Influencing energy and water use within a home system of practice

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Abstract

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.

Keywords: Home system of practice; monitoring; behavior; energy efficiency; water efficiency; routines

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 [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 minute 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 60ºC. 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 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 to 30 minutes) 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 120L/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 (6.15L to 6.85L per filling cycle) and washing machine (28.5L to 43L 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

Figure 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 (Figure 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). Figure 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. Figure 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.

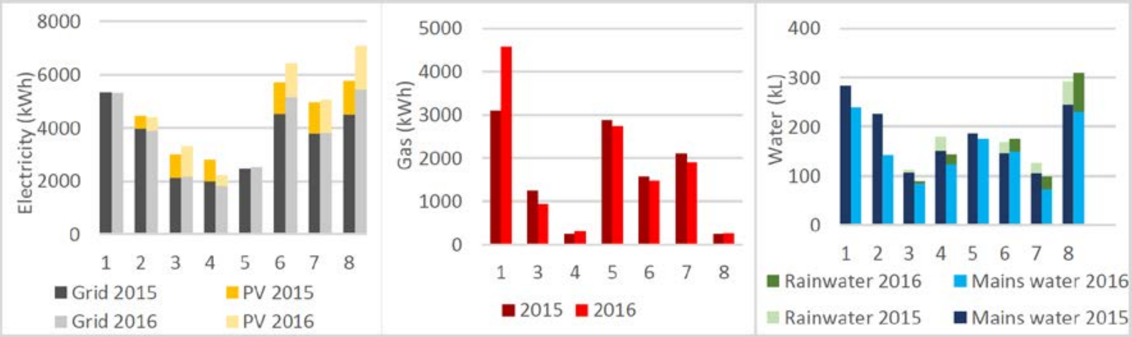

Figure 1. Variation in total energy and water use in all homes in 2015 and 2016. Home 5 did not provide electricity bills and therefore PV electricity use was not included in the graph

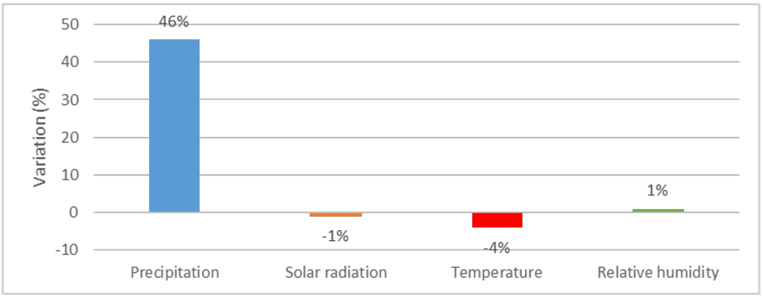

Figure 2. Mean daily weather variation in 2016 compared to 2015

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 Figure 4. The grey line in Figure 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 Figure 4 alone; therefore, a Wilcoxon signed-rank test was used.

