End user engagement with domestic hot water heating systems: Design implications for future thermal storage technologies

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ARTICLE INFO

Keywords:
- Occupant behaviour
- Hot water heating types
- User centred design
- Thermal energy stores

ABSTRACT

The strategies used by householders for heating and using hot water heating have a significant impact on energy consumption in domestic buildings. A better understanding of the interaction between occupants and hot water heating systems can improve the energy efficiency of a building. This paper maps the interaction between occupants and their current domestic hot water heating systems to provide insights for the design of future thermal energy storage systems. A total of 35 householders from the Midlands region of the UK took part in semi-structured contextual interviews about their current strategies for the provision of hot water and the way they engage with their heating systems. Using the DNAs framework as an analysis lens, drivers, needs and actions relating to the provision of hot water were evaluated and four distinct hot water heating types are presented: On Demand, For All Eventualities, Just Enough and Sunny Days. Findings provide insights into occupants’ behaviour in relation to hot water heating usage and design implications for thermal energy storage technologies.

1. Introduction

In the UK, 29% of the energy use is attributed to the domestic buildings [1]. One of the contributors to this energy consumption is the demand for domestic hot water, making up 20% of the domestic consumption; approximately 6% of the total UK energy use. Considering the UK’s target of reducing the greenhouse gas emissions by at least 80% by 2050 [1], innovation in the design and deployment of future energy technologies is essential. These technologies include thermal energy storage systems. Whilst phase change or thermochemical storage may be a technology for the future, many homes have a current thermal energy store in the form of a hot water tank to supply domestic hot water. However, there is a lack of understanding about the interactions between occupants and these systems and limited knowledge on potential barriers to adopting future thermal energy stores, which will be needed in order to design future socially, technically and economically viable systems. This paper aims to fill this gap by identifying occupants’ engagement with current domestic hot water systems in order to determine user insights for the design of future thermal energy stores.

Currently, a number of technologies are proposed to help reduce emissions from the domestic sector in the UK, with a focus on electrification of heating including the deployment of electric heat pumps within homes [2]. This will increase the demands placed on the production and supply of electricity, with the additional complication of significant variances in demand across seasons to match the temperate maritime climate in the UK. This will inevitably require demand side response (shifting) and local generation of electricity. To support these two developments, energy storage will become an important feature [3]. Electrical and thermal energy storage could mitigate the need for new energy plants and their associated costs. Distributed thermal stores are already present in 13.7 m UK households [4] as hot water storage cylinders; a 100 L cylinder, with water heated to 50 °C, can store about 6 kW h. Measurements have found average hot water use to be 122 litres/day with an energy content of 4.7 kW h which, when aggregated across the UK, equates to about 65 GW h/day [4]. Thermal stores offer a means of decoupling supply from demand and differ from traditional hot water cylinders as they present a means of storing energy from multiple energy generating sources and could enable householders to store heat for later use over a period of hours, days, weeks or even months [5]. Thermal energy stores enable householders to take advantage of variable pricing of electricity during peak and off-peak hours where available and, for occupants with home energy generation technologies (which provide intermittent energy generation at less controlled times) such as solar thermal and photovoltaic (PV) systems and/or heat pumps, thermal storage systems can improve the overall efficiency [6]. Interactions with energy systems depend heavily on occupants’ perceived comfort [7], however studies often

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https://doi.org/10.1016/j.erss.2018.10.009
Received 1 April 2018; Received in revised form 31 August 2018; Accepted 9 October 2018
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focus on the average occupant behaviour, neglecting individual variability [8]. Misconceptions regarding domestic heating systems and their contribution to global warming [9], the required energy to heat water [10] and the benefits of using different heating systems in context [11] can affect the energy consumption [12,13]. It has been argued that occupants focus on those energy-related behaviours that impact positively or negatively on their personally held values, including motivational values relating to self-enhancement and self-transcendence [14,15]. Self-enhancement values may drive an individual to gain personal pleasure and excitement (hedonism) or to safeguard an individual’s resources (egoism). Self-transcendence values relate to ensuring the welfare of others (altruism) or the environment (biosphericism). The values reflect occupants’ inner motivations that lead to subsequent judgements and actions [11]. The use of a hot water heating system within a home is influenced by these values through the provision of hot water for oneself or others in the household. People’s subsequent choices and actions are also impacted by the available technology [16]. Therefore, occupants’ heating strategies may counteract the efficient use of a thermal energy storage system, if they are motivated by personally held values. In order for a technology to be utilised effectively within real-world contexts, developers need to ensure that the drivers and motivations behind end user behaviour are considered in the design.

