with previous research which showed that warmth is closely related to comfort [66]. However, is has also been demonstrated that temperature adjustments do not necessarily impact on thermal comfort [45].

Table 5
Changes in ambient cooling and heating. The significance of the null hypothesis was evaluated at a 95% confidence level (p-value = 0.05). The population size represents the number of identified cooling and heating occurrences through the year.

Home	Energy source	Parameters	Year	Heating			Cooling		
				Internal temp. (°C)	Time of day	Length of time (h)	Internal temp. (°C)	Time of day	Length of time (h)
1	Gas	Median	2015	21.47	17:30	4.75	No cooling		
			2016	20.98	13:00	2.87			
		P-value		0.140	<0.05	0.764			
		Significance		constant	earlier	constant			
2	Elec	Median	2015	19.82	6:07	1.75	27.46	13:30	2
			2016	19.74	6:45	1.75	27.48	13:30	2
		P-value		0.350	0.195	0.790	0.549	0.318	0.297
		Significance		constant	constant	constant	constant	constant	constant
3	Elec	Median	2015	20.87	16:48	1.25	25.98	15:07	1.25
			2016	18.63	12:57	1.13	25.5	13:26	2.75
		P-value		<0.05	0.332	0.387	0.088	0.197	<0.05
		Significance		decrease	constant	constant	constant	constant	increase
5	Elec	Median	2015	19.58	10:40	1.88	No cooling in the living area		
			2016	20.14	11:15	2.5			
		P-value		0.524	0.682	0.453			
		Significance		constant	constant	constant			
6	Elec	Median	2015	20.28	17:37	1.00	25.38	17:22	1.25
			2016	19.96	17:30	2.00	25.52	15:22	2.5
		P-value		<0.05	0.953	0.172	0.158	<0.05	<0.05
		Significance		decrease	constant	constant	constant	earlier	increase
7	Elec	Median	2015	21.44	17:45	3.25	No cooling in the living area		
			2016	20.6	17:15	4.25			
		P-value		<0.05	0.342	0.130			
		Significance		decrease	constant	constant			

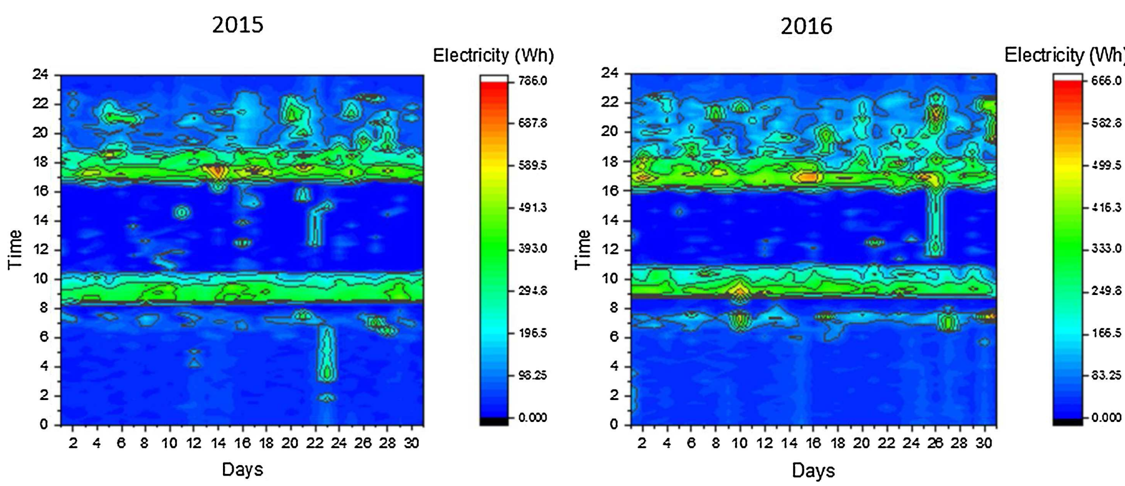

Fig. 6. Heat maps depicting the average grid electricity use in home 6 in 2015 and 2016 for all months of the year. The distinct horizontal bands in the morning and afternoon are related to the use of the pool pump.

Major practice (i.e. cooling and heating, irrigation and personal showering) changes consisted in a one-off alteration in the technology element of the practice; for instance, interrupting the irrigation of garden areas, reducing the temperature of the heating system or automating practices. These did not require constant effort or a change in meaning and did not affect established routines, being therefore easier to achieve. While not all changes resulted in positive outcomes, results indicate that participants are more prone to adjusting the technology element of the practice and adapt as they gain skills.

3.2.2. Changes to the building system

In addition to modifying everyday practices, participants also made alterations to the building system following the home audits. The thermal imaging camera identified gaps in the insulation of most homes, especially around the ceiling cornices, around lighting and above hatch doors (Fig. 7a, b). Solar heat gain through windows and exposed paved areas were also identified (Fig. 7c, d). Following the audit, homes 1–4 reported having made physical modifications to the building envelope to reduce undesired heat gain in summer (Table 2). The occupants of home 2 added insulation to the ceiling, closing some of the gaps. They also installed a removable shade sail to protect North facing windows. Removable shading devices (shade sails, curtains and screens) were also installed to protect exposed windows in homes 2–4.

Home 2 also installed flow restrictors on all the taps to reduce water use; home 3 mulched their garden to reduce evaporation rates; home 1 installed an additional vent in the roof to reduce heat accumulation and replaced their halogen light bulbs with LEDs as the halogen bulbs stopped working; home 8 installed a second 3000L rainwater tank, fixed the greywater system which had not been working in 2015 and installed a timer in the solar hot water

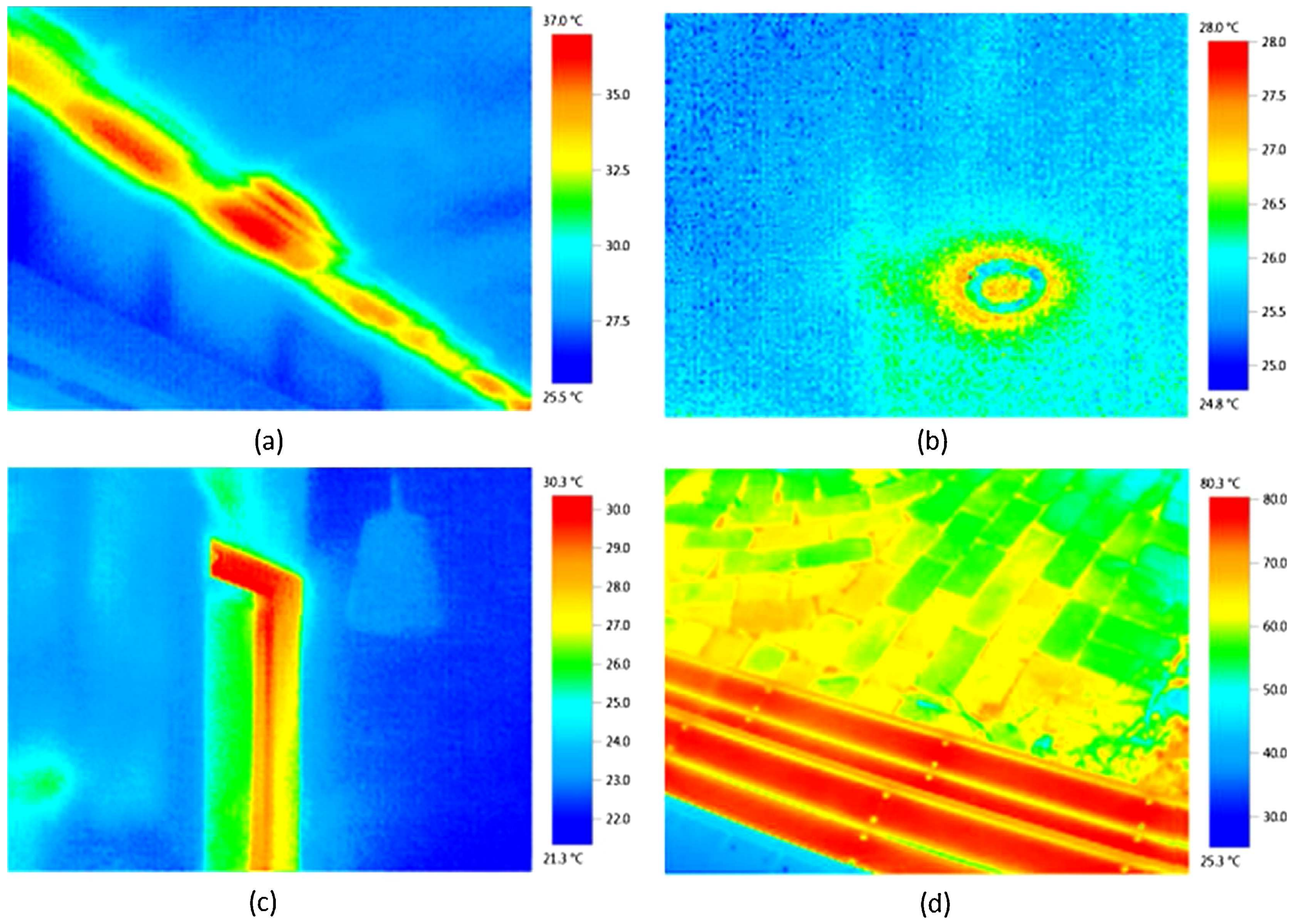

Fig. 7. Thermal images of missing insulation in (a) the ceiling and (b) around lights; and solar heat gain through (c) windows and (d) paved areas.

system to prevent it from functioning unnecessarily through the night (Table 2). The main factor impacting grid electricity use in home 8, however, was related to a fault in the PV system, which stopped working for several weeks at a time following wet weather events (Table 2).

Five out of eight homes made physical changes to the building system in the second year of the project. The installation of shading devices was the most popular one as they were considered easy to achieve and the effects were tangible and immediate.

3.3. Participants insights

Overall, five of the homes reduced energy and/or water use in 2016 (Table 1). Interviews revealed that some of the participants were enthusiastic about the project from the start while others had a shift in attitude through the second year. During the first interview, at least one individual per home said that they considered it important to reduce greenhouse gas emissions as well as to reduce their energy and water use. This could be seen as a limitation of this study since participants were selected on a voluntary basis, resulting in a sample that was naturally interested in sustainability. However, this pre-disposition did not necessarily result in action. During the second round of interviews (six months after the start of the behaviour change period), three homes revealed that they had not made any modification to either their practices or to the physical system of the home as they believed they had already done enough and that further changes would impact on their lifestyle and comfort. However, as the project progressed, these participants expressed a reflection about their energy and water use more frequently, for instance, thinking twice before turning on the washing machine or reflecting about their bills when receiving them. In fact, all participants revealed that seeing their data regularly made energy and water use more tangible, helped to increase awareness and reinforce existing knowledge even if the data was not always consciously acted upon.

Learnings also influenced other choices such as deciding whether to buy fruit trees or native plants for the garden. Some participants also mentioned thinking about their waste, food consumption and transportation as a result of this research.

When asked about reasons for making specific changes, the most common reasons were cost and simplicity. One of the participants said that if changes were challenging then they were unlikely to make that choice. According to participants, some of the changes to the building system had already been considered in the past but never executed and the audits and interaction with researchers gave them motivation to finally carry them out.

Participants also mentioned gaining the skills necessary to change following the audits; for instance, stopping the irrigation of dead plants, visualizing standby consumption or understanding the function of the PV panels. However, it was also mentioned that while the operation of the PV was better understood, home occupants could not take advantage of them since they were not at home during the day.

The mother in the home that reduced the most energy and water (home 3) mentioned that everything that was already integrated in her own routine was easy to change, for instance, changing her way of doing dishes and washing clothes. However, switching off standby power was hard to remember.

Challenges encountered by the participants were all related to changing established habits and routines. Comments included the fact that changing certain habits was incessant, anti-social or inconvenient. Comfort was usually prioritized over economic or environmental benefits. Families with children had more difficulty in making practice changes as they were not willing to risk their children's comfort and wellbeing. Moreover, influencing children's practices and intra-home practices was not an easy task.

3.4. Use of feedback and other behaviour change tools

Whilst all homes demonstrated interest in the online feedback system at first, interviews revealed they were not adopted by participants in the long term. In fact, six months after the introduction of the feedback system, half of the participants had never used it more than once. Three participants reported to have used the website occasionally during the project; but only one looked at it frequently at the start of the year when working at home. However, use decreased after going back to work, especially after summer, as energy use became less interesting in autumn. At the end of the project, this same participant revealed that log in to the website was only when suspecting that something was not working as expected. In fact, the website helped this home to detect a water leak and an interruption in the PV electricity generation (Table 2).

This finding is in agreement with previous research that found that the use of dashboards is often not integrated into users' routines and end up drifting to the background after the novelty period wears off [11,12]. The reasons for not using the website included being too busy, forgetfulness, lack of skills to understand the graphs and the belief that resource reduction could not be achieved. Some homes also reported having found the website slow to load and others mentioned that they wanted to see the data in real-time and that the one-day delay made seeing the impact of their changes difficult.

When asked about the usefulness of the website, a common answer was that it was not useful but interesting. One of the participants commented that the only times he logged in to it was to show it to colleagues.

The opinions about the report, on the other hand, were more positive. Participants appreciated receiving them monthly by email without having to look for them. The fact that information was presented in a concise way and interpretation was provided, made it easier for participants to understand. Some participants also mentioned that the reports made them think about their energy and water use and reflect on possible changes that could have caused variations.

The audit was seen as the most valuable experience for participants, in particular the visualization of heat gains and losses with thermography. According to the participants, the identification of improvement opportunities directed specifically at their homes was helpful. Two of the homes also mentioned the feedback data as being useful, despite not having made the most of it.

Suggestions given for improvement of the behaviour change program included receiving instant feedback on a tablet or mobile phone, having automatic alerts sent to their mobile phones whenever data abnormalities were detected (e.g. leaks) and meeting other participants to keep motivation high through the project.

4. Conclusions

Five homes succeeded in reducing resource use. 74% of the changes involved alterations in technology, either in the building system or in the form of automation. These were popular as they were considered to be easy one-off solutions. A change in manual practices, on the other hand, is classified as a curtailment behaviour [4], involving the daily reproduction of a task, and therefore considered by participants as being too much effort.

A change in practice was perceived as negatively impacting on comfort and lifestyle. Previous research has discussed the meaning of comfort and ways people seek it through warm showers, drinking tea or turning the heater on [67]. These meanings are engrained in the practice-as-entity and challenging to change. For instance, individuals having long personal showers may do so for relaxation rather than getting refreshed [27]. As such, a change in personal shower length affecting relaxation purposes is unlikely to occur. A change in the technology, on the other hand, does not impact meaning and is more likely to be accepted.

Moreover, it is essential that practices meet certain needs and become integrated into routines which are part of a SOP [68]. Modifying practices that are interlocked in a system can prove to be challenging. For instance, the use of the feedback website to inform decisions did not become a part of routines, except for one participant who initially turned it into a daily tool to pass time. The reports, however, became integrated into the users' routines of checking e-mails. The use of appliances during daylight hours is not effective as it often coincides with business/school hours.

Automation, on the other hand, enabled practices to become dis-interlocked from user routines and act independently while ensuring that everyday needs were met. For instance, the automatic standby switch enabled users to enjoy their appliances when needed while saving energy and personal effort; and dishes could be washed during the day while users were at work. Dis-interlocking practices by making them automatic or impacting the technology element of already automated practices is more attractive to home occupants. This might be a better solution to promote resource reduction in homes rather than attempting to modify skills, meanings or other interlocked practices.

While information campaigns and the development of home information systems remain popular tools to influence resource consumption in residential dwellings, they do not consider the home system as a whole and they do not take user needs and interlocked practices into account. This research has shown through a mixed method approach that technology is the preferred and most accepted method to reduce energy and water use in the home. Yet, their success depend on the consideration of user needs and skills and their full integration into the home SOP.

Acknowledgements

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Appendix A. Home characteristics and occupancy. A is an adult, YA is a young adult, T is a teenager and C refers to children. Homes 4 and 8 use passive solar design to avoid the need for cooling and heating systems.

Home	Residents (No)	Energy technologies	Water technologies
1	A (2), YA (1)	Electric solar hot water, electric cooling, gas heating	–
2	A (2), C (2)	Electric solar hot water, 1.5 kW PV, electric cooling and heating	–
3	A (1), T (2), YA (1)	Gas solar hot water, 2.66 kW PV, electric cooling and heating	Rainwater tank

4	A (2)	Electric solar hot water, 1.68 kW PV, no cooling, portable electric heating	Rainwater tank
5	A (2), C (3)	Instantaneous gas water heater, 3.5 kW PV, electric cooling and heating	–
6	A (2)	Gas solar hot water, 1.8 kW PV, electric cooling and heating	Rainwater tank
7	A (2), YA (1)	instantaneous gas water heater, 2 kW PV, electric cooling and heating	Rainwater tank
8	A (2), C (2)	Electric solar hot water, 2.28 kW PV, no cooling or heating	Rainwater tank

Appendix B. Monitoring equipment specification used to measure gas, grid electricity, water use, internal temperature and solar electricity generation in the eight homes.

Parameters monitored	Meters & Sensors
Gas	Ampy 750 gas meter & pulse counter Elster IN-Z61
Grid electricity	Schneider Electric iEM3110
Mains water and rainwater	20 mm Elster V100 & MEB7454 ‘T’ probe or Actaris TD8 & Cyble sensor 2W K = 1
Internal temperature	Kimo TM110
Solar electricity generation	Schneider Electric iEM3110
Thermal imaging	Testo 870

Appendix C. Longitudinal interview questions.