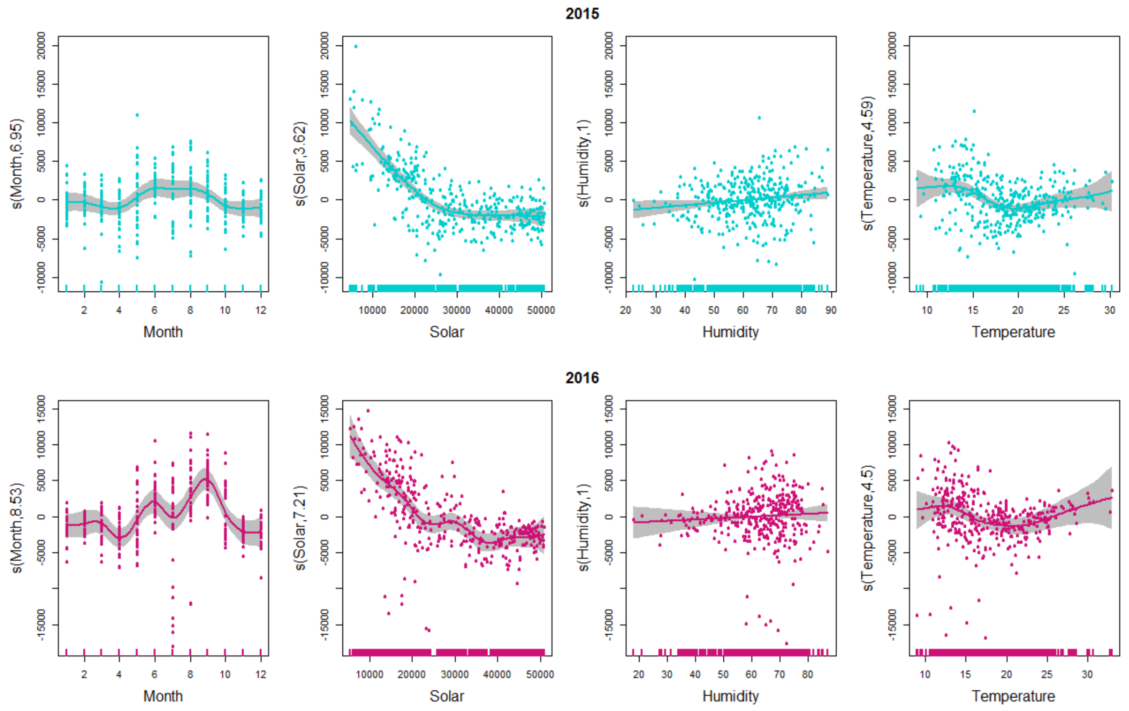

Figure 3. Example of temporal and weather impacts on grid electricity use in home 1 between 2015 and 2016

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.