Previous research has focused on simulating the impact of occupant preferences on building energy consumption using either building simulation tools or occupant modelling [17–19]. However, a common finding across energy simulation studies is the discrepancy between the predicted and actual energy consumption of the building [20–22]. This discrepancy is explained by the fact that extant knowledge on the effectiveness of the implementation of thermal energy storage technologies is based on statistical analyses and modelling [23], lacking insights regarding occupants’ behaviour when planning new domestic buildings as well as when retrofitting [8]. A recent review that synthesised existing evidence on the influence of occupants’ behaviour on building energy consumption highlighted the gap of knowledge in the field and the need for more relevant research to be undertaken [24] and others have identified that human behaviour and occupant preferences are the most overlooked factors when it comes to energy consumption in domestic buildings [25]. To address this gap, this paper takes a user centred design approach to ensure that context of use is considered and focuses on occupants’ behaviour and their engagement with their hot water heating systems [26]. This approach is in contrast to a technology-led design process which focuses on the development of the capabilities of the technology itself as an isolated object; such a process often results in products, services and systems that require users to adapt their attitudes and behaviours in order to learn and use them effectively [27]. In this research, in order to explore occupant interactions with the domestic hot water system, both semi-structured interviews and use of behavioural frameworks are employed to identify occupants’ needs and requirements.

A number of theoretical cognitive-behavioural frameworks1 have attempted to categorise the different types of occupant-energy interactions with a focus on the role of social human behaviour in energy consumption. However, these frameworks are mainly concerned with the stochastic and reactive nature of human behaviour, in a specific space as a function of time. One recent framework has attempted to capture key elements influencing occupants’ energy behaviour: the DNAs occupant behaviour framework [28]. The DNAs framework suggests that four main components underpin the relationship between occupants’ behaviour and energy in buildings: the drivers of behaviour, the needs of the occupants, the actions carried out by the occupants and the systems acted upon by the occupants. The framework was developed to implement fast and accurate occupant behaviour models into building simulation tools and reduce the gap between the predicted and measured energy performance of buildings. Drivers provoke energy-related occupant behaviour; occupants’ needs for feeling satisfied with the environment should be met and, if not, certain actions should be taken to satisfy their expectations by interacting with the building’s systems (e.g. equipment, mechanisms or measures). The framework was developed with the purpose of use in building performance simulation programs to improve simulation assumptions on occupancy presence and adaptive interactions [29], but it provides a lens through which to consider occupants’ direct interaction with hot water heating systems. This paper draws upon the DNAs occupant behaviour framework [28] to understand the interaction of occupants with their hot water heating systems in the UK. This framework takes the cognitive processes of users’ energy-related behaviour and structures actions and thoughts into a format that can be of value to the technology designers. This bridging role has been identified in literature as an important step to understanding occupant behaviour in the context of engineering solutions [30,31].

This paper adopts a novel, multimethod approach, combining insights gained from semi-structured interviews with 35 householders in the East Midlands area of the UK and the use of DNAs occupant behaviour framework [32]. The study makes an original contribution to knowledge in three important ways. First, it introduces an innovative methodology to explore occupant interaction with hot water heating systems using a bespoke hot water timeline tool that encourages participants to talk about hot water usage. Second, a typology of hot water heating strategies is developed based on reported hot water usage and occupants’ drivers, needs and actions underpinning the interaction between the occupant and the hot water heating system. Finally, it provides insights on user requirements for future thermal energy stores and adds to the canon of knowledge by exploring how different heating strategies might affect the design of future thermal energy stores.

2. Materials and methods

To understand how current experiences with hot water heating systems can inform the design of future thermal energy stores, a series of in-depth interviews were undertaken, aided by a bespoke and engaging timeline tool. Then, insights from the interviews were used to develop a typology of hot water heating strategies leveraging the DNAs occupant behaviour framework [28].