Summer 2015/2016	Winter 2016	Summer 2016/2017
Who lives in this house?		
Why did you decide to participate in this project?		What impacts did this project have on your household?
How important is it for you to reduce your energy consumption?	Last time we talked about your views on energy and water conservation and on whether you found it important. Do you still think of it the same way after the last 6 months?	
How important is it for you to reduce water consumption?	Are you more conscious of your energy and water usage on a daily basis? Why do you think that is?	
How important is it for you to live in a comfortable home?		
How do you think people view reducing their greenhouse gas emissions?		
Is that how it is in your local community?		
Do you think more people now think it is important to reduce their greenhouse gas emissions compared to a year ago?		
Is there support to reduce greenhouse gas emissions in your community?		
Is there support to reduce greenhouse gas emissions in your household? Do you talk about it?	Are your kids/rest of the family participating?	Did others in your family get involved? Did anyone else change habits?
Have you tried reducing your energy/water usage in the past?	Since I came here last have you made any changes to your routine?	Have you made any physical changes to your house?
	Why did you make these specific changes/Why not?	Have you changed any of your habits during the past 12 months? Which ones?
Which barriers did you encounter?	Are you finding anything particularly difficult? Why?	
What facilitated making changes?	Has anything helped you make these changes?	What motivated the change?
		What were the best tools in your opinion (feedback, audits, reports, etc)?
	How often are you logging into the website?	Did you use the website? Why? Why not?
	How useful are you finding the information on the website?	
	How useful are you finding the reports?	Did you use the reports? Why? Why not?
		What in your opinion could have improved your experience?
		What were your learnings from this project?

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The home as a system of practice and its implications for energy and water metabolism

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A B S T R A C T

Policy and regulations for residential houses often consider the physical system alone and tend to focus on the energy performance of the building. This ignores the effect of occupants' everyday practices and their interaction with the building technologies. This research applies practice theory and the concept of system of practice to eight Australian homes with the objectives of providing a deeper understanding of the complexities of the home system as well as providing approaches to enable (rather than persuade) resource reduction. The homes were investigated through explanatory design mixed methods which combined results of one year of longitudinal quantitative data collection and home occupant interviews. The results revealed that practices are performed in a sequential temporal spectrum as part of a routine and are influenced by interlocked practices as well as interlocking routines from other home occupants. Practices also follow established daily patterns reflected by a frequency distribution curve where the standard deviation reflects the degree of habituality of the practice. Highly interlocked practices with a high degree of habituality are challenging to affect. However, automation could enable resource intensive activities to be dis-interlocked from an established routine and make change within the home system of practice easier and more flexible.

Keywords: Home system; Everyday practice; Energy; Water; Automation; Routines

1. Introduction

The home can be considered a juxtaposition of the physical system including associated energy, water and resource metabolic flows (Harder et al., 2014) with the occupied social system of everyday practice (Guy and Shove, 2000) (Fig. 1). The concept of metabolism is used to describe the flow of materials and energy through an urban system, which similarly to living beings, consumes resources, transforms them internally and generates waste (Girardet, 2010).

The implementation of technologies which lead to more efficient buildings, including energy and water efficient appliances, renewable energy and sealed building envelopes, has been a significant focus for research (Moore, 2012). In contrast, the home itself is not well understood and a theoretical and practical understanding of the complexities of occupant behavior and their interaction with the physical system of the building is an emerging area of investigation (Keyson et al., 2017). Attempts at reducing home resource use through changing attitudes and values and intelligent design features, may be confounded when users resist external control or refuse to change their behavior (Scott et al., 2012). Another approach has been to classify homes into simple typologies with targeted policy or resource criteria but these encounter similar issues of push back from the home residents (Ashton et al., 2016).

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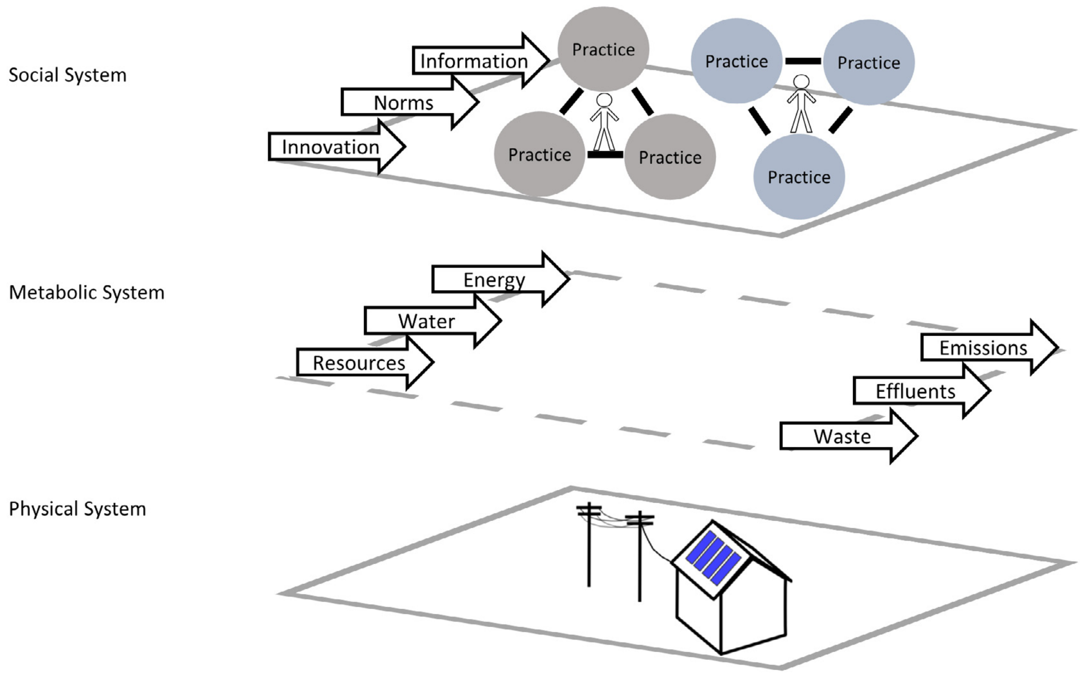

Fig. 1 – The home system, which includes the physical building system, metabolic flows and occupant practices, which are connected in a system of practice (SOP).

Proponents of practice theory argue that innovative user technology cannot be adopted without innovation in practice (Shove et al., 2012; Strengers and Maller, 2014). Smart meters, feedback displays and automation technologies are increasingly deployed to reduce energy and water consumption in residential homes (Faruqui et al., 2010; Fischer, 2008; Jain et al., 2012; Yew et al., 2012). However, these technologies do not necessarily fulfill their objectives if they fail to become embedded in the habits and routines that compose the practices of daily life (Brynjarsdóttir et al., 2012; Strengers, 2011). As a consequence, reducing energy, water and resource use in homes depends on the available infrastructure and technology, but also on occupant's everyday practices (Shove et al., 2007).

Practice theory (Shove et al., 2007), also termed social practice theory (Schatzki, 1996), identifies practice as the preferred unit of analysis rather than the individual (Reckwitz, 2002; Røpke, 2009, 2001; Schatzki, 2002; Schatzki et al., 2001; Shove et al., 2012, 2010, 2009, 2007; Warde, 2005). The advantage is that this approach provides a holistic view to understanding occupant behavior as it recognizes that elements of place and broader societal aspects affect the way practices are carried out in addition to individual values and attitudes (Hargreaves, 2011). Moreover, practice theory posits that individuals do not use resources for the sake of it, but rather as a means to achieve an objective. Therefore, comprehending the external context and occupant needs is crucial to understanding home resource use.

A practice is characterized as a routine behavior composed of several elements which are interconnected (Reckwitz, 2002). As practice theory is still emerging, there is a lack of a unifying model of assessment, however most models feature a number of elements (McMeekin and Southerton, 2012; Schatzki, 1996), the doings and sayings which collectively form the entity of a practice. These previous models can be collated into the three elements of practice defined here as meaning, skill and technology (Fig. 1). Meaning is the aspirations, emotions, ideas, perceptions, symbolic meanings and values associated with the practice (Shove et al., 2012). Skill refers to the know-how, technique, and understandings for accomplishing a practice (Scott et al., 2012), although an important distinction of skill exists between implicit know-how and explicit rule-based or theoretical knowledge (Gram-Hanssen, 2010a). Technology is referred to as the devices used to perform a practice which are the infrastructure, materials and objects (Gram-Hanssen, 2010b). Practice theory should not be confused with the study of cultural practices that is currently being undertaken by cross-cultural psychologists (Kashima, 2014; Kashima et al., 2015; Kashima and Gelfand, 2012).

The implication of applying practice theory to the study of household resource use is that the sources of changed behavior lie in the development of practices (Warde, 2005). The quantitative monitoring of technologies utilized in a home reveals the performance of the products (Foulds et al., 2013), but not necessarily how the resource use fits into the broader systems of the home. Habits and routines co-evolve with practices (Shove, 2004) and the practices relating to the use of resources in the home are manifested in their daily performance (Chappells et al., 2011). Practices exist both in the historical collective reproduction of them as practice-as-entities and in their performance by individuals (Schatzki, 2002), the former being the storage of knowledge and learnings of the elements of the practice (meaning, skills and technology) within a practitioner's mind. Some household members have similar practice-as-entities in that everyone understands practices the same way and thus perform them similarly, resulting in resource use patterns, such as similar shower times. When practice-as-entities vary, we see intra-home and interpersonal variances in resource use and the performance of practices that are related to household habits and routines (Røpke, 2009). Section 3.1.1 outlines in more detail how a change in one part of the practice entity can influence the performance, and as such resource use, of the practice.

This paper builds on the approach that the continual reproduction of habits and routines that compose practices within a home are connected in a system of practice (SOP) (Watson, 2012). The interconnectedness between practices is referred to as interlocking (Fig. 1) (Macrorie et al., 2014a; Spurling et al., 2013; Spurling and McMeekin, 2014) which emphasizes that individual practices are inseparably bound up in the spectrum of everyday practices that are combined in bundles across space and time (Macrorie et al., 2014a, b).

The objective of this research is twofold; firstly, it aims to understand how practices are bound up in the home SOP, especially in a context where houses are becoming more energy efficient; and secondly, it aims at understanding how these practices can be changed to promote resource savings given their layers of complexity. Previous studies of SOPs in the resource use literature have focused on broader societal systems, investigating how these systems influence everyday practices (Macrorie et al., 2014a, b; Watson, 2012). Our research scales down to, and provides interpersonal detail on, the home as a SOP and concentrates on the influence that everyday practices have on energy and water use. This research contributes to understanding how resource reduction can be enabled in the multifaceted system of the home.

This research is based on the longitudinal monitoring of eight Australian energy efficient homes. The analysis of selected practices in the homes was carried out through a mixed methods approach, which combined quantitative and qualitative methods to provide holistic insights into the home SOP and better understand the interaction between occupants and the building technologies. The analysis started with a discussion of the targeted practices in isolation, describing through statistics how they are influenced by meaning, skill and technology. The analysis then focused on the integration of these practices in the home SOP, discussing the influences of interlocked practices and other home occupants. The last section of the analysis discusses automated practices, which unlike other everyday practices, are dis-interlocked (i.e. disconnected or isolated) from the SOP and may provide an opportunity to enable resource use change.

2. Materials and methods

Eight homes were established as Living Laboratories (Burbridge et al., 2017; Leminen et al., 2015; Leminen and Westerlund, 2012; Liedtke et al., 2015) to investigate the effect of everyday practices on energy and water use in the home system (Herrena, 2017). The two most water intensive practices in Australian homes are garden irrigation and personal showering, representing 39% and 25% respectively of the total water use in the home (Water Corporation, 2010). The highest energy related practices consist of cooling and heating, using approximately 40% of the total energy use in the house (DEWHA, 2008) and generating 16% of operational greenhouse gas emissions (Lawania and Biswas, 2017). Accordingly, this research is scoped to concentrate mainly on the practices of personal showering, garden irrigation and home heating to represent some of the key practices in the home SOP. The practices of reticulated irrigation, dishwasher use and pool cleaning are also introduced to discuss automated practices.

The homes are located in Fremantle, Western Australia (WA), and possess characteristics that make them more energy efficient than the average WA dwelling. For instance, they all have passive solar design characteristics; that is, they take advantage of afternoon breezes to cool the house in summer as well as direct sunlight and thermal mass to increase thermal comfort in winter. Moreover, seven of the houses possess solar photovoltaic (PV) panels on their roofs (Table 1). Minimum house energy efficiency standards are currently mandated in Australia and internationally and PV panels are increasingly adopted in suburban homes (ABS, 2016; Green and Newman, 2017). The understanding of the home SOP in the context of energy efficient homes is important to ensure that they perform to their full potential.

The eight homes were selected through two distinct methods; response to a media advertisement and contact through a mail drop. Households that submitted an expression of interest were further selected to provide a cross-section of demographic profiles (Table 1).

Empirical analysis was conducted through an explanatory design mixed methods approach (Creswell et al., 2003; Creswell and Plano Clark, 2007). Quantitative data was continuously collected through sensors and convergent qualitative data was collated through semi-structured interviews that focused on the habits and routines of the occupants. This builds on previous research concerning the analysis of daily energy practices through the integration of monitoring data with qualitative interviews to provide insights beyond those of non-integrated approaches (Foulds et al., 2013).

2.1. *Quantitative data collection*

The eight homes had their gas, grid electricity, internal temperature and water use monitored for the full year of 2015. Sensors were connected to existing meters, sending pulses to a data logger (Schneider Electric COM'X 200), which then transmitted the data in csv format to a cloud via a 2G wireless internet connection. Data was collected at 15 min intervals, resulting in a total of 35,040 data points per meter or sensor at the end of the year. The following meters and sensors were employed to gather gas, grid electricity, temperature and water data respectively: Ampy 750 gas meter and pulse counter Elster IN-Z6; Schneider Electric iEM3110; Kimo TM110; Actaris TD8 and Cyble sensor 2W K = 1. Home 3 has a rainwater tank designed for use in the outdoor area and a separate water meter was installed in the rainwater tank outlet to measure hand watering of the garden.

2.2. *Data analysis*

The first stage of the data analysis involved the graphic identification of patterns of energy and water use associated with the defined everyday practices. An algorithm was developed to process all the data and identify daily resource use related to ambient heating, garden irrigation and personal showering. The highest summer water peaks (higher than 120 L/interval) were attributed to garden irrigation. Water use for personal showering represents the second highest water peaks of the data. Water volumes used for personal showering were identified in the winter months by an increase in water use concurrently with an increase in gas or electricity use for water heating. The water volume range for personal showering as identified for the winter months was extrapolated to the rest of the year as some of the houses possess solar hot water systems which limit water heating in summer. Previous Australian research has shown that showering volumes between winter and summer can differ by around 8L/person (Rathnayaka et al., 2015), which corresponds to a shower length difference of less than one

Table 1 – House characteristics and occupancies.

Home	No. occupants	Occupation	Efficient technologies
1	2 adults 1 young adult	Retired Full-time worker	Solar hot water
2	2 adults 2 children	Full-timeworker / stay-at-home parent Student / preschool toddler	PV, solar hot water
3	1 adult 2 teenagers 1 young adult	Full-time worker Students Unemployed	PV, solar hot water
4	2 adults	Full-timeworkers	PV, solar hot water
5	2 adults 3 children	Full-timeworker / stay-at-home parent Students	PV
6	2 adults	Full-time workers	PV, solar hot water
7	2 adults 1 young adult	Full-timeworkers Full-time worker	PV
8	2 adults 2 children	Full-timeworker / part-time worker Student / preschool child	PV, solar hot water

minute. These seasonal differences could have impacted on the results; however, it is assumed that the variation is captured by the wide shower volume range of 50 to 120 L per interval that was detected by the algorithm. This attribution correctly excludes the use of the water in the dishwasher (6.15 L to 6.85 L per filling cycle) and washing machine (28.5 L to 43 L per filling cycle) for each home. A similar algorithm was used to identify energy used for ambient heating. A significant increase in energy (electricity or gas according to the heating system of the house) followed by a concomitant increase in the internal temperature during winter was attributed to the practice of manually regulating the heating system. The temperature sensor was placed in the living area to ensure that temperature increase from kitchen practices was not mistaken for ambient heating practice.

Personal shower practice was analyzed separately for weekdays and weekends due to an identified difference in routines. Shower lengths were determined by dividing the volume of water used by the volumetric flow rate of the shower head. This method does not specifically differentiate between water used for showers or baths, the latter being undertaken exclusively by only 5% of the Australian population (Water Corporation, 2010).

Statistical analysis was undertaken through the graphic software OriginLab 2017 which provided a systematic analysis of the data set for the eight houses with a total of 35,040 data points per meter (gas, grid electricity and water) or sensor (temperature) in each home over the year. Distributions of personal shower and irrigation lengths and times were plotted as histograms; those depicting lengths had a specified bin size of 1 min and those depicting time of day had 48 bins (30-minute resolution). Peak analyses generated fitted curves providing coefficient of determination (R^2), coefficient of variation (CV), mean (μ), mode (Mo) and standard deviation (σ). These parameters were used to interpret the elements and interlocking of practices as well as patterns of intra-home practices.

The non-parametric Mann–Whitney U-test (Rosner and Grove, 1999) was conducted to identify statistical differences related to the showering practice during the week and weekend as well as mornings and afternoons over one year. We understand that this test is for unpaired data and was used correctly in this study. Morning and afternoon showers as well as week and weekend showers are independent variables and the samples are not paired, which excluded the use of a non-parametric paired t-test. The reasons that the samples are treated as independent populations are the following:

- The morning and afternoon showers as well as week and weekend showers may be taken by different (or a different number of) occupants of the same house;
- The showering practices may be different in the mornings and afternoons as well as during the week and weekend;
- The number of showers (N) in the morning and afternoon differs (as shown in Table 3);
- The population of showers taken during the week over the course of one year is significantly larger than the population of showers taken during the weekend for the same period.

The analysis relating to diurnal energy use in the homes was through line graphs and contour plots.

2.3. *Qualitative data collection*

Semi-structured interviews (Kallio et al., 2016) with household members were conducted at the end of the quantitative data collection period in two stages. Initially the occupants were shown a summary of their monthly energy and water use and asked to identify reasons for any significant change in use between months (Foulds et al., 2013). The second stage of the interview targeted everyday practices in terms of meaning, skill and technology as well as household configuration and lifestyles. This second stage included participant articulation through a home survey with considerations of garden watering, thermal conditioning and washing practices as well as home technology. During this stage occupant routines and possible barriers to changing practices were revealed (Foulds et al., 2013). The explanatory design mixed method approach (Lave and Wenger, 1991) uses qualitative data to provide an in-depth explanation of the measured quantitative data and data from interviews to interpret everyday practices in the home (Foulds et al., 2013).

Care was taken to minimize influence on home occupants as a result of this research as this might lead to practice

Table 2 – Description of the showering length distribution for the eight homes. Statistically valid Gaussian (G) and Lognormal (LN) distributions are identified and numbered in a daily time sequence.