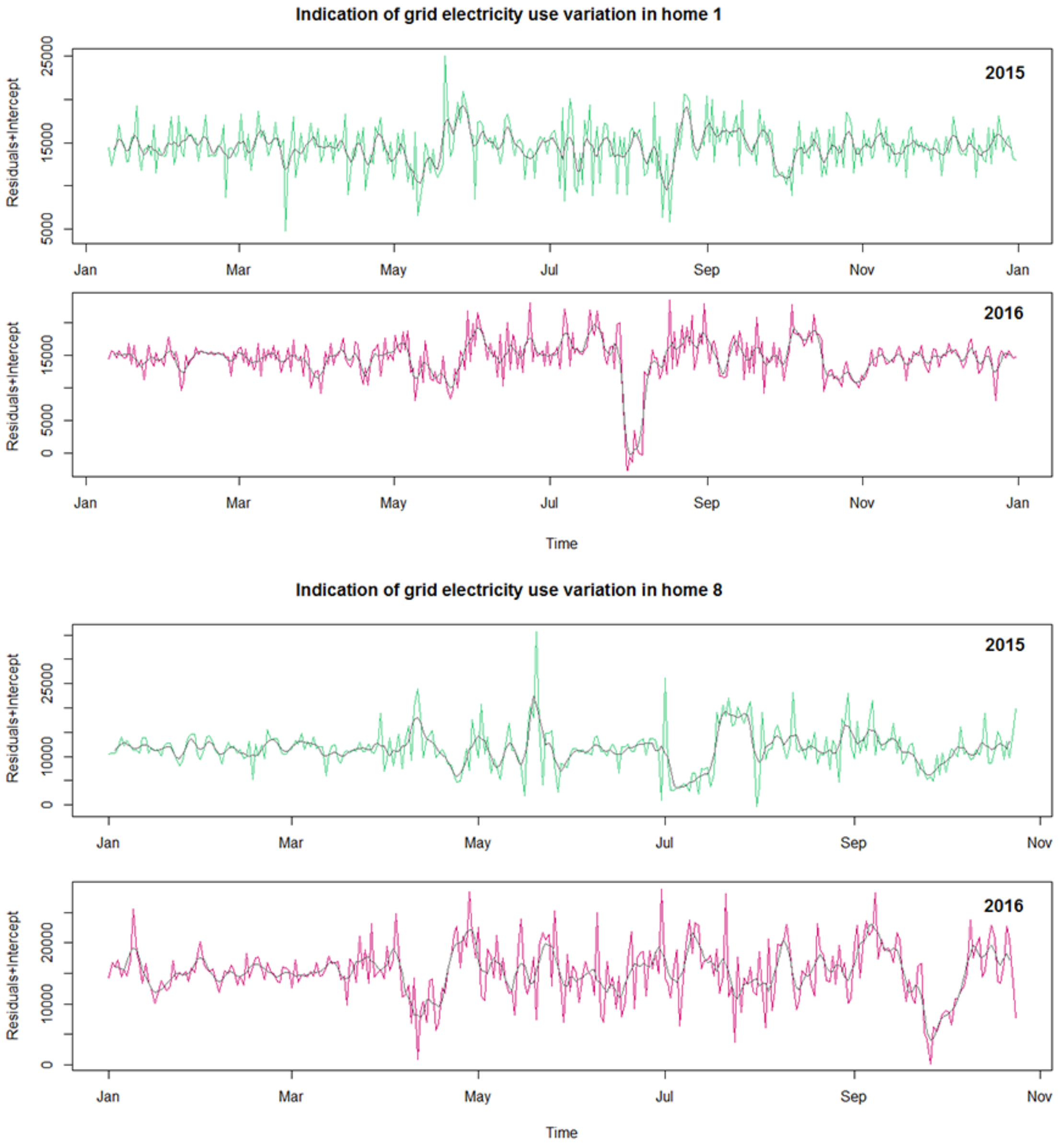

Figure 4. Examples of energy and water use variation in home 1 and home 8 between 2015 and 2016

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

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 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 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 seconds (Table 3). The shorter shower time belonged to home 4 who showered for a median of 5 minutes in 2016. This is still higher, however, than the 4-minute 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).

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			
			Skill	Meaning	Technology	
					Change	Failure
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				External shade cloth	
	Gas - constant					
	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 - constant	Personal showers		Shorter showers		Water leak in 2015
		Irrigation			Installation of an automated irrigation system	
8	Electricity - increase	Standby power			Standby automation	PV interruption
		Dishwashing			Dishwasher automation Installation of a timer in the solar hot water system	
	Gas – constant					
	Water - constant	Irrigation			Less efficient sprinkler system New rainwater tank New greywater system	Water leak in 2016

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		.520	.900	<0.05	<0.05	.114	<0.05	<0.05	.944
Significance		constant	constant	decrease	decrease	constant	decrease	decrease	constant

3.2.1.2. Irrigation practice

- 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 rank_{2015} = 40.59, mean 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 established (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.

- 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 minutes, 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 (Figure 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).

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		.485	<0.05	.906
Significance		constant	decrease	constant

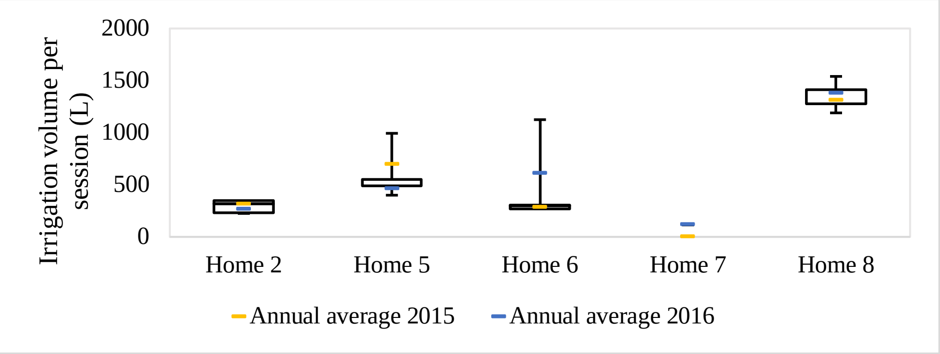

Figure 5. Distribution of the volume of water used per garden irrigation session with an automatic reticulated system.

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^{o}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^{o}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).

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. (^{o}C)	Time of day	Length of time (h)	Internal temp. (^{o}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		.140	<0.05	.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		.350	.195	.790	.549	.318	.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	.332	.387	.088	.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		.524	.682	.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	.953	.172	.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	.342	.130			
		Significance		decrease	constant	constant			

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 minutes (Figure 6). These minor alterations resulted in the decrease of grid electricity use by an average of 300Wh per day.