2.1. Data collection and analysis

A series of contextual semi-structured interviews with a purposive sample drawn from 35 households was undertaken. Inclusion criteria included: 1) owner-occupiers in the Midlands region of the UK; 2) having a gas central heating system to heat their home and hot water; 3) at least two people living permanently in the dwelling. Participants were selected into quotas based on the type of hot water heating system (combination gas boiler to provide instant hot water or standard gas boiler with a separate hot water cylinder. Some participants in each group also had photovoltaic panels for the generation of electricity and one participant with a hot water tank also had a solar thermal system to heat hot water). For those with a hot water cylinder, the mean capacity was 149 litres (range 117–180 L), with water heating set to a mean temperature of 60 °C (range 45–70 °C). Within the quotas, participants were purposively selected to represent a wide range of household types, family structures, incomes and educational background to provide a sample of the population which allowed for different domestic situations to be explored; it was not intended to be representative but exploratory, as is common in rich qualitative studies with small samples.
2.2. Development of hot water heating types

Insights identified from the thematic analysis were used to develop a set of hot water heating types, to account for the interaction between occupants and hot water heating systems. Patterns and distinctions between the hot water heating types were aided by the DNAs framework by assigning characteristics from the data, including:

a. The drivers underpinning the choice of hot water heating usage and engagement.
b. Interviewees’ needs relating to the heating system, often expressed in terms of dissatisfaction to their current system.
c. The actions undertaken by the interviewees to satisfy their needs.
d. Characteristics of their hot water heating system that impacted on their usage.

Finally, a narrative for each hot water heating type was developed with reference to the interview transcripts and the timeline. In cases of uncertainty, the researchers consulted the transcripts for evidence to ensure appropriate categorisation. Quotes from the primary data were used to illustrate the hot water heating types to give them ecological validity. The resulting hot water heating types were reviewed by the research team, referring back to the original data, to increase the reliability of the analysis [23]. The approach followed is schematically represented in Fig. 2.

3. Results

3.1. Householder characteristics

Participants were drawn from a sample with a range of family types, household income, social statuses and hot water systems. The interviewees were part of a family with children (80%, n = 28) or a couple (20%, n = 7) of which three were retired couples. Families comprised of two to five permanent occupants (median = 3.3). There were 14 families with their youngest child under five years of age and 14 families with older children still living at home. Mean household annual income band was £40,000–50,000 (range £15,000–£149,000), and properties ranged from pre-1850 to post 2002, with property types including detached, semi-detached and terraced house and bungalow (single storey).

3.2. Hot water and heating systems characteristics

All participants lived in a property with a gas boiler for the primary delivery of heat. Of the 35 properties, 14 had a combination boiler and 21 had a system with a hot water cylinder. All the households with hot water cylinders were able to heat their hot water using a gas boiler and 10 cylinders were additionally fitted with an electrical immersion heater (although eight of these were used either rarely or never). Of the 14 properties with combination boilers, four also had solar photovoltaic (PV) systems. Of the 21 properties with hot water cylinders, six also had solar systems (five had PV panels fitted, which used excess electricity to run the immersion heater contributing to the heating of the hot water, and one had solar thermal panels which also contributed to heating the hot water in the cylinder). Table 1 shows the hot water systems in the sample group. Hot water heating types

The analysis identified that occupants had certain needs from their current heating system regarding the provision of hot water which related to hot water temperature, delivery time and quantity of hot water. Failure to meet occupants’ needs triggered a number of system and behaviour–related actions in order to restore their personal and their family’s comfort, expressed by either employing avoidance behaviours or by taking actions such as using overrides or alternative heat sources.
to satisfy their hot water needs. Drivers were also linked to system-related factors and personally held values. Four distinct hot water heating types emerged from the analysis with commonalities in the users’ engagement with the heating system. These are referred to here as On Demand, For All Eventualities, Just Enough and Sunny Days and are described in summary in Table 2 and in more detail in the following paragraphs.