Home	Weekdays				Weekend			
	Shower, n	Mo (min)	σ (min)	R^2	Shower, n	Mo (min)	σ (min)	R^2
1	1 (LN)	6.1	1.6	0.98	1 (LN)	6.4	1.6	0.99
	2 (LN)	11.0	4.3		2 (LN)	12.5	3.5	
2	1 (LN)	4.5	2.0	0.94	1 (LN)	4.3	0.9	0.98
					2 (LN)	9.3	4.5	
3	1 (LN)	4.1	0.8	0.99	1 (LN)	4.0	0.6	0.96
	2 (LN)	8.0	5.0		2 (LN)	6.6	4.5	
4	1 (LN)	4.9	2.9	0.84	1 (LN)	4.4	1.4	0.84
5	1 (LN)	4.4	1.5	0.97	1 (LN)	4.3	0.9	0.95
	2 (LN)	13.9	10.1		2 (LN)	12.5	9.5	
6	1 (LN)	7.0	4.8	0.95	1 (LN)	4.3	5.4	0.93
7	1 (LN)	5.3	2.3	0.97	1 (LN)	4.9	2.2	0.87
8	1 (G)	7.1	1.1	0.97	1 (LN)	6.9	0.9	0.98
	2 (LN)	11.2	1.6		2 (LN)	10.6	3.2	

Mo — Mode; σ — standard deviation; R^2 — coefficient of determination

Table 3 – Comparison between morning and afternoon shower lengths (minutes) in homes with more than one showering practice (multiple modes). The statistical significance (Sig) of the Mann–Whitney *U*-test results are evaluated at a 99% confidence level. For s the difference between the two populations is statistically significantly different and for ns the difference between the two populations is not statistically significantly different. N is the total number of morning or afternoon showers in the year.

Home	N morning	N afternoon	Median (min)		P-value	Sig
			Morning	Afternoon		
1	256	175	6.89	8.55	.000	s
3	415	231	7.11	6.44	.703	ns
5	253	99	6.67	12.56	.000	s
8	168	94	9.11	9.28	.368	ns

and behavior modifications. For instance, the researchers did not maintain contact with participants after equipment installation and until the end of the monitoring period. While the participants were aware of the overall research intentions, the behavioral and practice aspects of the project were not emphasized. The longitudinal nature of this experimental design also reduces the chances of everyday practices being affected in the long term by occupant knowledge of the presence of monitoring equipment (Keyson et al., 2017). While there is still a possibility that practices might have been initially affected despite the measures listed above, the large number of data points (35,040) collected over the year reduces the likelihood of the results being significantly impacted.

3. Results and discussion

Patterns of energy and water use in the home were considered in terms of each individual everyday practice (Section 3.1); interlocking practices and other elements that compose the home SOP (Section 3.2); and automated practices acting independently of the home SOP (Section 3.3). Information and insights gathered from the interviews were used to support the quantitative results (Creswell and Plano Clark, 2011), relating them to other interlocked practices and wider influencing factors outside the home.

3.1. *Everyday practice*

The practices of personal showering, garden hand watering and home heating were chosen for analysis through contemporary practice theory (Macrorie et al., 2014a). The selected practices were discussed in terms of the three influential practice entity elements, which are defined as meaning, skill and technology.

3.1.1. *Personal showering*

Personal showering is the predominant form of bathing for cleanliness, warmth and feeling fresh in many (although by no means all) cultures, and is an established practice that has been performed daily by most home occupants, although not necessarily with the same meaning (Shove, 2003). The length of a shower is a key component of the water metabolism of the house as a system (Kenway et al., 2014).

The histograms representing the frequency distribution of the length of showers ($151 < n < 939$, where n is the number of identified showers in a home) in each home over one year had one or more modes which generally followed a lognormal distribution curve (Fig. 2 and Table 2). It is posited that the lognormal curve reflects the practice elements affecting shower length (e.g. meaning, skill and technology). The implicit

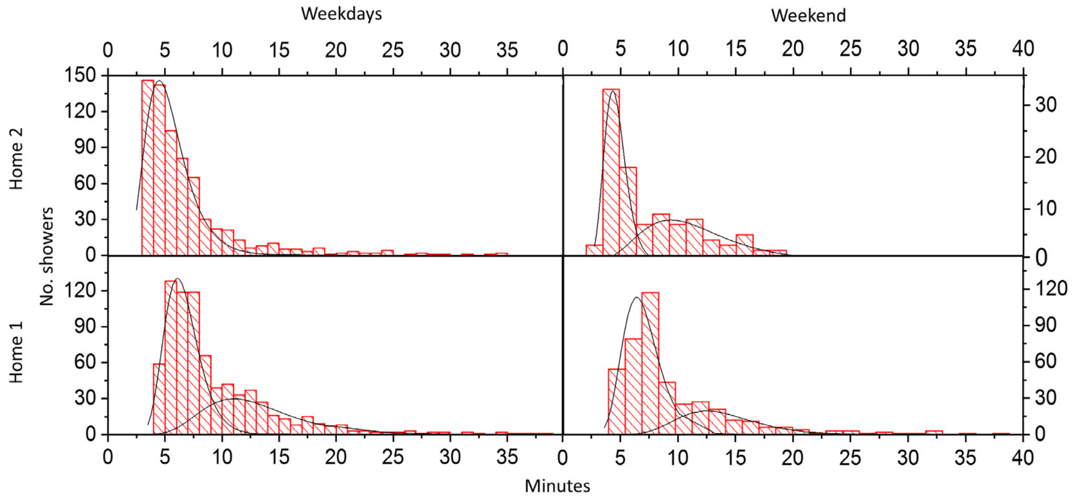

Fig. 2 – Shower length histograms and corresponding fitted (frequency) curves for two homes. During the week the occupants of home 1 have different intra-home showering practices while the occupants of home 2 follow the same practice. The weekend frequency distributions reveal a mix of showers with dispersed meanings. The statistics of the aggregate data for all homes are presented in Table 1.

know-how skills and shower head technology should not fluctuate over time, unlike the meaning for personal showering, which can frequently change and be the influential element for the practice (Shove et al., 2010). Consequently, the distribution curves represent variations in shower length driven by variations in meaning; the mode being the most frequent length and meaning for the showers. The interquartile range of the lognormal distribution (i.e. higher number of showers) represents the main routine for the showering practice, while the upper quartile (i.e. less frequent and longer showers) could indicate alternative meanings for the practice (Fig. 2). Where technology and skills are constant, the meaning of practices can be determined and described by the coefficient of variation (CV) and the standard deviation (σ) of the frequency curve; with a lower CV or σ value indicating a higher degree of habituality (Table 2). Showering length frequency distributions presenting more than one mode could represent the routine of distinct inhabitants with different showering practice-as-entities or different showering meanings for the same occupant.

For instance, during weekdays, in home 1 (a home with three occupants comprising a retired couple and their working granddaughter) the showering length histogram of the household contains two peaks (i.e. two modes) (Fig. 2); the first has a frequency curve with an associated Mo value of 6.1 min (σ value 1.6 min, μ value 6.6 min) and the second has a Mo value of 11 min (σ value 4.3 min, μ value 12.9 min). Interviews with this home revealed that the retired couple share a similar practice-as-entity that differs from their granddaughter. The granddaughter enjoys long showers and weekly baths, articulating a different meaning to showering and bathing than her grandparents. The second curve with associated Mo value of 11 min could therefore be attributed to the granddaughter. Her showering practice (σ value 4.3 min, CV value 0.4) is also less habitual and routine based than her grandparents (σ value 1.6 min, CV value 0.2), which is reflected in the larger standard deviation and coefficient of variation (Table 2).

The occupants of home 2 (one working adult, one stay-at-home parent and two preschool children), on the other hand, all possess the same weekday showering practice with the personal showers following only one single-modal lognormal frequency distribution (Mo value 4.5) (Fig. 2 and Table 2). This indicates that there is a similar meaning or meanings for personal showering between all the occupants.

The local water authority in Perth, Australia, faces serious water shortages for the city and widely promotes for personal showers under 4 min (Water Corporation, 2010), attempting to introduce explicit rule-based knowledge (McMeekin and Southerton, 2012) into the skill of personal showering practice. The Mo values in Table 2 reveal that this is not met for any home. The closest Mo values to 4 min usually occur for the first early morning shower where the meaning is to freshen up before work (weekday) or the day ahead (weekend) (Table 3). This explicit knowledge may not affect the longer showers due to the heterogeneity of meanings associated with the upper quartile of the frequency distribution curve. The later showers are generally longer (Table 3) than the morning showers as they are situated between different routines. They are likely to be more flexible than the morning showers, since they are less constrained by scheduled activities such as work and school. Later showers may also hold meanings other than cleanliness which might include relaxation at the end of a busy day or warmth on a cold winter day, hence the extended length of showering time (Shove, 2003).

The semi-structured interviews confirmed that occupants of the same home can have different meanings for personal showering, affecting the length of shower. Motivations mentioned by the households included showering for relaxation (teenagers in house 3, granddaughter in house 1), showering for the purpose of health (husband in house 4), showering for cleanliness alone (preschool children and stay-at-home mother in house 5) and the social expectation of everyday showering by colleagues in a work place culture (husband in house 5). Those who attribute health or relaxation to their showering practice mentioned enjoying long showers. One of the participants having showers for cleanliness purposes (house 5) also revealed not showering on a daily basis but compensating instead, with long showers when doing so (Mo value 13.9 min, σ value 10 min, Table 2).

Shower lengths between weekdays and weekends were not statistically significantly different for six of the homes at a 99% confidence level (Table 4). The similarity in shower

Table 4 – Comparison between weekday and weekend showers. The statistical significance (Sig) of the Mann–Whitney *U*-test results are evaluated at a 99% confidence level. For s the difference between the two populations is statistically significantly different and for ns the difference between the two populations is not statistically significantly different. N is the total number of weekdays or weekend showers in the year.

Home	N weekdays	N weekend	Time		Length	
			P-value	Sig	P-value	Sig
1	778	423	.002	s	.310	ns
2	697	102	.286	ns	.044	ns
3	939	377	.001	s	.110	ns
4	413	288	.000	s	.124	ns
5	416	155	.000	s	.749	ns
6	479	165	.947	ns	.000	s
7	543	212	.000	s	.709	ns
8	376	167	.751	ns	.285	ns

lengths as well as the positive skewness of the length distribution curve shows that a personal shower routine of a regular length of time is followed each day to achieve a specific meaning and that shorter showers are unlikely to occur, unless the skill or technology elements of the practice are altered (Shove, 2003). The reduction of personal shower length may be particularly challenging for occupants whose degree of habituality for showers is high.

3.1.2. Garden hand watering

The other water intensive practice in households is outdoor use (Ashton et al., 2016). The same pattern of habits and routines identified for showering was also found for the practice of hand watering the garden (Table 5), which uses similar volumes of water on each occasion. Hand watering practices depend mostly on technology (garden size) and user skill. A household will not use water for irrigation unless there is a garden, which may be reliant on a household member having the meaning, skill and technology for undertaking the practice of gardening. The volume of water applied to the garden follows a lognormal distribution (Table 5) which indicates that households follow a similar irrigation pattern each time. Homes 1 and 4 both possess gardens (approximately 85 m^2 and 220 m^2 respectively) with lawns as well as decorative and edible plants, requiring larger volumes of water compared to home 3, who only plant in pots located in a paved courtyard. Larger watering volumes (reflected in a greater σ value) especially for homes 1 and 4 could represent meanings other than maintaining plant health. For instance, home 1 occupants revealed that the practice of hand watering is sometimes undertaken twice daily and consists of a pleasurable activity. This is consistent with previous research which identified other meanings for irrigation, including enjoyment (Syme et al., 2004). The σ value for home 3, on the other hand, is only 8 L, indicating that the occupants of this home may only have the one meaning of maintaining plant vitality for garden watering.

3.1.3. Ambient heating

Practices to regulate indoor comfort based on temperature have also been performed by people over their lives using various technologies with different meanings and skills. This practice has become increasingly resource intensive with the broad uptake of reverse cycle air-conditioning and heating units in homes in Perth (Strengers, 2010) and in the studied homes. It was observed that households follow different heating practices. Home residents were not strictly motivated by thermal needs when they operated the heating system. Some turn on the heater as part of a routine for the colder months, when arriving home from work, whereas others seek a hedonic experience instead of wearing warmer clothes when the temperature falls (Eon et al., 2017; Shove, 2003).

Fig. 3 provides the example of three homes that operated the heater during weekdays in July 2015, the middle of the Australian winter. In home 1 the heater was switched on for two hours in the morning (07.30 to 09.30) when the internal temperature was on average 18 °C. This occurred when the occupants woke up and was based on their morning routines as well as the experience of feeling cold. As they left the home for their daily activities, the heater was switched off, and this routine was repeated through the winter months. The heater was then switched on again for the rest of the evening, between 17.30 and 23.00, when the occupants were at home and the external temperature had dropped. According to home 1 occupants, they turn the heater on while watching television in the evenings. The occupants of home 5 only switched the heater on during the late morning, at around 10.00, even though their house was on average 2° colder than the other two homes and the heater in this home was not usually used in the evenings. This indicates that the occupant's practice-as-entity could be influenced more by the meaning or the technologies they associate with heating than the internal temperature itself (Shove et al., 2010). Home 5 possesses PV rooftop panels, which according to the occupants, are the main driver for the time when the heater is switched on. Their preference in the evenings and early mornings is to wear warm clothes rather than use the heater. A different heating practice was encountered in home 7, which only uses the heater in the evenings, from around 17.30 to 22.00, after arriving home from work. According to these participants, comfort and convenience are the main reason to use the heater. Our results indicate that regardless of the thermal temperature in the household, the occupants use the heating technology with various meanings and interlocked with their daily routines.

3.2. Interlocking practices

While individual practices are influenced by meaning, skill and technology, they are also constrained by other home occupants and interlocked practices inside and outside the

Table 5 – Hand watering irrigation practice in the three homes that practice hand watering; the other five homes possess reticulation systems set on a timer. Modes of time are expressed as times (t) and volumes are expressed in liters (L). Statistically valid Gaussian (G) and lognormal (LN) distributions are identified.

Home		Hand watering, n	Mo (t, L)	σ (min, L)	R^2
1	Time	1 (G)	8.57	49	0.90
		2–5 (G)	11.47–20.57	22.3–46.6	
	Volume	1 (LN)	125.9	21.2	0.97
3	Time	1 (LN)	6.6	33.0	0.78
	Volume	1 (LN)	21.5	8	0.98
4	Time	1 (LN)	6.45	30.0	0.82
		2–3 (G)	10.31–18.44	30.0–102.0	
	Volume	1 (LN)	149.2	92.5	0.85

Mo — Mode; σ — standard deviation; R^2 — coefficient of determination.

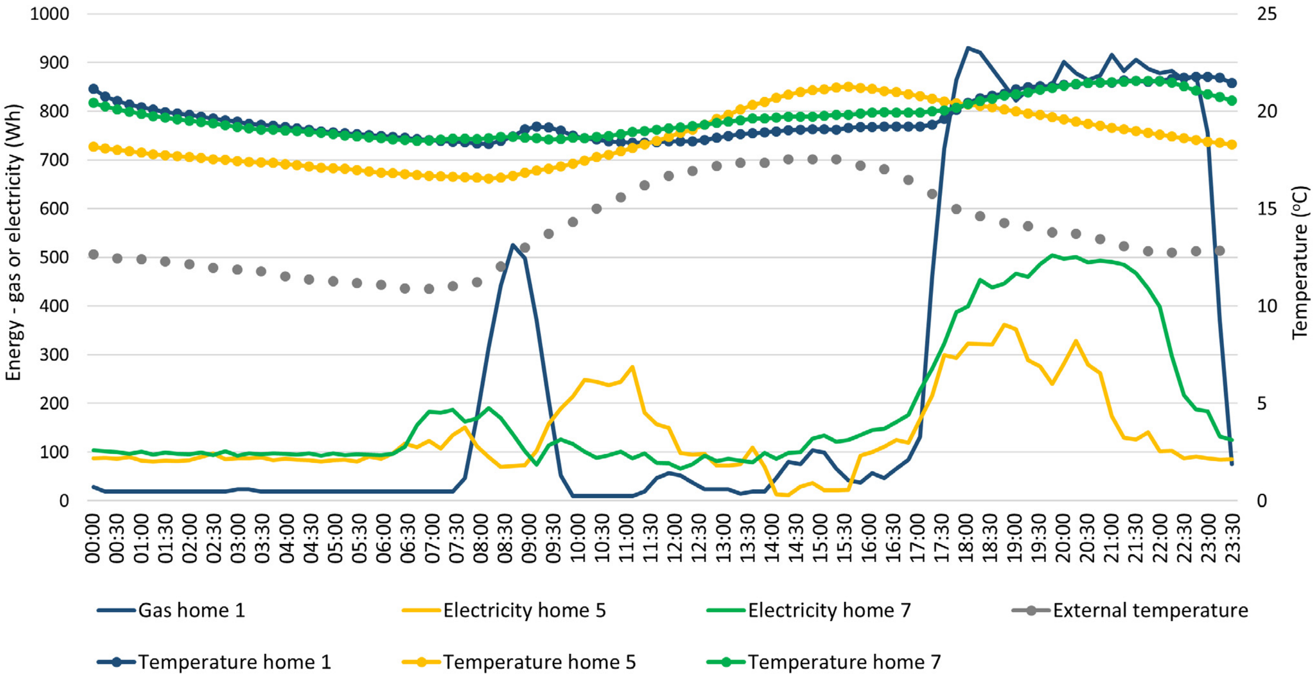

Fig. 3 – Average use of the heating system on weekdays in homes 1, 5 and 7 in July 2015, in the middle of the Australian winter. An increase in internal temperature alongside an increase in energy (gas or electricity depending to the heating system of the home) use is attributed to the practice of heating.

home system. The term interlocking refers to the interconnectedness and interdependence of practices in a routine. For instance, the practice of composting relies on the practice of gardening and/or the practice of cooking and cannot exist without one or the other. These practices are all connected in the home SOP.

Previous research has related the time of practices to occupant lifestyles and socio-economic status (Ashton et al., 2016). For instance, peak water use occurs earlier in houses occupied by early risers who are economically active and therefore bound by the practices of breakfast, transport and work. Late risers, on the other hand, do not have a specific water use pattern (Keyson et al., 2017) and are not interlocked in binding activities constraining the hour of water use. Similar results were observed in this research.