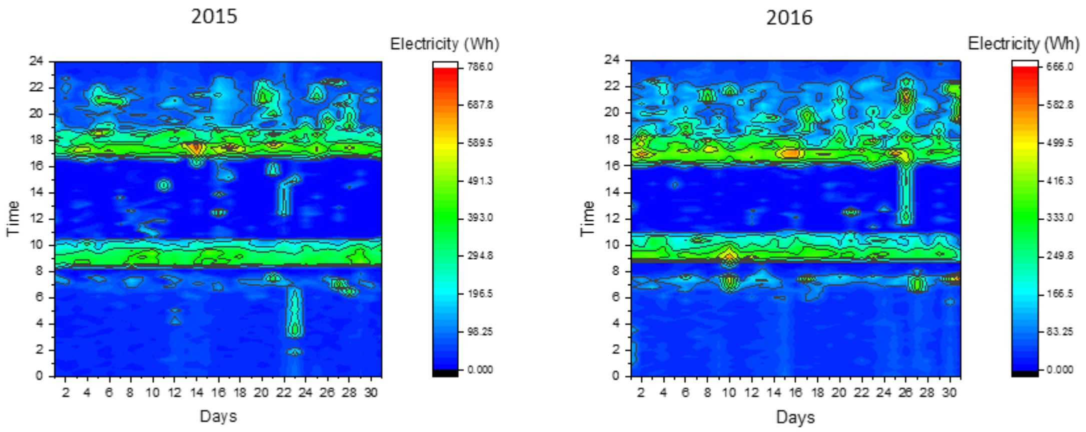

Figure 6. Heat maps depicting the average grid electricity use in home 6 in 2015 and 2016 for all months of the year. The distinct horizontal bands in the morning and afternoon are related to the use of the pool pump.

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].

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 (Figure 7 a, b). Solar heat gain through windows and exposed paved areas were also identified (Figure 7 c, d). Following the audit, homes 1, 2, 3 and 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, 3 and 4.

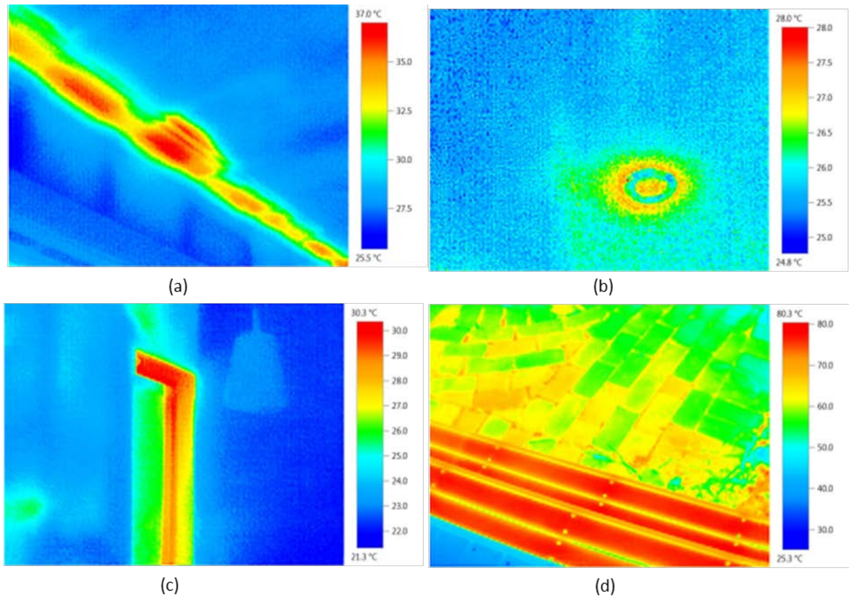

Figure 7. Thermal images of missing insulation in (a) the ceiling and (b) around lights; and solar heat gain through (c) windows and (d) paved areas

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 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.

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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, 1.5kW PV, electric cooling and heating	-
3	A (1), T (2), YA (1)	Gas solar hot water, 2.66kW PV, electric cooling and heating	Rainwater tank
4	A (2)	Electric solar hot water, 1.68kW PV, no cooling, portable electric heating	Rainwater tank
5	A (2), C (3)	Instantaneous gas water heater, 3.5kW PV, electric cooling and heating	-
6	A (2)	Gas solar hot water, 1.8kW PV, electric cooling and heating	Rainwater tank
7	A (2), YA (1)	instantaneous gas water heater, 2kW PV, electric cooling and heating	Rainwater tank
8	A (2), C (2)	Electric solar hot water, 2.28kW 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	20mm Elster V100 & MEB7454 'T' probe, 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? Why did you make these specific changes/ Why not?	Have you made any physical changes to your house? 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?