The On Demand hot water heating type was employed by 14 of the 35 participants and included all those with combination boilers, where hot water was heated instantly. The presence of a combination boiler meant that participants did not need to plan their use of hot water as it was always available on demand; one participant commented “It’s instant…you don’t have to wait.” The predominant drivers for this approach were the convenience as well as the immediacy of hot water. Participants in the On Demand and For All Eventualities hot water heating types considered altruistic values (the well-being of other people) by placing value on the household harmony through their use of the hot water heating system, ensuring there was sufficient hot water for all needs.

The Just Enough hot water heating type was employed by 13 of the 35 participants who typically used two pre-programmed activation times that were short in duration. Participants set their heating times to provide sufficient hot water only for their predicted daily tasks, with heating times that matched routine times of peak use, such that the timer was set so the hot water was heated just before and during routine periods of use. One participant talked about experimenting with programme times: “I had it on for longer and dropped it down to about an hour and it still seems to have enough hot water for us.” A number of participants in this type reported taking comfort from having instances where they did not have sufficient hot water for some tasks as evidence that their pre-programmed times were sufficient yet not excessive.

Table 1

| Current hot water heating systems in the sample. |
|-----------------------------------------------|
| No Solar/PV | Solar/PV | Total |
|---------------|--------|-------|
| Hot water tank | 15 | 6 | 21 |
| Combination boiler | 10 | 4 | 14 |
| Total | 25 | 10 | 35 |
suggesting a type of egoistic value, with a focus on their finances. Participants displaying the Just Enough hot water heating type were driven by the perceived efficiency, cost of their system and lifestyle choices. For the Just Enough users, it was evident from the interviews that their systems covered the majority of their hot water needs with reported instances of dissatisfaction being rare. Where there was insufficient hot water, participants were willing to use reactive overrides and wait or use an alternative hot water supply, such as boiling a kettle, to meet their needs.

The Sunny Days hot water heating type was employed by just three participants in the sample. Participants in this heating type had either solar PV systems (n = 2) or a solar thermal system (n = 1). This hot water heating type was predominately employed in the summer when the need for space heating is minimal. These participants did not have any set preprogrammed times for the boiler to heat the hot water, instead they used only their PV or solar thermal systems to heat the hot water. Participants in the Sunny Days hot water heating type had no control over timing or duration of hot water heating; this was determined by the presence or absence of sunlight. All three participants commented that the utilisation of the “free” energy was appealing to them with one participant reporting using hot water “without feeling guilty” with it providing “an endless supply”. Participants in the Sunny Days hot water heating type were partly motivated by the egoistic financial benefit of the system and partly by biospheric values. These users were dissatisfied with the insufficient hot water in the months outside summer and often struggled with the insufficient PV energy to heat hot water at these times. However, these users tolerated a little wait to satisfy their needs (e.g. postponing tasks) or used limited overrides from their central heating system to cover hot water needs.

### 3.3. Switching hot water heating type

Additional insights gained from the interviews indicate that some participants switched hot water heating types regularly while others never switched. A total of 12 participants reported actions that demonstrated they changed hot water heating types; nine switched from Just Enough to For All Eventualities, two switched from Sunny Days to For All Eventualities and one switched from Sunny Days to Just Enough. Switching hot water heating type was triggered by consistent drivers: to accommodate less routine events (e.g. guests) and to match the sleep/lifestyle patterns, e.g. varying between weekdays and weekends. Some participants, in particular those in the On Demand and For All Eventualities types, never switched heating type, suggesting that their current provision matched their needs. The Just Enough users switched to For All Eventualities by extending heating times through the use of the continuous setting (n = 4), using the boost (n = 2) or advance options (n = 3). This was driven by a need for hot water at unexpected or additional times (to match changes in routine) rather than the limited capacity of their hot water cylinder. A larger store would be seen as an unnecessary investment to this waste-sensitive group. The Sunny Days users switched types during the majority of the winter, when there was the insufficient hot water from the solar PV during less sunny days.