This section will explore interlocking practices in the SOP by discussing the practices of personal showering and garden hand watering.

3.2.1. *Personal showering*

The time of shower and the habituality and routine nature of the practice (reflected in the σ values in Table 6), are influenced by other interlocked practices in the system. Home 3, for instance, comprises a mother and her three teenage sons. The mother works in a full-time job and therefore her time of taking a personal shower is constrained by the practice of work as well as other interlocked practices that form her daily routine, such as waking up in the morning, eating breakfast and transport to work. Her sons, on the other hand, have a flexible schedule and are often at home during the day. The showering time histogram for home 3 (Fig. 4) reveals two weekday peaks, one in the morning (Mo and μ at 07.22), which has a σ value of 55.8 min, and one in the evening (Mo and μ at 17.19), which has a σ value of 225 min (Table 6). The morning shower, which is taken over a shorter time-period may be attributed to the mother, while the afternoon showers, spread over a longer time period (therefore less habitual and routine based), may be attributed to the sons,

Table 6 – Description of the showering time distribution for the eight homes during weekdays and the weekend. Statistically valid Gaussian (G) distributions are identified and numbered in a daily time sequence. Showers that do not have a clear distribution shape were not evaluated.

Home	Weekdays				Weekend			
	Shower, n	Mo (time)	σ (min)	R^2	Shower, n	Mo (time)	σ (min)	R^2
1	1 (G) 2–6 (G)	8.06 8.43–21.32	8.60 26.4–95.2	0.96	1 (G) 2–5 (G)	9.22 11.48–21.13	53.8 19.4–89.5	0.93
2	1 (G) 2–3 (G)	6.29 9.12–18.37	19.20 92.2–147	0.92	NA	–	-	
3	1 (G) 2 (G)	7.22 17.19	55.8 225.0	0.85	NA	–	-	
4	1 (G) 2 (G)	6.49 16.11	25.8 145.2	0.91	1 (G) 2–3 (G)	7.50 9.31–17.38	34.6 103.5–136.0	0.93
5	1 (G) 2 (G)	7.53 18.36	25.8 61.8	0.94	NA	–	-	
6	1 (G) 2–3 (G)	6.53 17.14–21.15	33.6 56.4–63.6	0.89	1 (G) 2–4 (G)	9.50 12.17–21.17	64.9 33.9–156.4	0.85
7	1 (G) 2–4 (G)	6.47 8.50–17.32	14.6 29.6–62.3	0.98	1 (G) 2 (G)	10.17 17.07	73.6 25.6	0.88
8	1 (G) 2 (G)	7.22 19.23	12.6 13.3	0.75	NA	–	-	

Mo — Mode; σ — standard deviation; R^2 — coefficient of determination

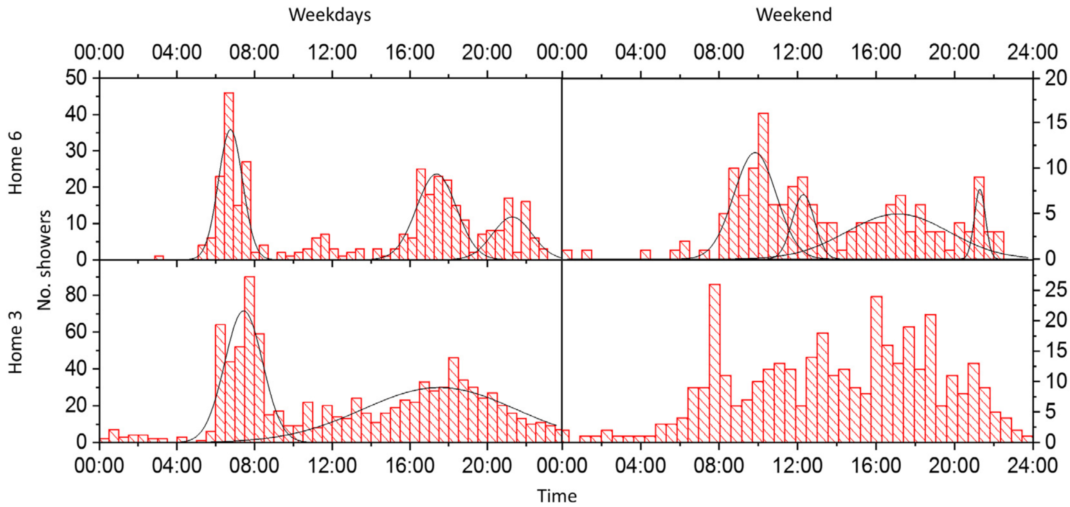

Fig. 4 – Personal showering time histograms and corresponding distribution curves for two homes. Shower times generally follow a Gaussian distribution curve (Table 6).

who are likely to have showers when convenient rather than as part of an interlocked routine.

Home 6 consists of a working couple whose weekday shower times follow the same patterns as the mother of home 3 (Fig. 4). Morning showers have a small σ value (33.6 min), as they are constrained by the interlocked practice of work (Table 6). Evening showers, on the other hand, have higher σ values (56.4 and 63.6 min) as evening routines are more flexible and less interlocked (Table 6).

Showering times were statistically significantly different during weekdays compared to weekends for five of the homes at a 99% confidence level (Table 4). There is also a higher σ value during the weekend for the time that showers are taken than for weekday showering (Table 6 and Fig. 4). Weekend showers are usually taken later in the day and show a greater time distribution for most households compared to weekdays. The weekend shower distributions of homes 2, 3, 5 and 8 are multimodal and cannot be attributed to a specific routine. This demonstrated that although personal shower time is generally tightly interlocked with other practices this may realign in a different context when new home dynamics emerge (e.g. during weekends).

Shower time histograms follow a Gaussian distribution curve (Fig. 4 and Table 6). This could be explained by personal showers occurring at certain times of the day based on routines and interlocked practices. However, once in the shower, meaning and skill combined with the available technology take over and showering practitioners tend to follow certain procedures for achieving cleanliness or comfort. This is demonstrated in Fig. 3 by the length of the shower during the weekend being similar to that of the shower during the weekday. While the shower time varies based on the interlocking practices and routines to be followed that day, the actual process of showering remains the same for these occupants.

3.2.2. *Garden hand watering*

As with personal showering, hand watering takes place during defined periods of the day, when occupants are at home before or after going to work and becomes part of an interlocked daily routine (Table 5). Interviews revealed that garden watering practices are also variable over time and are dependent on skills as well as on the practices of other home occupants. For instance, home 6 revealed that while they did not irrigate their garden in the past, they decided to establish a new lawn, creating the need for a new watering practice to be interlocked into their daily routines. On the other hand, home 2 revealed that they had been trying to grow vegetables but did not have the skill required and decided therefore to cease the watering of their vegetable beds. Home 1 explained that they need to water the lawn daily due to their dog's waste. The local water company also promotes for conservation of water use in the garden (Water Corporation, 2017). However, requesting the occupants of home 1 to reduce external water use may never work simply because their watering practice is interlocked with the practice of the dog relieving itself. Replacing the existing garden water hose for a more efficient fitting or training the dog to go elsewhere would be a more effective solution to influence the water metabolism of the home.

While other research has posited that practices are bound in complex spatial and temporal bundles (Macrorie et al., 2014b), we demonstrate here that distributed, interlocked home practices are reproduced in a sequential temporal spectrum. This sequential spectrum can re-align when social conditions change, as is evidenced through the difference in interlocked practice times between weekdays and weekends (Table 6, Fig. 4).

3.3. *Automated systems*

Given the complexity of everyday practices and their interconnectivity in the home system, affecting them is challenging and unlikely to occur without taking a holistic perspective (Brynjarsdóttir et al., 2012). Traditional behavior change approaches that attempt to persuade change through the provision of information and feedback displays assume that individuals are driven mostly by reason (Steg and Vlek, 2009). This often ignores that practices are bound in space and time and reproduced sequentially as part of an established routine (as discussed in Section 3.2). Modifying them requires therefore either a change in the practice elements, including meaning, or a complete re-alignment of the home SOP. Another solution is to separate, or dis-interlock, practices from the home SOP, for instance, through their automation.

Four of the homes in this research use automatic irrigation to water the garden. The quantitative monitoring data showed that the irrigation volumes were frequently readjusted through the year. According to the research participants, these readjustments were the consequence of other interlocked practices, for instance, the establishment of a new lawn. Local regulations require that reticulated irrigation is only used on allocated days, times and months of the year. However, results revealed that three of the homes programmed the irrigation system incorrectly, watering on the wrong days or times. The innate flexibility of the automated irrigation promptly enables practice modifications. However, skills are still needed to operate the system. This is especially true for new homes that come with pre-installed and pre-programmed automated garden systems, as was the case for home 7. Interviews revealed that the occupants were not able to detect when the irrigation was on due to the underground drip irrigation pipes and their poor understanding of the reticulation settings. In this case automation also gave a sense of disconnection from the practice and the occupants were therefore less engaged in its performance.

If used and programmed correctly, automation can positively influence the use of resources in the home system without it becoming directly interlocked with other practices. The semi-structured interviews with occupants of homes 3, 6 and 7 revealed that since moving into a home fitted with PV panels, they have modified their dishwashing practices, programming the dishwasher to run during daylight hours. In this case, the practice of washing the dishes was dis-interlocked from the practices of cooking, eating or working. On the other hand, dishwashing became interlocked with the skill and technology related to both the operation of the dishwasher and the understanding of the solar technology.

A third example of automation was the use of an automatic pump to conduct the practice of pool cleaning. Home 6 has a pool pump on a timer, functioning twice per day, once in the morning (8.00 to 10.30) and once in the evening (16.30 to 18.45). Whilst the practice of pool cleaning is interlocked with the practice of swimming, it does not depend on any other practice, and functions independently of the home SOP. This practice, however, is also dis-interlocked from the solar system which could power the pool pump thereby avoiding the use of grid electricity. The occupants of home 6 were not aware of this advantage, lacking the skills to reduce the energy related to the practice of pool cleaning.

4. Conclusion

Policy and regulations for residential houses often consider the physical infrastructure alone and tend to focus on the energy or water performance of the building. However, they fail to include users as an integral part of the system. Behavior change programs that are based on socio-psychology theories (Ajzen, 1991; Cialdini et al., 1991; Festinger, 1957; McKenzie-Mohr, 2011) attempt to influence consumers through information campaigns or feedback technology. However, this approach also ignores the fact that homes are complex systems made of people, technologies and practices that are reproduced in bundles across space and time. This research applies the concept of SOP to homes and uses practice theory to provide an understanding of occupants' everyday practices and the intricacy of the interactions between home occupants, the building infrastructure and natural resources.

Detailed quantitative and qualitative data collected over one year were used to analyze resource intensive practices in eight Australian homes in order to provide a holistic insight into the home SOP and understand what is required to enable effective resource savings. Results revealed that practices are performed in a sequential temporal spectrum as part of a routine and are influenced by interlocked practices as well as the routine of other home occupants. Moreover, the manner by which practices are performed are dependent on intrinsic human needs which may be challenging to influence through behavior change programs alone.

Rigid and habitual routines that are highly interlocked have smaller standard deviations related to the time that practices are performed in comparison to more flexible routines. These rigid routines may prove harder to influence. Routines, however, are re-aligned when there is a change in context (e.g. at the weekend). Personal showers and hand irrigation lengths follow a similar pattern every time they are accomplished. For instance, individuals tend to have personal showers of the same length everyday but longer showers that have meanings other than getting clean also occur. The lognormal distribution shape of personal showers indicates that shorter showers are unlikely to happen. Similarly, the use of the heating system is not only directly related to the temperature, but also to other interlocked practices and personal expectations.

Information campaigns that do not address users' needs and fail to understand the intricacies and interlocking of the home SOP are unlikely to have significant impact on energy and water use. Automation, on the other hand, can enable resource intensive activities to be dis-interlocked from an established routine and make change within the SOP easier and more flexible.

This paper has demonstrated through a rich data set how practices are shaped by the routines that they are part of and how a SOP perspective providing a holistic insight into the home could be beneficial to influencing household metabolism and technology into the future.

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Appendix A Audit factsheets

LIVING LABS

JOSH'S HOUSE

LOW CARBON LIVING CRC

AN INTRODUCTION TO SAVING ENERGY

EASY WAYS TO SAVE ENERGY AROUND THE HOME WITHOUT SPENDING A CENT!

Heating/Cooling

- Close off sections of the house that are not being heated or cooled.
- On sunny winter days, pull back the curtains to let warmth in through the windows.
- On hot summer days, close the windows and draw the curtains.
- Set thermostats on cooling units between 24 - 27°C.
- Set heating thermostats to 18 - 20°C.

Kitchen

- Set your fridge thermostat between 3 - 4°C.
- Place the fridge out of direct sunlight and away from heat sources.
- Let steam from hot food stop before putting it into the fridge.
- Wait until the dishwasher has a full load before running it.
- Use energy saving dishwasher cycles.
- Microwaves cook food three times faster than standard full size ovens, saving up to 70 per cent of electricity used for cooking.
- It takes a lot of energy to bring food / water to the boil, but once boiling the energy setting can be cut by two-thirds.
- Use the oven light to check on food in the oven rather than opening the door.
- Thaw frozen food in the refrigerator.

Laundry

- Adjust the water level to match the load.
- Use the soak cycle to remove stains.
- Use warm or cold water settings rather than hot.
- Use a clothes line to dry your washing.

Bathroom

- Have a short shower instead of a bath.
- Set your storage hot water system to just over 60°C. (Instantaneous to 50°C).

General

- Remember to turn off appliances at the wall when they are not in use.
- Turn heating and cooling appliances off when you leave your home.
- Switch off the bar fridge if you are not using it for an event.

LOW CARBON LIVING CRC   Curtin University   City of Fremantle   JOSH BYRNE & Associates

WANT TO SAVE EVEN MORE?

Why not invest in:

- replacing incandescent light globes with compact fluorescent light globes;
- installing a pelmet and lined curtains that reach to the floor;
- shading windows with awnings;
- insulating your ceilings, walls and under timber floors;
- using reversible ceiling fans. They only cost around one cent per hour to run and can reduce your heating and cooling costs;
- getting an approved service agent to regularly service your heating and cooling appliances;
- installing flow regulators and low-flow showwerheads;
- making sure your fridge/freezer doors seal properly;
- purchasing PCs, monitors, printers, fax machines and copiers that "power down" after a user-specified period of inactivity;
- considering a pool blanket to reduce heat loss if you have a pool;
- upgrade your old fridge to an energy efficient model;
- switch to a solar hot water system.

MAKING A BIG INVESTMENT?

Check this out:

When you buy an appliance you should compare the size, features, price and running costs. For electric and natural gas appliances the energy rating label provides a useful guide. Look out for the energy rating sticker on appliances in the shop, or do your research at home by looking up the most energy efficient options on www.energyrating.gov.au

For more information contact Christine Eon: christine.mouraeon@postgrad.curtin.edu.au

The researchers acknowledge 'Be Living Smart' for use of the factsheet content.

NATURAL HEATING AND COOLING FOR A COMFORTABLE HOME

Making small changes to your home can help get the most out of the natural energy from the sun to heat your home in the winter and the breeze to cool your home in summer. Be smart about the way you use heaters & air conditioners and you can have a more comfortable home and lower bills.

WHY?

A home that is set up for natural heating and cooling will be more comfortable and have lower bills. Energy use in a typical home costs the planet around 6,600 kilograms of greenhouse gas and the occupant $1,500 in bills each year. Around a quarter of the energy used in most WA households is for heating and cooling. Up to half of this energy is wasted, so switching to natural heating and cooling could cut these costs in half.

HOW IT?

The smart solutions for a more comfortable home are:

- Shading windows so as to reduce summer heat but still gain winter warmth
- Insulating to keep comfortable temperatures for longer
- Reducing draughts and managing cooling breezes
- Using ceiling fans to move warm air in winter and create your own breezes in summer
- Adjusting heater and air conditioning settings
- This guide shows you how to act on these smart solutions.

SHADE YOUR WINDOWS FROM THE SUMMER SUN

WHY?

The effect of the sun on windows can be the equivalent to a one bar electric heater for every square meter of window. An unshaded window can make a room degrees hotter for several hours. This is good in the winter, but a big problem in the summer. Closing curtains or blinds inside the house will help, but external shading is more than twice as effective – don't let the summer heat in at all.

HOW DO I DO IT?

Shading windows to the east or west

Windows to the east or west are often the biggest problem because the morning and evening sun is low and cannot be blocked out by the eaves of the house. Shading for east or west windows needs to be low over the window and removable in the winter (to let the heat in).

Some shading options are:

- Install an awning blind – available from major hardware stores for between $100 and $400 (for DIY installation). These are lifted easily and cut out about 70% of the heat.

- Roller shutters can be professionally installed for between $600 and $900, providing insulation, noise control as well as shading – see 'Window Roller Shutters' in the Yellow Pages.
- Apply window tinting – this will cost around $200 per square meter of window and will cut the heat by 50%. But also reduces the natural light all year round.
- Grow a small tree, large shrub or a pergola with a vine outside the window. Deciduous varieties drop their leaves and let winter sun in. Planting can cut 60% of the summer heat from a window.
- Simply hanging shade cloth from the outside of the window frame or eaves is an effective and low cost solution.

Shading windows to the north

- Most houses have eaves to shade windows to the north from the high summer sun. The lower winter sun can come in under the eaves to warm the house. For north windows:
- Add fixed awnings where there are no eaves. Solar-passive homes often have solar pergolas to shade windows and outdoor areas to the north. These pergolas have angled slats to let in the winter sun.

Take extra action in summer:

Early on hot days, close windows, doors, curtains and pull down exterior blinds to block out the summer heat.

- When the temperature is cooler outside than inside open all windows to capture cooling breezes.

Use a fan – it will cool you a few degrees, and cost 95% less than running an air-conditioner.

Minimise your air-conditioner use and set it to 24oC-27oC degrees (every extra degree of cooling adds 10% to the cost).

Take extra actions in winter:

- Open blinds and curtains during the day to let the free heat of the sun in.
- Use an electric blanket or hot water bottle, to warm your bed before you go to sleep. This will save the use of a room heater.
- Use reversible ceiling fans and set heaters to 18o-21o degrees (saving 10% in heating for every degree).
- Gain more savings by:
- Sealing the gaps around windows and doors (a draught stopper for under doors, sealant around window frames and plastic/ foam weather strip inside door frames).
- Closing internal doors so that you heat/ cool only the rooms that you are going to use.
- Dressing for the season (warmer clothes in winter and light clothes in summer).
- When buying heaters or coolers look for the right size and the most energy efficient model (see www.energyrating.gov.au or compare star rating stickers).
- Replacing paving with a waterwise garden bed (paving located in the wrong place can create a heat trap that transfers or reflects heat into the house).

ROOF INSULATION

WHY?

- Most heat is lost or gained through the ceiling and roof of your home. By installing or upgrading insulation you can improve the comfort of your house. You can reduce your heating/ cooling costs and your unwanted heat loss/gain by up to 30% and save around $130 a year on energy bills.

HOW DO I DO IT?

The main types of insulation are:

- Bulk insulation that traps small air pockets, slowing the rate of heat transfer.
- Reflective insulation that bounces heat preventing it from entering or leaving your home.

Some of the most important things to consider before buying your insulation are:

- The R-value measures the products resistance to heat flow - the higher the R-value the better the insulation.
- The environmental benefits of different products. Some polyester insulation contains recycled PET (the plastic commonly used in drink bottles). Some cellulose fiber contains recycled paper. Glass fibre insulation contains recycled glass.
- Before you insulate, it's very important to fix other sources of heat gain and loss from your home by shading windows from the summer sun and blocking draughts around windows and doors. Insulating a home with sources of unwanted heat can create an "oven" effect and increase cooling costs.

WHERE CAN I FIND AN INSULATION SUPPLIER?

A list of insulation suppliers is available by using the Yellow Pages or see: www.yellowpages.com.au

WHAT ARE THE COSTS?

The cost of fully installed ceiling insulation, in a typical 150 square metre home, is around $1,200.

For more information contact Christine Eon: christine.mouraeon@postgrad.curtin.edu.au

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HOW TO CONVERT DOWNLIGHTS TO A MORE ENERGY EFFICIENT OPTION

Halogen downlights are common in Australian homes. Halogen lights are designed for 'task' lighting (e.g. bench-tops or pictures), but are an expensive option for general room lighting.

- Low voltage halogen lamps are not low energy lamps: each 50 watt lamp generates more than a kilogram of greenhouse gas every 20 hours.
- Each standard halogen downlight uses 50 watts of power and the transformer in the ceiling uses a further 10-12 watts —similar to an ordinary 60 watt globe, but you need more of them to light a room.
- Due to the heat generated by halogens, insulation cannot easily be installed over the fitting, reducing the efficiency of roof insulation.

WHAT CAN I DO?

- There are alternatives for each of the halogen downlight types.
- 240 volt downlight lamps (GU10 type globes) can be directly replaced with an 11watt Compact Fluorescent Globe (CFG).These are available at hardware stores and over the internet for approximately $15-20 per globe. Some CFG's are slightly longer than a normal halogen globe so you should replace one unit initially to determine if the CFG will fit.
- For 12 volt downlights (MR16 type globes), replace the 50 watt lamp with a lower wattage, higher efficiency globe, such as a 20 watt infrared coated (IRC) globe. These globes are available at hardware stores and cost approximately $4 per globe. This will reduce lighting costs significantly.
- In 12 volt systems, both 50w and 20w lamps can be replaced by 3 watt LED (Light Emitting Diode) globes with an energy saving of around 90% over standard halogen lamps. LEDs provide a 'cold' light (nearer to daylight) and less light than a standard lamp. They are ideal for replacing halogen lamps when multiple downlights have been installed or to highlight a painting. They are less suitable for replacing one or two halogens over a kitchen bench-top (switch to 20w halogens for that situation). LED globes are available from hardware stores for around $10 -20 each.

HOW DO I DO IT?

1. Turn off the lamp and wait for at least 10 minutes for the halogen bulb to cool down.
2. Remove the safety tempered glass (by pushing it toward the bulb holder to release the clip or by removing the screws, depending on the model)
3. Use a non-linen cloth to pull the bulb out of the bulb holder.
4. Use a non-linen cloth to hold the replacement bulb and insert it into the holder.

5. Replace the safety tempered glass: rest it on the clip while pushing it toward the bulb holder in order to make room for the glass to rest on the other end.
6. Turn the lamp or fixture back on.
7. Contact your local council for information on how to dispose of the old globe.

If you are planning to install halogen lights as general room lighting in your home, think again as you could substantially increase your lighting costs.

WHY?

Throughout the year we use a lot of electricity within our homes. Electricity used for lighting an average Australian home generates around three quarters of a tone of greenhouse gas and costs around $100 per year. A home with many halogen down lights could easily spend twice this amount on lighting. Switching a 50w lamp to a Compact Fluorescent or LED alternative will pay for itself with a few years and save you money over the life of the globe.

Remember, it's not the volts that matter: more watts means higher energy consumption, resulting in larger bills and more greenhouse gas emissions.

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HOW TO ADJUST AN INSTANTANEOUS WATER HEATER

Water heating accounts for about 30 percent of an average Australian household's energy use, "costing" up to $400 and creating 3,000kg of greenhouse gas. The thermostat on your hot water system needs to be set high enough to deliver water at the required temperature. However the thermostat is often set much higher than is required, increasing your electricity or gas bill.

WHAT CAN I DO?

You can reduce your water heating costs by simply lowering the thermostat setting on your water heater.

HOW DO I DO IT?

All instantaneous water heaters can be adjusted. Temperature controls for instantaneous water heaters can have simple mechanical controls or sophisticated electronic controls.

Electronic Controller

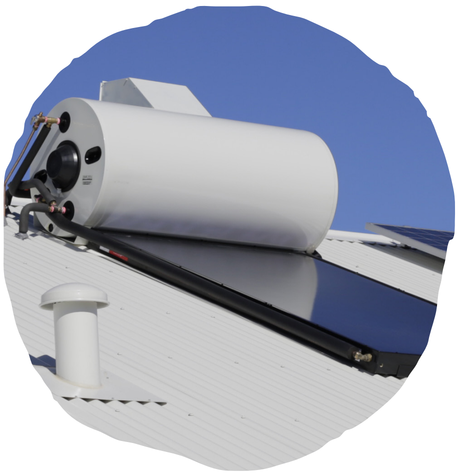
- If you have an electronic control simply use the controller to reduce the temperature to the desired level. Set water temperature to 40-45ºC for a satisfying shower and 55ºC for kitchen use (e.g. washing up).
- If a controller is not installed, the water heater defaults to the preset outlet temperature. The preset outlet temperature setting of this type of water heater cannot be adjusted by the householder. This setting can only be adjusted by a licensed gas fitter or an Accredited Service Agent.

Manual Control

On some units the temperature controls are accessible on the front of the hot water system. Other units have a cover that you can lift or unscrew by hand to reach the thermostat controls. If the cover hasn't been opened for a while keep in mind there may be spiders inside.

To set the temperature:

1. Locate the thermostat control.
2. Reduce the temperature to 50ºC.
3. After turning it down, check the water temperature with a thermometer at the tap farthest from the water heater. Thermostat dials are often inaccurate and several adjustments may be necessary before you get the right temperature.
4. Mark the beginning temperature and the adjusted temperature on the thermostat dial for future reference.
5. If you plan to be away from home for at least 3 days, turn the thermostat down to the lowest setting or completely turn off the water heater.



Altering the setting of the thermostat on your instantaneous water heater is generally easy for the householder. Prior to changing the temperature consult your water heater owner's manual for instructions. If in doubt, a plumber or handyman will be able to alter the temperature setting within a few minutes.

WHY?

Instantaneous water heaters are often set to heat water to a much higher temperature than is actually required. This means more energy is used to heat the water. It is not unusual to find temperatures over 70°C . By reducing the water temperature setting on your instantaneous water heater to 50°C* you can significantly reduce your water heating bill. In addition reducing the water temperature minimizes the risk of scalding. Hot water can produce 3rd degree burns in less than 6 seconds at temperatures above 60°C.

*Storage systems are set to 60°C or higher to reduce health risks associated with storing hot water.

HANDY HINT

Save money by setting the water temperature so that you can have a satisfying shower with little or no cold in the mix - pay to heat just the water you want to use!

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STANDBY POWER CHECKLIST

WHAT CAN I DO?

Many appliances use energy even when they are not in use simply to maintain a convenient 'ready' or 'standby' state. Most of the energy used by appliances on standby is just wasted. Some appliances have a 'master switch' that allows you to turn power off, whilst others need to be switched off at the wall. If an appliance has a glowing light, responds to a remote or is warm to touch when not in use, then it is in standby mode and consuming power.

WHY?

Standby Power is about 10% of the typical household energy bill. This costs you around $100 and contributes 750kg of greenhouse gas to climate change.

HOW DO I DO IT>

Different appliances have different solutions.

- If the appliance has a master switch (like the power button on the front of many television sets) switch that off.
- If there is no master switch – turn it off at the wall (no need to unplug from the socket).
- If the wall socket is hard to reach – buy a power board with individual switches that can be put in an easy to reach position.
- If several appliances have clocks on them – choose the ones to turn off (perhaps switch the microwave and radio off at the wall, but keep the oven clock on). Have you turned off at the wall or at the master switch the following appliances?

✓	Stereo	✓	Computer monitor	✓	Scanners	✓	Mobile phone/ MP3 chargers (even when no device is being charged)
✓	TV	✓	Printer	✓	Pool equipment	✓	Electric toothbrushes
✓	Set top boxes	✓	Computer speakers	✓	Microwave	✓	Air conditioners
✓	Game console	✓	Broadband box/ modem	✓	Washing machine	✓	Room Heaters

Turn these things off after every use, or at least every night before you go to bed. Even though most standby power is wasted energy, sometimes it serves a purpose such as retaining settings. A shut down computer usesW power for its internal clock – you can switch a computer off at the wall, but you will need to replace the battery sooner (perhaps just make sure that it is shut down and the screen and printer are off after every use).

Do not turn off the following:

- security systems;
- smoke alarms;
- time controlled equipment like reticulation systems;
- regularly used appliances with a clock or timer such as video recording equipment (some newer models have a 'sleep' mode that retains settings, but uses less power than when on full standby).

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SET UP YOUR FRIDGE

Refrigerators, freezers and bar fridges are one of the largest users of energy in the home because they run 24 hours a day, 365 days of the year. Running a family fridge plus a bar fridge could be costing a household up to $200 per year to run and generating 1,500kg of greenhouse gas. A 'spare' fridge in the garage and a wine cooler on the bench-top can be even more costly (both financially and to the environment). Simple changes to the position, setting, maintenance and number of fridges that you run will make a very big difference to everyday costs. The age of your fridge also makes a big difference – newer fridges are generally much more energy efficient than older models.

WHAT CAN I DO?

Run only the fridges that you need day to day – switch the bar fridge on only for parties. Adjust the temperature settings and position of your fridge to minimize running costs. Upgrade to a new energy efficient fridge and dispose of the old one.

HOW TO DO IT

Count how many?

Check the number of fridges, freezers and coolers that you have running. Look inside – does everything need to be kept cool all of the time? If you are chilling more drinks than you need for an ordinary day, then move the essentials into your main fridge, switch off the bar fridge/ second fridge/ wine chiller, prop it open and save on running costs.

Check what condition?

Check door seals by placing a business card in between the seal and the closed door – if it won't stay in place your seals need replacing and the cold air (and dollars) are 'draining out of the fridge. Get new fridge seals fitted by a fridge maintenance supplier (or plan to upgrade to a new model).

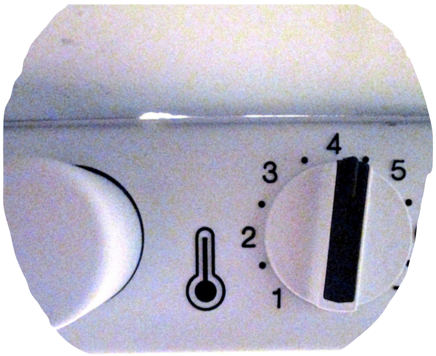
Look - where is it?

A fridge should have good air flow around it (to let the hot air that is extracted as part of the chilling process) to ventilate away from the unit. A cooling space behind and above a fridge will improve its efficiency. A second fridge in a hot room such as a garage or back verandah will use more energy trying to beat the heat from the hot room – move it or throw it out.

Act - Set it up?

A fridge should be set to between 3°C – 4°C, and the freezer unit to between -15°C to -18°C. Get a good quality fridge/freezer thermometer (available from kitchen shops for around $8.00 – it will pay for itself many times over!) and leave it in a closed fridge for at least an hour without opening the door. By leaving the fridge closed you will be measuring the normal working temperature and not the 'spike' caused by opening the door. If the fridge is below 3°C, then turn the temperature up, if it is above 4°C then turn the temperature down. Repeat the exercise for the freezer unit (aiming for -15°C to -18°C). The saving from a fridge/ freezer running at the right setting (as compared to one running too cold) can be around $20 a year!

Follow Energy Wise tips



Running costs and healthy food storage temperatures are maintained by:

- not leaving the fridge/ freezer door open for long periods of time;
- keeping the fridge well stocked (or putting empty, but sealed, plastic containers inside to trap the cold air and prevent it from 'falling' out every time the door is opened);
- thaw frozen food in the fridge (just allow a little longer);
- let the steam from hot foods disperse before storing in the fridge.

Why?

The energy, financial and environmental costs of fridges can be large.

Action	Saving (each year)
Swith off the bar fridge (except for parties)	Save 280kg CO2 & $40
Change the setting to the recommended level (on a large 5 star model running 4oC too cool)	Save 75kg CO2 & $15

AN INTRODUCTION TO SAVING WATER

There are many ways we can save water in and around the house and garden. Simple things like taking shorter showers, using waterwise appliances and making your garden waterwise don't take a lot of effort. Saving at least 6 buckets of water a day is easy to achieve for most households.

BIG SAVINGS

Take shorter showers and install a water efficient shower head.

Showers account for one third of all water used inside the home, so an easy way to save is to keep your showers short. An eight minute shower in a conventional (12 litres per minute) shower uses approximately 35,000 litres of water each year. A four minute shower would use approximately 17,500 litres a year less. If you installed a water efficient 3 'Star' (nine litres per minute) shower head and had a four minute shower, you would save approximately 20,000 litres a year.

Install a dual flush toilet system

The toilet uses about a quarter of the water inside the home. By installing a dual flush system a household could use 75% less water than a standard single flush toilet, saving 30,000L a year.
Single flush toilet = approximately 44,000 litres a year
Dual flush toilet = approximately 11,000 litres a year

Buy a 4.5 'Star' washing machine

Washing machines use around a quarter of water in the home. When buying a new washing machine choose one with a WELS rating of four stars or more. Go to www.waterrating.gov.au for more information.
Conventional washing machines = approximately 60,000 litres a year
Water efficient washing machines = approximately 25,000 litres a year

Brushing your teeth

Instead of running the tap when you brush your teeth simply wet your toothbrush before you begin and use a glass of water to rinse.

Running water while brushing for two minutes each day = approximately 14,000 litres a year
Using a cup (250ml) of water while brushing your teeth = approximately 180 litres a year

Fix a leaking toilet or tap

A leaking toilet or tap wastes around 9,000 litres of water per year. To check your cistern, place a few drops of food colouring in the tank. Without flushing it, look for colouring in the toilet bowl. If it's getting through, you've got a leak, and it's time to call a plumber.

Run your dishwasher full

Operate your dishwasher only when it's full. Older dishwashers can use up to 40 litres. New water efficient models use less energy and only around 15 litres of water, saving around 9000L a year.

Older model dishwasher 40 litres per wash per day = approximately 14,000 litres a year

4 'Star' rated dishwasher 15 litres per wash per day = approximately 5,000 litres a year

MORE EASY WAYS TO SAVE WATER

Plant a waterwise garden

The garden and lawn account for around half the water used by households. Choosing waterwise plants for Perth, sticking to water roster days, mulching and installing drip irrigation are just some ways to save water and have a great looking garden. To find out more go to www.watercorporation.com.au and click on 'Save water'.

Pool Covers

With more than your entire pool's volume of water being lost every year through evaporation, you can save water and money by regularly using a pool cover.

Washing your car on the lawn

When it's time to wash your car, use a bucket, as a running hose wastes up to 20 litres of water a minute.

Use a broom - not a pressure washer

When we need to clean down driveways or paved areas use a broom. Using a hose or a pressure washer is a fast way to waste water and attracts a fine if caught.

Trigger hoses save

Switch from a running hose to a trigger spray and target your water use.

Install a rainwater tank

Each year, around 40,000 litres of water could be collected from your home's roof area and used for flushing the toilet, doing laundry and watering the garden, thereby taking pressure off our drinking water supplies.

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HOW TO INSTALL A WATERWISE SHOWERHEAD

The type of showerhead you have in your home has a large impact on your energy and water consumption – this affects your environmental footprint and bills.

Showers account for one third of all water use inside the home, so an easy way to save is to keep your showers short and install waterwise showerheads. Conventional showers use around 15 litres of water per minute. Three star showerheads use nine litres per minute. By making the change and reducing your showers by two minutes, you can save approximately 20,000 litres of water a year (or five buckets a day).

Water heating accounts for about 30% of the total energy costs in many Australian homes, generating around 2,000 kilograms of greenhouse gas emissions per annum.

Heating water represents one of the largest energy use (gas or electric) in the home, costing up to $400 each year. This expense will increase as the price of electricity and gas continues to rise.

HOW DO I MAKE THE CHANGE?

Prior to purchasing a new showerhead, find out what you have now:

1. Place a 10 litre bucket under the showerhead. Turn the shower on full for 30 seconds.
2. Turn off tap.

If the bucket is more than half full the showerhead is a conventional one. If the bucket is less than half full the showerhead is likely to be waterwise.

Is my hot water system suitable to change to a waterwise showerhead?

If you have an instantaneous water heating unit or a gravity-fed hot water unit, check with the heater manufacturer. The reduced flow rate of some three star showerheads may be too low for some heater models. If your existing water heater is not suitable and is old, consider replacing it with a high efficiency or solar hot water system.

My hot water system is suitable, what next?