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**Table 2**

Overview of hot water heating types for the provision of hot water (including percentage of participants for each factor, identified from the thematic analysis).

| Characteristics                                                | Drivers                                                                 | Needs                                                   | Actions                          |
|----------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------|----------------------------------|
| Hot Water Heating Type: On Demand (n = 14)                      | Convenience (100%)                                                      | Limited time taken to reach the required hot water temperature (43%) | Avoid simultaneous usage (57%) tactile checks (43%) |
| • Hot water heated on demand, usually through a combination boiler | No interaction (100%)                                                   | Stable hot water temperature (14%)                      |                                  |
|                                                              | Efficiency (100%)                                                       |                                                          |                                  |
|                                                              | Immediacy (79%)                                                        |                                                          |                                  |
|                                                              | Quantity (50%)                                                         |                                                          |                                  |
|                                                              | No planning (29%)                                                      |                                                          |                                  |
|                                                              | Suits non-routine lifestyle (22%)                                      |                                                          |                                  |
|                                                              | Household harmony (22%)                                                |                                                          |                                  |
| Hot Water Heating Type: For All Eventualities (n = 5)           | Convenience (100%)                                                      | Efficiency without waste (60%)                          | Overrides (60%) waiting (40%)    |
| • Frequent heating up of hot water and storing excess for all eventuations | Immediacy (80%)                                                        |                                                          |                                  |
| • Hot water system set to continuous or prolonged heating times | Cost effectiveness (80%)                                               |                                                          |                                  |
| • Individual heating time periods exceeded 120 to 240 minutes, with a maximum of 300 minutes per day | Not interaction (60%)                                                  |                                                          |                                  |
|                                                              | No planning (60%)                                                      |                                                          |                                  |
|                                                              | Household harmony (60%)                                                |                                                          |                                  |
|                                                              | Suits non-routine lifestyle (20%)                                       |                                                          |                                  |
| Hot Water Heating Type: Just Enough (n = 13)                    | Convenience (100%)                                                      | Efficiency without waste (60%)                          | Overrides (77%)                  |
| • Two pre-programmed boiler heating times of short duration providing ‘just enough’ hot water | Cost effectiveness (100%)                                               |                                                          | Alternative hot water supply (54%) |
| • Timing periods were set to coincide with routine time of peak use | Suits routine lifestyle (85%)                                           |                                                          | Waiting (54)                     |
| • Programmed heating times ranged from 30 minutes to 120 minutes with a maximum of 240 minutes (in total) a day | Suits sleep patterns (69%)                                              |                                                          | Tactile checks (46%)              |
|                                                              | Avoiding wasted heating (77%)                                           |                                                          |                                  |
| Hot Water Heating Type: Sunny Days (n = 3)                      | Cost effectiveness (100%)                                               | Sufficient PV energy to heat hot water (67%)            | Use of overrides (100%)          |
| • No set programmed times                                      | Sufficient hot water (100%)                                            |                                                          | Tactile checks (67%)             |
| • Use of solar thermal and PV to heat water in summer months    |                                                                         |                                                          | Alternative water supply (67%)    |
| • No control over timing or duration of heating                 |                                                                         |                                                          | Waiting (67%)                    |
4. Discussion

The derived heating types in this research demonstrate a diversity amongst occupants in relation to hot water usage and engagement with their current heating systems. Participants were found to employ one predominant heating strategy, often influenced heavily by the system they had or their personal values, or switch from one approach to another in particular circumstances. The drivers for each hot water heating type were centred around safeguarding personal interests, be it comfort for themselves and their household, without necessarily considering the environmental consequences. This contrasts with the Just Enough and Sunny Days users who were driven by egoistic and biophysical values. An understanding of these drivers, and the actions taken as a result, can help identify user requirements for thermal storage as part of future heating systems. These future energy systems are likely to include heat pumps, sensible, phase-change and thermochemical energy storage, and increased use of photovoltaics and community district heating, combined with variable pricing tariffs.

On Demand users were influenced by the contextual domain in their household (primarily the presence of a combination boiler), which allowed for lifestyle flexibility which was highly valued. As a consequence, On Demand users are likely to be resistant to a change in service delivery and would only be interested in a future heating system if it provides hot water on demand, to maintain their household harmony. The On Demand users avoided advance planning, so would be favourable towards heating systems that require limited interaction. A common dissatisfaction reported among On Demand users was the time taken to reach an adequate hot water temperature; thermal storage could provide a suitable buffer to avoid these delays. Simultaneous usage of hot water without experiencing instances of inadequate hot water through loss of pressure was also important to these users and so a thermal store that can maintain rate of hot water delivery and meet demand would be favourably received.