Most hardware stores and bathroom suppliers sell water saving showerheads. Expect to pay between $40–$100 for a good quality showerhead.

I'M A RENTER, WHAT ABOUT ME?

As showerheads are a fixture of the property, ask your landlord for permission before changing them.

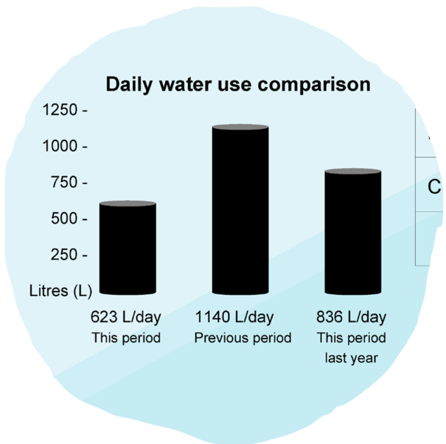
INSTALLING A THREE STAR WATERWISE SHOWERHEAD

Regulations in Western Australia suggest that any 'plumbing work' should be done by a plumber. So call a plumber, make a cup of tea and watch as they do the following simple job:

Step 1 – With the shower taps turned off (no need to cut off the water supply to the entire house), unscrew the showerhead.

Step 2 – Clean and dry the pipe threads and then wrap three layers of thread tape around them.

Step 3 – Screw the new showerhead on (don't overtighten). Run the shower for a few seconds to check for leaks. Tighten only if necessary.



WATERWISE TOILET SOLUTIONS

Toilets account for around one quarter of water use in the home. A single flush cistern can use more than 50,000 litres each year. A modern, water efficient dual flush toilet will use only around 15-20,000 litres. A leaking toilet, where the water trickles continuously from the cistern in to the bowl, can waste around 9,000 litres of water a year.

WHAT CAN I DO?

There are several easy ways to save toilet water:

- Check for leaks.
- Convert to low flush.
- Use the half flush.
- Plumb in a rainwater tank.

HOW DO I DO IT

- Remove the toilet cistern lid.
- Add several drops of food colouring (enough to give the water in the cistern a strong colour) and do not flush. Return and check the water in the toilet bowl after 30 minutes. If the water down in the bowl is becoming coloured then the cistern is leaking.
- If you have a leak it is possible to replace the washer inside the toilet cistern (hardware stores sell toilet washer sets often with step by step instruction on the back). It can be a tricky job to remove the washer from under the flushing mechanism, so you may prefer to hire a plumber to fix it.

CONVERT TO LOW FLUSH – BUY A "4 STAR" OR "5 STAR" TOILET

- Replacing one old toilet can save more than 20,000 litres of water each year and $15 off your water bill.
- Research the water efficiency of toilet sets on the market by logging onto www.waterrating.gov.au or looking at the star rating sticker in the hardware/ plumbing store.
- Choose the model that you want and book a plumber to install the new toilet set (it is best to replace the cistern and bowl because the manufacturer matches the flush to the design to get best results).
- A new "4 star" toilet set, plumbed in, will cost around $600 but will deliver savings on your water bill for years to come.

USE THE HALF FLUSH

- Using the half flush will save water. Getting into the habit can be a challenge so try putting a reminder notice on top of the cistern.

WHY?

- Conventional toilets use up to 12 litres of water with every flush. A "5 star" toilet can use as little as 2.3 litres on the 'half flush'. By making the change you can save thousands of litres of water per year and reduce your water bill.
- When looking for a plumber, be sure to choose an endorsed Waterwise plumber. See www.watercorporation.com.au under: "Save water". "Waterwise specialists" for a list of waterwise plumbers.

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HOW TO FIX A LEAKING TAP

Leaking taps are a common plumbing nuisance. The problem is usually a worn washer, which is very simple to fix.

WHAT TO DO?

Replace the washer in your tap.

HOW TO DO IT

Regulations in Western Australia define any work inside the pipes or tap ware as "plumbing work" which should be done by a plumber. So call a plumber, make a cup of tea and watch as they do the following simple job.

METHOD - THE PLUMBER WILL:

1. Cut off the water supply to the tap by turning off the isolating valve under the sink. Older houses may only have the water mains tap out at the water meter (usually in the garden). Open the leaking tap to release any water left in the pipe.
2. Plug the basin to avoid losing tap parts down the drain. Remove the tap's cover with a screwdriver to expose the screw. The screw is usually under the hot or cold sign. Some taps will have screws on the side.
3. Undo the screw and remove the handle.
4. If the tap is enclosed with a metal cover, unscrew by hand or use a wrench. Use a cloth over the cover to protect the finish from scratches.
5. Use a spanner or wrench to unscrew the tap bonnet. Completely take out the spindle to see the large body washer, O-ring and the jumper valve (this one should just fall out. If not, pull it out with pliers).
6. Replace the body washer, O-ring and jumper valve then refit bonnet and spindle – make sure not to over tighten the nuts.
7. Reassemble the tap in reverse order, close it and then open the water mains.
8. Check that the leaking has stopped.
9. If your tap continues to leak after replacing the washers, it may need to be reseated. The licensed plumber will be able to reseat the tap.

WHY?

Not only does a leaking tap create an annoying noise, it can waste around 4,500 liters of water per year if left unchecked. With climate change resulting in less rainfall it is important to undertake permanent water efficiency measures to save as much water as possible. Fixing a tap also saves you money on your water bill!

When looking for a plumber, be sure to choose an endorsed waterwise plumber. See www.watercorporation.com.au under: "Save water". "Waterwise specialists" for a list of waterwise plumbers.

10 House Living Labs Study: A research project by Curtin University and the CRC for Low Carbon Living.
For more information contact Christine Eon: christine.mouraeon@postgrad.curtin.edu.au
The researchers acknowledge 'Be Living Smart' for use of the factsheet content.

YOUR GUIDE TO WATERWISE GARDENING

Water is a precious resource and Western Australia is being severely impacted by climate change, resulting in the driest years on record. The average Perth household uses around half of their water in the garden, which makes it a great place to start saving water. Waterwise gardens use less water and are low maintenance, leaving you with more time to relax and enjoy your surroundings. Follow the tips provided for a beautiful waterwise garden.
Having a waterwise garden will:

- Save water - every drop counts!
- Reduce your impact on the environment (e.g. less fertilizer leaching).
- Reduce maintenance (less pruning and mowing required).
- Save money on water bills!

WHERE DO I START?

Select waterwise plants to create an attractive, low maintenance garden that helps conserve our precious water resources.

HOW DO I DO IT?

Planning and Design

Some basic planning is critical to achieve a beautiful and waterwise garden – just follow these handy hints:

- Take the time to observe the microclimate in different parts of your garden (e.g. sunny, shady, windy, etc) – this will allow you to select plants that are best suited to particular conditions.

Consider the topography of your garden for positioning different plants. Choose hardy, deep rooted plants for sloping areas where water tends to run off rather than infiltrate the soil. Place thirsty plants in depressions where rain (and irrigation) water collects.

- Group plants with similar water requirements together so you can irrigate them efficiently – this is called “hydrozoning”. Waterwise Garden Centres label their plants as ‘one, two or three drop plants’ to assist you with grouping them in the garden. To locate the nearest accredited centre just follow the ‘Save water’ links from www.watercorporation.com.au.

- The majority of your garden should be set aside for hardy “one drop” Waterwise plants which are suitable for Perth conditions. Keep the area for thirsty or “three drop” plants (including vegetables and annual flower beds) to a minimum, and locate these close to the house for maximum enjoyment.

- An incredibly diverse range of Waterwise plants are available, so you can create any style of garden you like – including Mediterranean, cottage, formal and even tropical themes! Garden design ideas and compatible species lists are available from the Water Corporation at www.watercorporation.com.au

Plant Selection

- The Perth area has unique and challenging gardening conditions due to our Mediterranean climate, with long, hot, dry summers and short, cool winters. Consider using native plants that are ideally suited to your conditions and need minimal watering once established. Local native (or indigenous) species have the added bonus of providing food and habitat for local fauna. There is a huge range of hardy exotic species that are well suited to Western Australia's conditions but are not invasive weeds. You can get some help in choosing stunning waterwise plants for your garden from a number of places.
- Visit your local accredited nursery or garden centre and enquire about species suited to your area. They can also help you to identify your soil type characteristics, including texture and pH (a measure of soil acidity/alkalinity)
- The Water Corporation's "Waterwise Plants for Perth" is an excellent database of native and exotic plants that (once established) will flourish on one watering a week or less during summer – follow the links from www.watercorporation.com.au.
- The Wildflower Society of Western Australia provides species lists for the different Western Australian soil types – visit the website http://members.ozemail.com.au/~wildflowers/Soils.html.

WATER CORPORATION waterwise

Timing

Autumn (April and May) is one of the best times to plant in Perth due to the cooler weather. Give your new plants the best chance to thrive by planting at the right times.

Lawn

Lawns typically need more water than hardy shrubs and ground covers. They are also higher maintenance, so when planning your garden, carefully consider whether you need lawn, and if so keep it to the minimum area required.

Hardy ground covers or stylish paving can make a great lawn replacement (but avoid creating heat traps near the house from pavers that transfer summer sun into the house slab or reflect heat up onto windows).

If you do decide to have lawn, choose a water-efficient species such as Saltene, Zoysia or one of the soft leafed Buffalos. Soil preparation is also important to improve the water efficiency of lawns.

Potplants

If establishing a garden in pots, use a premium grade potting mix – it has a higher water holding capacity so you will not need to water as often.

Unglazed clay pots are porous and dry out quickly. Coat these with a sealing agent prior to planting, but make sure the drainage holes are clear.

PREPARING YOUR WATERWISE GARDEN – SOIL CONDITIONING AND MULCHING

Adding soil conditioner to your garden beds and pots along with a layer of coarse mulch can help you create a thriving, water-efficient garden.

Soil conditioning – what can I do?

The secret to a flourishing garden is well prepared soil...so be ready to get your hands dirty!

A well conditioned soil:

- Is filled with plenty of organic matter and abundant soil life.
- Has a pH (soil acidity/alkalinity) neutral to slightly acidic (pH 6-7).
- Is free draining while still able to retain moisture and nutrients.

The first rule of successful, low maintenance gardening is to feed the soil, not the plants. A well conditioned soil will support plants without the need for regular applications of chemical fertilisers, which can quickly leach through our sandy soils and contaminate groundwater and water ways.

How do I do it?

To improve the quality of your soil, add organic matter such as:

- Compost – make your own with a range of organic household materials, with the added benefit of reducing your household waste.
- Worm castings – become a worm 'farmer' and get your 'workers' to create this wonderful soil conditioner.
- Aged animal manures (e.g. chicken, sheep, cow, horse) – these are great for growing veggies and other hungry exotic plants. Remember that manure is nutrient rich and should be used lightly. It may also harm some native plants. There are specialist slow release fertilisers for natives – just ask your local nursery for further advice.
- Packaged organic fertilisers (e.g. blood and bone, chicken manure pellets and liquid organic fertilisers) – these feed your plants and also improve the soil (just follow the product recommendations).
- Organic mulches – these break down to improve the soil.

Organic matter can be dug in prior to planting or laid on top of soil in an already established garden. Either way, it will break down and improve your soil. Always add soil conditioners prior to planting and at least twice a year to established plants. Check your soil pH with a kit from your local nursery. Most plants prefer a pH of around 6-7. If your soil is not within this range, the local nursery will be able to recommend an appropriate product to adjust the pH level, or suggest plants suited to the conditions. Remove all weeds from your garden area – weeds compete with plants for soil nutrients and water. Apply wetting agent to your soil in early Spring and late Summer to counter Perth's water repellent soil.

Why?

BENEFITS	SOIL CONDITIONING
Improves soil structure as well as moisture and nutrient retention	X
Encourages microbiological activity	X
Makes plants healthier	X
Reduces the water needs of your plants, helping you save water	X

MULCHING

WHAT CAN I DO?

There are three main types of mulches – feeding mulch (such as pea straw, shredded lupins or lucerne hay), woody mulch (such as wood chips or prunings), and permanent mulch (such as gravel or pebbles). Good waterwise mulches have coarse and irregular texture, allowing water to penetrate and the soil to breathe, whilst reducing evaporation and keeping the soil cool.

Soft mulches (such as feeding mulch) break down rapidly to feed the soil and need topping up regularly. These are suited for fruit trees, vegetable gardens and other hungry plants.

Woody mulches are better suited to deeper rooted hardy plants (such as natives) and are ideal for exposed areas as they are less likely to blow away.

Permanent mulches are mainly used for landscaping effects but also play an important role in retaining soil moisture. These are best suited to plants that have modest feeding requirements and don't drop leaves (such as succulents).

HOW DO I DO IT?

Mulch is best applied at the end of winter or the beginning of spring while the ground is moist from winter rain and before the hot, drying winds of summer. Condition your soil prior to mulching, lay mulch around your plants (keeping clear of the stem) in a layer about 5-10cm thick. Course woody mulch should be reapplied annually.

Before mulching:

- Remove any grass, weeds and dead plants from the garden;
- Put in any new plants;
- If installing an irrigation system, such as a drip system, do so before mulching

MULCHING TIPS

- Free mulch (shredded green waste) is often available from your local council. It can also be purchased cheaply from commercial tree loppers. Mulch Net is a local Perth company that arranges free mulch deliveries from tree lopping contractors (for more info visit www.mulchnet.com).

WHY?

BENEFITS	MULCHING
Improves moisture and nutrient retention in the soil	X
Suppresses weeds	X
Encourages microbiological activity	X
Makes plants healthier	X
Looks great	X
Prevents soil erosion in windy areas	X
Reduces the water needs of your plants, helping you save water	X

MAINTAINING YOUR WATERWISE GARDEN – EFFICIENT WATERING

WHAT CAN I DO?

By applying the right amount of water in the cool hours of the day and using drip irrigation you will save water and allow your garden to thrive.

HOW DO I DO IT?

Plan for Efficient Watering

Group plants in your garden together according to their water needs so you can irrigate them efficiently without over or under watering. A good place to start is with a Waterwise Garden Appraisal from your local Waterwise Garden Centre.

Watering Times

The best time to water your garden is at dawn when there are minimal evaporative losses and the risk of plant based fungal diseases is reduced. Irrigation run times vary depending on the application rate of your irrigation system, but typically range from 10 – 15 minutes per station. For assistance in determining ideal run times consult one of the Waterwise Garden Irrigators – you'll find contact details for these by following the 'Save water' links from www.watercorporation.com.au.

Watering Rosters

The Water Corporation's Water Efficiency Measures include a roster system for water users across WA. In Perth and surrounds, there is currently a two day a week roster for scheme users and an additional day for bore users. Your household watering days are determined by your house number (the last digit). Gardens can only be irrigated on your allocated days either during the morning (before 9am) or the evening (after 6pm and reticulation systems must be switched off during winter). These water efficiency measures have reduced water use in Perth by 45 million litres per year. To find out more about water efficiency measures, visit www.watercorporation.com.au

HOUSE OR LOT NUMBERS (ENDING IN)	WATERING DAYS FOR SCHEME AND BORE WATER USERS	BORE OWNERS ADDITIONAL DAY
1	Wednesday and Saturday	Monday
2	Thursday and Sunday	Tuesday
3	Friday and Monday	Wednesday
4	Saturday and Tuesday	Thursday
5	Sunday and Wednesday	Friday
6	Monday and Thursday	Saturday
7	Tuesday and Friday	Sunday
8	Wednesday and Saturday	Monday
9	Thursday and Sunday	Tuesday
0	Friday and Monday	Wednesday

Reticulation Systems – Drip Irrigation and Sprinklers

Substrata (under the mulch) drip irrigation is the most efficient way to water your plants. Water is applied directly to the roots, eliminating evaporative losses and overspray. As the water is applied to the soil rather than the foliage, fewer fungal diseases are experienced. Drip irrigation systems are reasonably priced and easy to install and maintain – please refer to the 'Installing Drip Irrigation' section further below for more information.

Sprinklers come in many varieties. The most efficient for Western Australia's conditions are the heavy droplet type which reduce wind drift and water loss. If using sprinklers it is very important to position them to get maximum uniformity of application over the area being irrigated. Avoid watering in the heat of the day or during windy times. When using a portable sprinkler and hose, always use a tap timer to ensure you don't waste water by forgetting to turn the sprinkler off.
For irrigation advice and support visit a WaterWise Irrigation Design Shop – you'll find contact details for these by following the 'Save water' links from www.watercorporation.com.au.

Hand Watering

Hand watering can be a very efficient method of watering – particularly if you use a 'trigger' nozzle to ensure minimal water wastage when moving between plants. It is important to ensure not to over water using this method. Try to keep hand watering to twice a week except in very hot conditions.

Diversified Water Sources

You can utilise rainfall by diverting water from gutters or laying paving to direct run off into garden beds to recharge soil moisture. By doing this, even light rainfall events can benefit your plants. Tanks can be used to store water for garden use but the types of small tanks that are suited to urban lots soon run out in summer. Household greywater can also be used in the garden by redirecting shower, bath, hand basin and laundry water through an 'approved greywater system'.

INSTALLING DRIP IRRIGATION

HOW DO I DO IT?

Drip irrigation is a watering system that saves water by delivering it in drips rather than a spray. It is easy to convert many existing irrigation systems to drippers. There are two main types of drip irrigation: Button drippers are individual dripper units that are manually attached to poly pipe and have either a fixed or adjustable flow rate. They are best suited to small pots and hanging baskets.

Drip-line products are fixed flow drippers set at regular intervals inside a length of poly pipe during the manufacturing process. They are ideal for garden beds as a substitute for sprinklers, particularly in narrow and irregularly shaped situations. In addition to a timer, a typical drip irrigation system will include a filter to prevent drippers from blocking up, as well as a pressure regulating valve and vacuum relief valves.

There are different drip products designed for specific applications, including bore water and greywater, and equipment such as a filter is required for optimum performance. Your Waterwise Irrigation Design Shop can assist you in making the correct choice – you'll find contact details for your nearest shop by following the 'Save water' links from www.watercorporation.com.au.

SPACING

Drip irrigation supplies a controlled amount of water to a limited portion of soil surrounding each plant and relies on the properties of the soil to spread the water laterally. It's important to tailor your system to your soil type, as water moves very differently through sand, loam and clay.