For All Eventualities users desire a system that provides sufficient hot water to meet all their needs, whether planned or not. These users have little tolerance to instances with insufficient hot water and so a thermal energy storage system could store sufficient hot water to cover ‘all eventualities’. The majority of the For All Eventualities users in this study considered their current hot water heating strategy to have minimal cost implications, as they heated water only to replenish hot water that had been used. Although the extended heating periods will inevitably result in a higher energy consumption, these users perceived their use to be cost effective and efficient. These users chose these prolonged heating times to avoid having to think, plan ahead and interact with the system; their needs may be met by a future system that does not require much interaction, but must deliver adequate hot water whenever needed.

The Just Enough users chose shorter specified heating times that were closely matched to routines. These users may be positive in the adoption of a future heating system if it provides hot water at times that match their daily routine and sleep patterns. As these users take comfort from instances where they did not have sufficient hot water for some tasks (suggesting carefully planned efficiency), they are likely to tolerate instances of insufficient hot water as long as the system is not seen as wasteful. The Just Enough users had experience with unsatisfactory water temperatures and may be interested in a system that provides feedback about hot water temperature and volume to enable them to plan their use and so heat sufficient hot water only for their daily routines without waste.

As the Sunny Days users had experience with intermittent energy generation, they are more likely to embrace future systems that are weather dependent. The Sunny Days users in this study were environmentally aware and thus these users may particularly appreciate...
the long-term environmental benefits of using efficient heating systems such as heat pumps with thermal stores. These users have tolerance to extended periods of unplanned hot water provision, but a system with a thermal energy store that could mitigate the variations in the hot water generation would provide an enhanced service. The Sunny Days users may make an investment to a system that is energy efficient and has environmental benefits, especially if this allowed some mitigation against volatile energy prices. Future systems that combine fast-response gas heating with solar PV and thermal storage are likely to meet the biospheric values of the Sunny Days user, whilst still delivering the household’s hot water demands throughout the year. A summary of the user requirements for thermal storage by hot water heating type is presented in Table 3.

The developed hot water heating types describe individuals’ usage and engagement with hot water heating systems within the UK households and align with current literature suggesting that occupants’ decisions to engage with an energy efficient system depends heavily on their knowledge, motivation to do so, contextual factors, values, trust in involved parties, potential costs and benefits and public involvement [31]. These factors may influence both use and adoption of energy-consuming technologies and renewable energy sources.

Importantly, the data from the interviews indicate that some participants switched hot water heating type as circumstances in their household changed. This indicates the need for a future system to be adaptable, to account for occupants’ changing behaviour, lifestyle, needs and preferences. It has been argued that occupants more readily adopt energy policies when they allow for flexibility and do not have negative consequences [40]. For the successful adoption and impact of future domestic heating systems, occupants’ drivers, needs and actions can highlight user requirements to be considered in the design [29]. Energy policies and the design of new energy efficient technologies will be more successful if they target important antecedents of behaviour, removing significant barriers to change [11].

5. Conclusion

This research has explored hot water usage and user engagement with hot water heating systems in order to understand how current experiences with hot water heating systems can inform the design of future systems and the role of thermal energy storage. Given the gap in knowledge around occupant interaction with hot water heating, the paper provides valuable insights on end user engagement with domestic hot water heating systems and identifies user requirements for future thermal storage technologies. This research explored occupants’ engagement, usage strategies and experiences with hot water heating systems through a series of interviews in 35 households with gas-fired central heating systems, typical of those used in the UK. The timeline tool developed specifically for this study enabled householders to talk about their hot water use in an engaging and informative way and offers an approach for further research where the underlying drivers for behaviour are sought. A typology of hot water usage types was developed from the collected data by considering the drivers, needs and actions that underpin occupants’ decisions to interact with their heating system. Four hot water heating types, including On Demand, For All Eventualities, Just Enough, Sunny Days, and associated user requirements for the design of future thermal energy storage systems for each type have been determined. The identified hot water heating types depict the heterogeneity of occupants’ behaviour patterns. User requirements for each type show differences, with a focus on convenience and immediate provision of hot water for some, and a tolerance to compromise or wait for others. Thermal storage can provide a viable solution to all these users by offering a buffer between supply and demand. In some cases, this buffer could be at a community level, in others it could be seasonal. Without storage, a move to more efficient systems that do not provide such fast-response heating is likely to leave users dissatisfied. For those that have become used to hot water on demand, any delay will be seen as a reduction in service. If prices increase significantly, those users that are currently heating hot water for all eventualities may need to change their approach as prolonged periods of heating becomes prohibitively expensive. Thermal storage also offers the opportunity to smooth intermittent supply. In order to facilitate the successful deployment of future energy efficient solutions to meet the UK’s targets for the greenhouse gas reductions by 2050, researchers should consider occupants’ energy-related behaviour alongside technological advancements to ensure successful adoption and impact of thermal energy stores at domestic and policy level. It is imperative that technology developers and engineers incorporate user insights into their design to ensure that products meet end user requirements. Improved understanding of occupant behaviour can inform the design of energy efficiency technologies leading to increased market uptake of thermal energy stores.

Funding

This work was undertaken as part of the End User Energy Demand Centre, i-STUTE (interdisciplinary centre for Storage, Transformation and Upgrading of Thermal Energy supported by the UK’s Engineering and Physical Sciences Research Council (grant number: EP/K011847/1). Access to the underlying data is available via the Loughborough University data repository, where participant consent allows.

Conflicts of interest

None.

References

[1] BEIS, Energy consumption in the UK, Retrieved from Department for Business, Energy and Industrial Strategy, 2018, https://www.gov.uk/government/statistics/energy-consumption-in-the-uk.
[2] BEIS, Digest of UK Energy Statistics (DUKES) 2018, Retrieved from Department for Business, Energy and Industrial Strategy, 2018, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data_file/736148/DUKES_2018.pdf.
[3] A. Arteconi, N.J. Hewitt, P. Polonara, State of the art of thermal storage for demand-side management, Appl. Energy 93 (2012) 371–389, https://doi.org/10.1016/j.apenergy.2011.12.045.
[4] Energy Research Partnership, The future role for energy storage in the UK Main report, Energy Research Partnership Technology Report, (2011) Retrieved from http://erpuk.org/wp-content/uploads/2014/10/S2990-EER-Energy-Storage-Report-v3.pdf.
[5] P. Eames, D. Loveday, V. Haines, P. Romanos, The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption Report The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Techni. Research Report (UKERC: London), Retrieved from (2014) www.ukerc.ac.uk.
[6] European Commission, The future role and challenges of energy storage, DG ENER Working Paper, (2013) Retrieved from http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy-storage.pdf.
[7] F.H. Rohles Jr., Thermal comfort and strategies for energy conservation, J. Soc. Issues 37 (2) (1981) 132–149.
[8] U.I. Dac, L. Georges, I. Sartori, V. Novakovic, Influence of occupant’s behavior on heating needs and energy system performance: a case of well-insulated detached houses in cold climates, Build. Simul. 8 (5) (2015) 499–513, https://doi.org/10.1007/s12273-015-0230-y.
[9] R.J. Boed, R.E. O’Connor, A. Fischer, In what sense does the public need to understand global climate change? Public Understanding Sci. 9 (2000) 205–218, https://doi.org/10.1088/0966-6625/9/3/301.
[10] G. Schuitena, L. Steg, Perceptions van energieverbruik van huishoudelijke apparaten (perception of energy use of domestic appliances), in: A.E. Brunner, P. Dekker, E. de Leeuw, K. de Ruyter, A. Smidts, J.E. Wieringa (Eds.), Ontwikkelingen in Het Marktonderzoek. Jaarboek 2005 MarktOnderzoekAssociatie (Developments in Marketing Research. Yearbook 2005), De Vriesbocht, Haarlem, 2005, pp. 165–180.
[11] L. Steg, G. Perlovich, E. van der Werf, Understanding the human dimensions of a sustainable energy transition, Front. Psychol. 6 (June) (2015) 1–17, https://doi.org/10.3389/fpsyg.2015.00805.
[12] O. Guerra Santin, L. Kard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy Build. 41 (11) (2009) 1223–1232, https://doi.org/10.1016/j.enbuild.2009.07.052.
[13] D. Yan, W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, A. Mhdavi,
Occupant behavior modeling for building performance simulation: current state and future challenges, Energy Build. 107 (2015) 264–278, https://doi.org/10.1016/j.enbuild.2015.08.032.