SOIL TYPE	CLAY	LOAM	SAND
Dripper interval	50cm	40cm	30cm
Line spacing	50cm	40cm	30cm

Installation

Drip irrigation can be installed into existing garden beds and laid in various patterns to suit the planting layout. Simply lay the drip line on the surface of the beds and mulch over the pipes to conceal them. If you are irrigating a veggie patch or annual flower beds where the soil is regularly worked, the lines may be left on the surface so they can be lifted when digging.

Once you have run the lengths of drip line along your garden beds, connect one end into the poly pipe supply line using a punching tool and drip line connectors. The other end can be capped using a piece of poly pipe – simply fold the end of the drip line and slip a small piece of the poly pipe over the end. Removing the poly pipe `cap´ allows the drip line to be flushed of debris for maintenance. If you are laying out a number of lines across a garden bed, the drip lines should be connected to a blank poly pipe `collection´ line that is capped off at both ends, so that if one end is opened, all the drip lines are flushed through the one point for convenience. Secure the drip line in place using pins made from stiff wire.

The use of drip line irrigation under lawn is becoming increasingly popular. Installing it under roll-on lawn prior to laying is the easiest method, but there are also machines available that can insert drip lines into established lawns. You will need to take measures against root intrusion in a subsurface area. This can be done by including a root-intrusion guard, a filter-like device that continually doses the irrigation water with a small amount of herbicide called trifluralin, a chemical that rapidly breaks down when it makes contact with the soil. In sandy soil, thorough soil conditioning is required to ensure even wetting of the root zone.

For more information on installing a drip irrigation system and for general information on creating a productive and waterwise garden – see Josh's book The Green Gardener by Penguin Book.

To have an irrigation system installed professionally, consult a Waterwise Garden Irrigator. Contact details for both can be found by following the 'Save water' links from www.watercorporation.com.au.

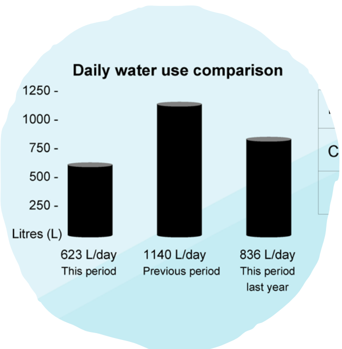
Waterwise Garden Maintenance Tips:

- Regularly check your irrigation system for leaks and blockages. Also check for dripping taps;
- Adjust your irrigation controller according to the seasons and switch it off in the event of rain and over winter;
- Apply wetting agents to aid water penetration if you have non wetting soil;
- Regularly top up your mulch to retain moisture in the soil;
- Remove weeds – they use water too!;
- Sweep paths and driveways rather than watering them.

Why?

The typical household uses about 660 litres of water per day (this is about 290 litres per person per day). These volumes are steadily decreasing with the application of water conservation measures. Water use in the garden is around half the total water demand for a typical household.

By planting a waterwise garden you can reduce your water consumption and save money on your water bill.



For more information contact Christine Eon: christine.mouraeon@postgrad.curtin.edu.au

The researchers acknowledge 'Be Living Smart' for use of the factsheet content.

YOUR CHECKLISTS TO HELP YOU SAVE ENERGY AND WATER

YOUR ENERGY CHECKLIST

WATER SAVING ACTIONS	ALREADY DOING	NEW ACTION
Zone sections of your house when heating or cooling		
Open curtains on sunny winter days		
Close curtains on sunny days		
Open windows in summer evenings to ventilate the house		
Shade your east and west windows in summer		
Set air conditioner between 24-27ºC		
Set air heater between 18-20ºC		
Set your fridge thermostat between 3 - 4°C.		
Let steam from hot food stop before putting it into the fridge.		
Use energy saving dishwasher cycles.		
Use warm or cold water washing machine settings rather than hot.		
Use a clothes line to dry your washing.		
Set your storage hot water system to just over 60°C. (Instantaneous to 50°C).		
Turn off appliances at the wall when they are not in use.		
Turn heating and cooling appliances off when you leave your home.		
Switch off the bar fridge if not necessary		
Make sure your fridge/freezer doors seal properly;		

YOUR WATERWISE CHECKLIST

WATER SAVING ACTIONS	ALREADY DOING	NEW ACTION
Take shorter showers		
Install a waterwise showerhead		
No running taps for rinsing (dishes or brushing teeth)		
Fix leaks		
Full dishwasher load		
Water wise washing machine		
Water wise toilet		
Catch cold water with a bucket		
Plant a waterwise garden		
Use a pool cover		
Don 't wash driveway or paths		
Water wise retic /trigger hose		
Install a rain water tank		

YOUR WATERWISE GARDEN CHECKLIST

WATER SAVING ACTIONS	ALREADY DOING	NEW ACTION
Choose waterwise plants		
Condition the soil		
Add mulch		
Switch to drip irrigation		
Stick to water roster day		
Collect rainwater		
Reuse greywater		
Apply soil wetter		
Minimise lawn areas		

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MY ENERGY AND WATER GOALS

I am aiming to:

☐ Reduce my electricity and gas usage by ……………….%

☐ Reduce my water usage by ……………….%

By taking the following actions:

………

………

………

………

………

………

………

………

………

………

………

………

………

………

………

(eg. turn off standby power, set my water heater, set my airconditioner to the optimal temperature, set my reticulation to 5 minutes, fit a waterwise shower head, use the half flush for the toilet)

I will achieve this by: ……………………………….(date)

Date: …………………………………………………… Signature: ……………………………………………………………………

TIP: Clip this action card to the fridge and follow your savings on the website: http://pmecurtin.homeftp.net/web/

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Appendix B Audit reports

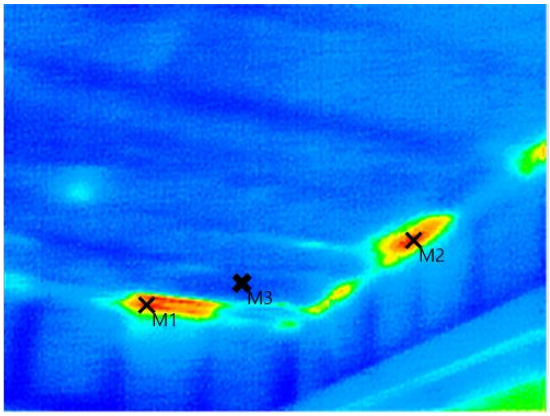
SUMMER AUDIT REPORT

HOUSE C

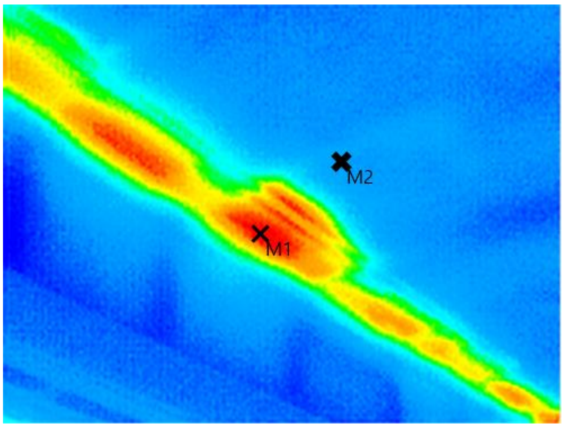
This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides some recommendations.

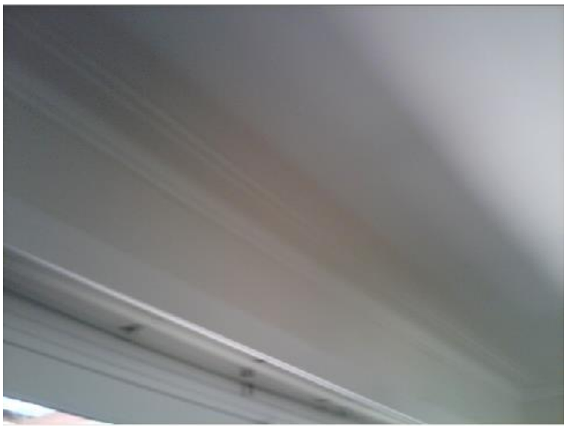
Heat Gain

- Insulation



M1: 36ºC, M2: 35.2ºC, M3: 27.3ºC

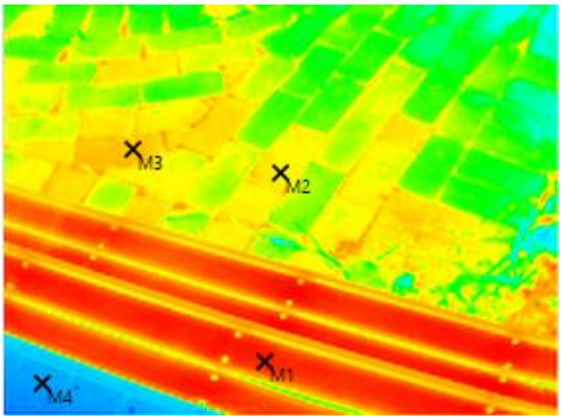




M1: 36.5 ºC, M2: 27.8 ºC

Some insulation is missing around the ceiling edge. Whilst you may not be able to close the insulation gaps at the moment, keep it in mind in case of future renovations.

- Deck and walkway



M1: 80ºC, M2: 66.4ºC, M3: 70.4ºC, M4: 40.9ºC

The exposed areas of your brick paved walkway can be at temperatures up to 70ºC in summer. Likewise, your desk can reach 80ºC when exposed to direct sunlight. Installing a removable sail or pergola can reduce your deck temperature up to 40 ºC and improve thermal comfort.

Electricity

Standby

Your stereo, laptop and kitchen radio have a combined standby of 61.5W. If left plugged in 24 hours per day, 365 days per year, you will be using 538 kWh per year. Consider switching these items off the wall when not in use.

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as dishwasher and washing machine.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Keep the windows shut and shaded during the day.

If you need cooling, keep in mind that ceiling fans and pedestal fans are more energy efficient than air conditioner. When the fan is not sufficient, make sure you set the air conditioner at a higher temperature, such as 24ºC.

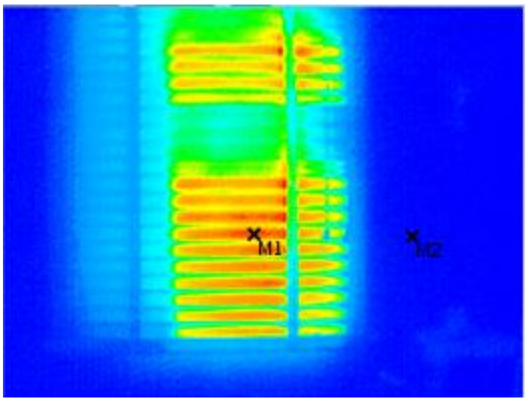
SUMMER AUDIT REPORT

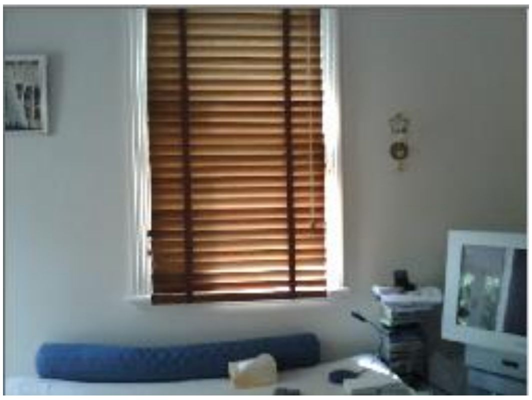
HOUSE E

This report summarizes some of the key points discussed during the summer audit, in December 2015.

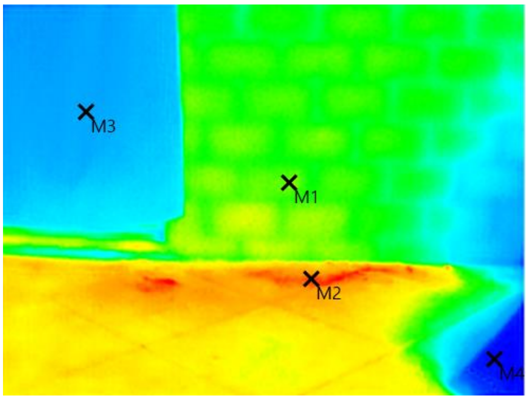
Heat Gain

- East facing Windows, walls and patio





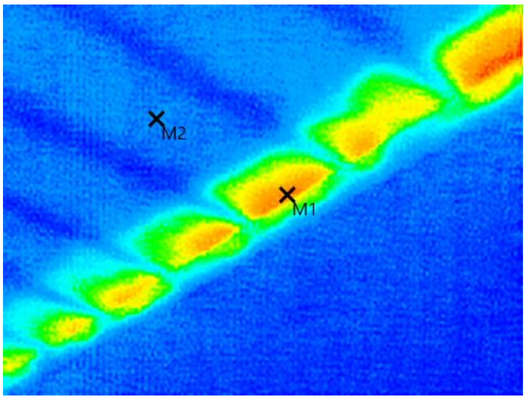
M1: 38.2ºC, M2: 25ºC

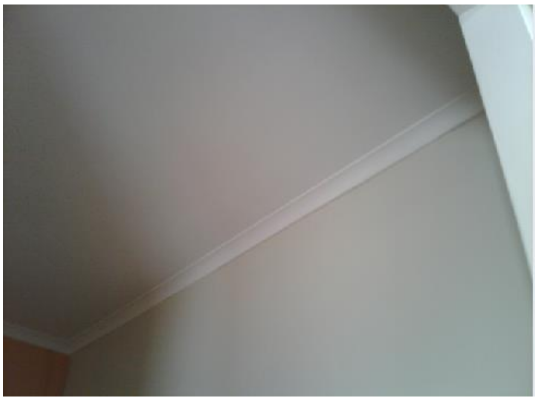


M1: 47.5ºC, M2: 55.3ºC, M3: 42.5ºC, M4: 33.7ºC

Installing an external awning on your East facing windows will be more effective to protect your house windows against the heat. A removable shade/pergola/sail in the patio area to the East of the house would also minimize radiation from your concrete floor into the house. Shading can decrease your patio temperature by around 20ºC in summer.

- Ceiling





M1: 29.4ºC, M2: 25.7ºC

There are insulation gaps around the edges of your ceiling. While you may not be able to fix this for the time being, keep it in mind if you do future house renovations.

Electricity

Appliances

The seal of the fridge located in your garage is starting to deteriorate. Consider replacing the seal to avoid losing cold air and improving the efficiency of your fridge.

We did some calculations and found out that if you decide to upgrade your two fridges (that currently use 1110kWh per year) with two modern ones, you will be able to cut your fridge consumption by half, saving on average 130 AUD per year!

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as the washing machine.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Keep the windows shut and shaded during the day.

Water

There are four main changes you can make to reduce your water usage:

- **Washing machine**: try reducing the amount of times you run your washing machine during the week. If you reduce your usage from 7 small loads per week to 3 large loads, you will be saving up to 240 litres of water per week.

- **Shower**: If reducing your shower length is not an option, you can save water by replacing your old high flow tapware with low flow fittings.
- **Rainwater tank**: a more effective use for the rainwater tank would be to connect it to the toilets and potentially washing machine, having scheme water as a backup. Good quality rainwater can be achieved by installing a first flush device, which diverts the first flow of rainwater that falls on the roof. Rainwater can go through a secondary filter before if required.

Water savings in the Garden

Areas where the grass has been damaged can be repaired by aerating the soil and covering it with a topdress soil. This provides nutrients to the soil and makes irrigation more efficient.

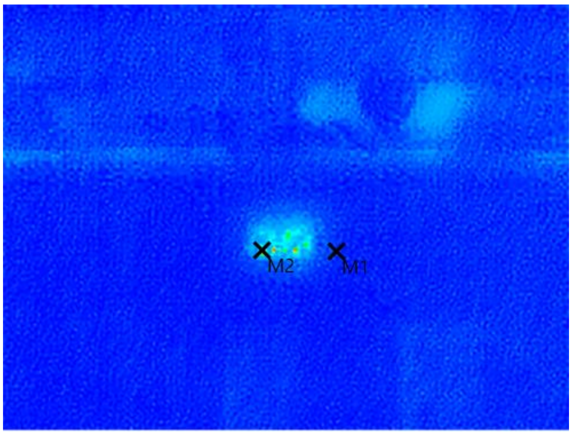
SUMMER AUDIT REPORT

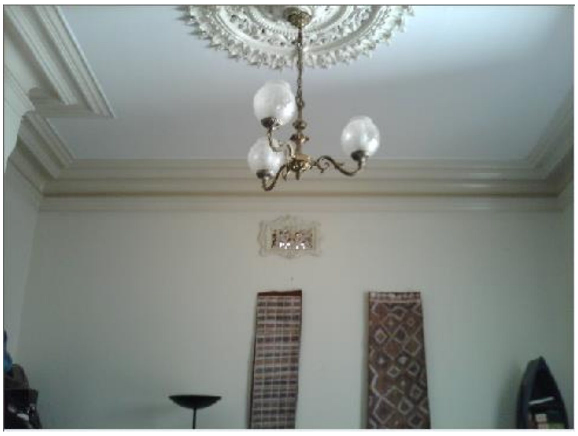
HOUSE F

This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides recommendations.

Heat Gain

- Vent





M1: 27.5ºC, M2: 36ºC

The temperature in the vent is nearly 10 ºC higher than the wall around it. Consider closing and insulating the vent (in the internal side of the wall) on not only to minimize heat gain in summer, but also to minimize heat losses in winter. Leave the external part of the vent open to allow moisture to escape to the environment.

- Shade

Install a retractable awning over the deck area so that solar heat gain is effective in winter and shading can occur in summer and hot shoulder periods.

You can buy retractable awnings from the following suppliers: http://www.bozzy.com.au/awnings, http://www.abcblinds.com.au

Electricity

Standby

Your TV and stereo unit have a combined standby of 33Watts. If left on standby all year round, you will be spending 65 AUD per year. Unplug these appliances off the wall when not in use.

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as dishwasher and washing machine.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Keep the windows shut and shaded during the day.

If you need cooling, keep in mind that ceiling fans and pedestal fans are more energy efficient than air conditioner. When the fan is not sufficient, make sure you set the air conditioner at a higher temperature, such as 24ºC.

Water

It is advised to install a first flush device in your rainwater tank to improve pump efficiency and rainwater quality.

Connecting your rainwater tank to the washing machine is a good idea to increase the tank yield throughout the year and further decrease mains water usage.

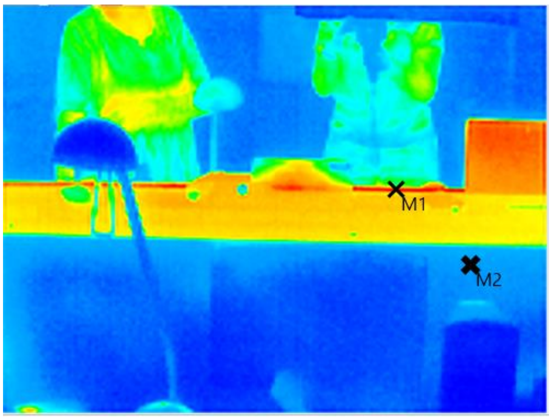
SUMMER AUDIT REPORT

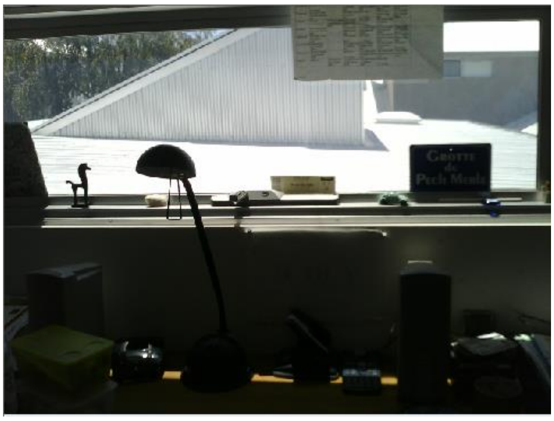
HOUSE G

This report summarizes some of the key points discussed during the summer audit, in December 2015.

Heat Gain

- East facing windows





M1: 44 ºC, M2: 27.8ºC

Your second story windows have no protection from the sun and are letting heat into your second floor. On the day of the audit, the areas exposed to the sun were reaching a temperature 15ºC warmer than the shaded areas. To achieve higher thermal comfort during summer and shoulder periods, consider installing external retractable awnings in all East facing window.

To dissipate the day heat, ensure good air flow through the second floor, especially at night, by opening all windows.

Electricity

Standby Power

The standby power in your living areas adds up to 60.5 Watts, being mostly used by the speakers and subwoofer. If all your living room appliances are left on standby 24 hours per day, 365 days per year, it will cost you 120 AUD per year. Consider switching your appliances off the wall when not in use.

A master switch with remote control can be employed to eliminate the hassle of disconnecting appliances off the wall individually.

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as dishwasher and washing machine.

Cooling

Keep your windows open at night to allow the thermal mass in your house to cool down after a hot day. Keep the windows shut and shaded during the day.

In very hot summer days that may require the usage of air-conditioner, if, possible, program it to turn on earlier during the day when the solar panels are still generating electricity so it cools down the house in advance before you arrive home from work. Running it at a higher temperature, such as 24ºC will also help you save energy.

Water

- Periodically clean the rainwater tank filter to ensure it is free of algae and leaves. This will increase the quality of water entering the tank and ensure the good functioning of the pump.
- Consider installing a first flush device in your rainwater tank. This will divert the first amount of dirty rainwater collection after a rainfall and keep the filter cleaner for longer.
- During summer, consider reducing your shower time to 5 minutes as your rainwater harvesting is lower at this time of the year.

Water savings in the Garden

Inspect the sprinklers periodically to prevent leakages.

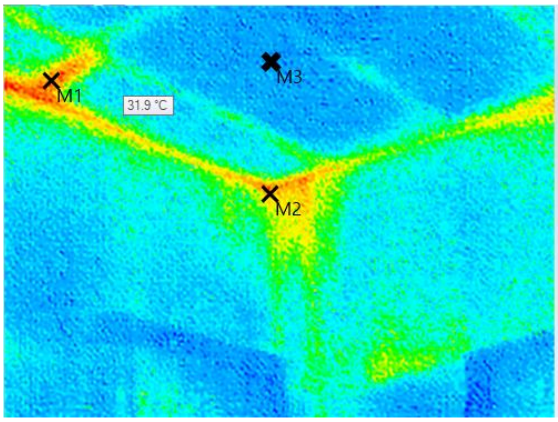
SUMMER AUDIT REPORT

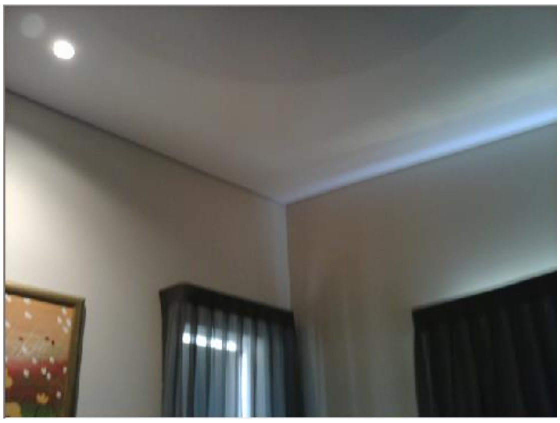
HOUSE H

This report summarizes some of the key points discussed during the summer audit, in December 2015.

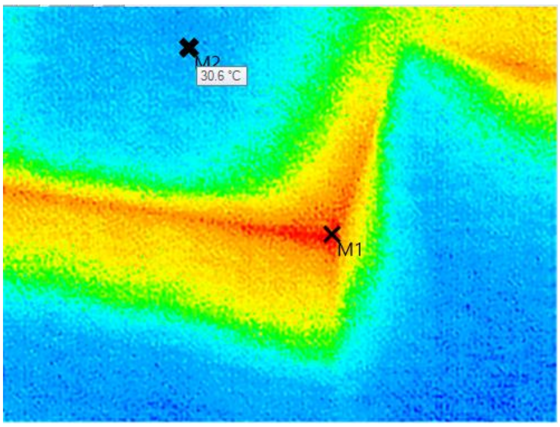
Heat Gain

- Ceiling





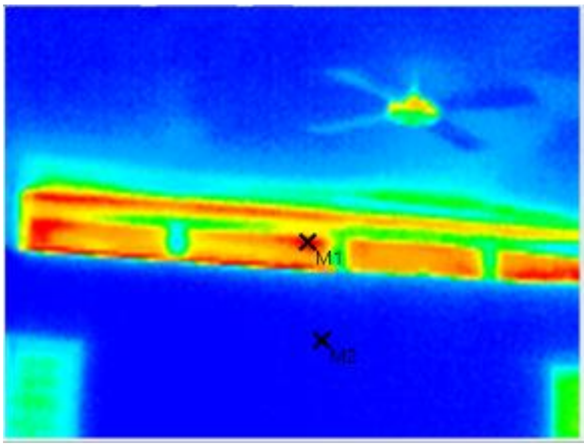
M1: 33.3ºC, M2: 33.3ºC, M3: 31ºC



M1: 32.7ºC, M2: 30.4ºC

The thermal images above show that there is missing insulation in parts of the ceiling. The house will be gaining heat in summer and losing heat in winter. Whilst you may not be able to close the insulation gaps, keep it in mind in case of future renovations.

- West facing windows



M1: 43.8ºC, M2: 30.1ºC

Your West facing blinds are nearly 14 ºC hotter than your walls. An external awning would be more effective to stop heat from getting into the house.

Electricity

Standby Power

The entertainment unit in the living area, consisting of a TV, DVD/Blueray, speakers and subwoofer has a standby of 14W, which is equivalent to 122kWh per year, or 28 AUD per year if left on 24 hours per day, 365 days per year.

It is recommended that these appliances are switched off at the wall when not in use. A master switch with a remote control such as “Bye bye standby” enables switching off standby more easily.

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as dishwasher and the washing machine.

Take advantage of the monitoring system to make sure that the solar panel is working, especially after a storm or a power cut.

Water

Take shorter showers in summer (4 minutes) as your rainwater harvesting is lower at this time.

Water savings in the Garden

Reduce the amount of turf by removing the front lawn, and replacing with very low water requiring plants such as coastal native species and/or succulents

The damaged lawn in backyard can be effectively fixed by aerating the area and top-dressing with soil. Increasing the irrigation time is not necessary.

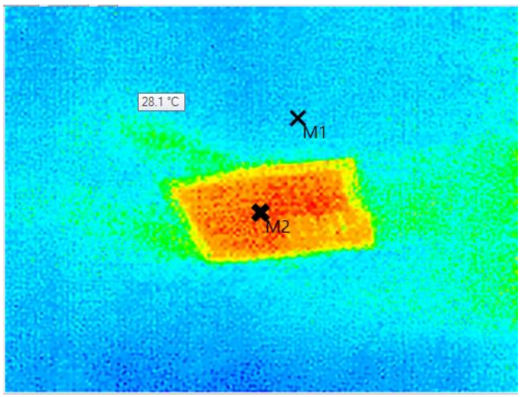
SUMMER AUDIT REPORT

HOUSE L

This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides some recommendations.

Heat Gain

- Ventilation duct



M1: 27.8 °C, M2: 30.1°C

In summer, the ceiling space can reach temperatures as high as 80°C. If not well insulated, your ventilation duct will heat up and blow hot air into your house. The image above shows that the temperature of the ventilation system is around 2°C higher compared to the rest of the ceiling.

Ceiling fans and pedestal fans are more energy efficient than ducted fan. Give preference to fans and at times of extreme heat when the air conditioner is needed, make sure you set it at a higher temperature, such as 24°C.

- West facing windows

Your house is gaining heat through the large West facing windows in your living room. External shading such as awnings or deciduous trees are cost effective solutions to protect the windows from the sun.

Electricity

Standby

You are using on average 62kWh of standby power per year, which is costing you 14 AUD per year. You can save money by switching your appliances off the wall when they are not in use, such as your entertainment unit and coffee machine.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Keep the windows shut and shaded during the day.

Ceiling fans or pedestal fans are more energy efficient than ducted fan or ducted air conditioner. In addition, ducted air conditioner may heat your house over time, as the roof cavity can be at temperatures as high as 80ºC in summer. Give preference to fans and at times of extreme heat when the air conditioner is needed, make sure you set it at a higher temperature, such as 24 ºC.

Water savings in the Garden

Keep the good practice of mulching your garden to reduce evaporation from the soil. Rock mulch can be used for native plants that are well established and require low levels of nutrients. Use tree bark mulch for slow nutrient release and straw mulch (triple C) for edible or high nutrient requiring plants.

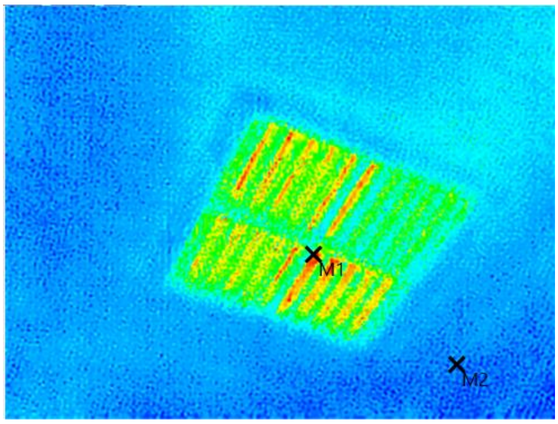
SUMMER AUDIT REPORT

HOUSE M

This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides recommendations.

Heat Gain

- Ventilation duct

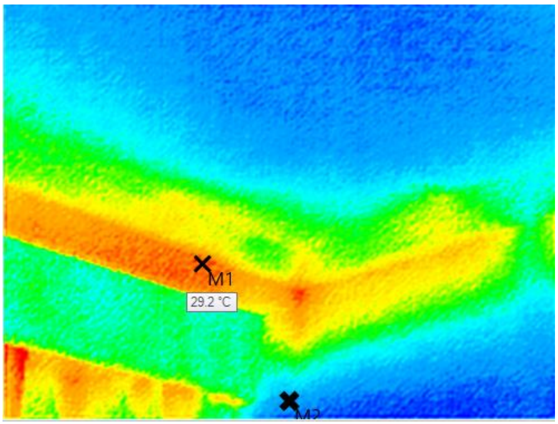


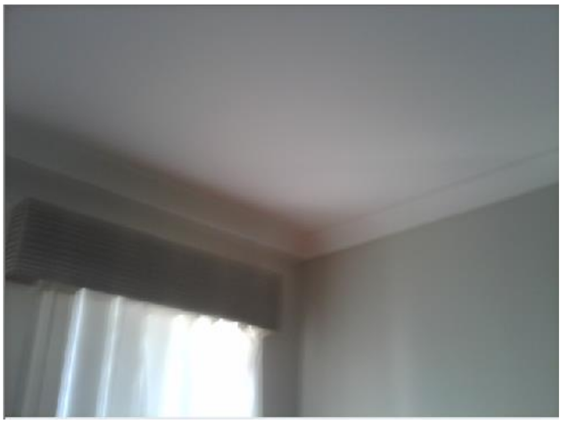
M1: 29ºC, M2: 26ºC

In summer, the ceiling space can reach temperatures as high as 80ºC. If not well insulated, your ventilation duct will heat up and blow hot air into your house. The image above shows that the temperature of the ventilation system is around 3ºC higher compared to the rest of the ceiling.

Ceiling fans and pedestal fans are more energy efficient than ducted fan. Give preference to fans and at times of extreme heat when the air conditioner is needed, make sure you set it at a higher temperature, such as 24ºC.

- Insulation





M1: 29.3 ºC, M2: 26ºC

The thermal images above show that there is missing insulation in parts of the walls and ceiling. The house will be gaining heat in summer and losing heat in winter. Whilst you may not be able to close the insulation gaps, keep it in mind in case of future renovations.

- East and west facing windows

The room being used as the office is located to the West of the house, subject to the hot afternoon sun. The heat in this room is due to the very large window directly exposed to sunlight and to the paved driveway, which stores and reflect heat throughout the day. For a short term solution you can install an external awning to protect the window from the sun. A longer term plan would involve planting a native deciduous tree in the garden across the window. The following species are recommended:

- Fremantle Malee (Eucalyptus Foecunda)
- Rottnest Island Tea Tree
- Eucalyptus Platupus

.Electricity

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as the washing machine and dishwasher.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Consider installing security screens if leaving windows open present an issue. Keep the windows shut and shaded during the day.

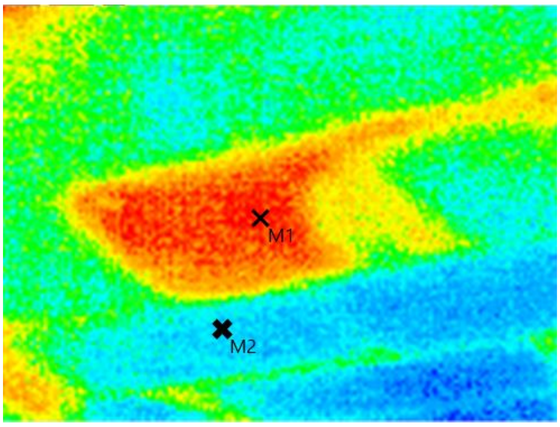
SUMMER AUDIT REPORT

HOUSE 0

This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides recommendations.

Heat Gain

- Insulation



M1: 26ºC, M2: 23.3ºC

The thermal images above show that there is missing insulation in parts of the walls and ceiling. The house will be gaining heat in summer and losing heat in winter. Whilst you may not be able to close the insulation gaps, keep it in mind in case of future renovations.

Electricity

- Take advantage of the higher solar production between 10am and 5pm to run the pool pump and all other energy intensive electric appliances, such as dishwasher and washing machine.
- In very hot summer days that may require the usage of air-conditioner, if, possible, program it to turn on earlier during the day when the solar panels are still generating electricity so it cools down the house in advance before you arrive home from work.
- Consider installing safety screens so you can keep your windows and doors open throughout the night to cool the house down.

Water

- Replace your existing spray irrigation for Betafilm Driplines to irrigate your garden beds along the driveway.

- Install a Hunter X-core controller to control watering in your garden in accordance to the weather.
- Take shorter showers (4 minutes)

Water wise plants

Water wise plant options for your garden include:

- Lulfitz Nursery (Wanneroo, Oakford)
- Dianella Seascape
- Lomandra Longifolia tamakas
- Grevillea Seaspray (foam Foliage)
- Chinese Star Jasmin (creeper for fence cover)

SUMMER AUDIT REPORT

HOUSE P

This report summarizes some of the key points discussed during the summer audit, in December 2015, and provides some recommendations.

Heat Gain

- West windows

Install an awning or sail outside your West facing windows so as to protect your house from the direct sunlight in summer. This will not only reduce the temperature in the workshop, but it will also be beneficial to helps keep the kids' room cooler, reducing the need for air conditioner at night.

- Insulation

Some insulation is missing around the windows in the living area. The house will be gaining heat in summer and losing heat in winter. Whilst you may not be able to close the insulation gaps, keep it in mind in case of future renovations.

Electricity

Solar PV

Take advantage of the higher solar production between 10am and 5pm to run energy intensive electric appliances, such as dishwasher and washing machine.

Cooling

Keep your windows and internal doors open at night to cool your house down after a hot day. Keep the windows shut and shaded during the day.

If you need cooling, keep in mind that ceiling fans and pedestal fans are more energy efficient than air conditioner. When the fan is not sufficient, make sure you set the air conditioner at a higher temperature, such as 24ºC.

Gas

Reduce your instantaneous hot water thermostat to 40ºC. This will reduce cold water mixing and therefore will enable a more efficient usage of the system. Temperature setting at 60ºC is only required when storing hot water in a tank, where salmonella can develop.

Also consider improving the insulation around the hot water pipe to avoid heat losses.

Water savings in the Garden

Check how much water is being used to irrigate your new lawn. 10ml of water twice per week is all the grass needs during summer. In shoulder periods (Spring and Autumn), reduce to once per week.

Grass patches can be effectively repaired by aerating the soil underneath and adding a high nutrient top soil.

Garden Plants

A good option of a climbing plant to cover the fence for privacy would be the Chinese Star Jasmin.

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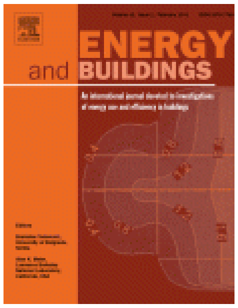

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