[14] L. Steg, G. Perlovich, E. van der Werff, J. Larvink, The significance of hedonic values for environmentally relevant attitudes, preferences, and actions, Environ. Behav. 46 (2) (2014) 163–192, https://doi.org/10.1177/00144820145245730.

[15] J.I.M. de Groot, L. Steg, Value orientations to explain beliefs related to environmental significant behavior, Environ. Behav. 40 (3) (2008) 330–354, https://doi.org/10.1177/0014482008320411.

[16] S.M. Sanzighi, Investigating energy-related occupants’ behaviors on energy consumption in residential buildings (opening/closing windows and blinds), J. Energy Nat. Res. 7 (1) (2018) 32, https://doi.org/10.11648/j.jernr.20180701.15.

[17] S. Yilmaz, S.K. Firth, D. Allinson, Occupant behaviour modelling in domestic buildings: the case of household electrical appliances, J. Build. Perform. Simul. 10 (5-6) (2017) 582–600, https://doi.org/10.1080/19401493.2017.1287775.

[18] D. Yan, W. O’Brien, T. Hong, X. Feng, H.B. Gunay, F. Tahmasebi, A. Mahdavi, Occupant behavior modeling for building performance simulation: current state and future challenges, Energy Build. 107 (2015) 264–278.

[19] V. Martinaitis, E.K. Zavadskas, V. Motuziene, T. Vilutiene, Importance of occupancy information when simulating energy demand of energy efficient house: a case study, Energy Build. 101 (2015) 64–75, https://doi.org/10.1016/j.enbuild.2015.04.031.

[20] A.C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap, Appl. Energy 97 (2012) 355–364, https://doi.org/10.1016/j.apenergy.2011.11.075.

[21] K. Schakib-Ekbatan, F.Z. Cakici, M. Schweiker, A. Wagner, Does the occupant behavior match the energy concept of the building? - Analysis of a German naturally ventilated office building, Build. Environ. 84 (2015) 142–150, https://doi.org/10.1016/j.buildenv.2014.10.018.

[22] Von Grabe J. (2016). A Psychological Approach to Understanding and Predicting Energy-relevant Human Interaction with Buildings: A Research … A Psychological Approach to Understanding and Predicting Energy-relevant Human Interaction with Buildings. doi: https://doi.org/10.1016/j.enbuild.2013.11.013.

[23] T. Dietz, A. Dan, R. Shwom, Support for climate change policy: social psychological influences, Rural Sociol. 72 (2007) 1061–1071, https://doi.org/10.1177/0036087070720412.

[24] S. D’Oca, T. Hong, J. Langevin, The human dimensions of energy use in buildings: a review, Renewable Sustainable Energy Rev. 81 (May 2017) (2018) 731–742, https://doi.org/10.1016/j.rser.2017.05.019.

[25] V. Haines, V. Mitchell, T. Ross, User centred design As an enabler of sustainable HCL 1-4, Br. HCI 2015 (13th-17th July) (2015) 2015, Lincoln, UK.

[26] V. Haines, V. Mitchell, T. Ross, User centred design As an enabler of sustainable HCL 1-4, Br. HCI 2015 (13th-17th July) (2015) 2015, Lincoln, UK.

[27] V. Haines, V. Mitchell, C. Cooper, M. Maguire, Probing user values in the home environment within a technology driven smart home project, Pers. Ubiquitous Comput. 11 (5) (2007) 349–359, https://doi.org/10.1007/s00779-006-0075-6.

[28] T. Hongs, T. D’Oca, S.C.T. Turner, An ontology to represent energy-related occupant behavior in buildings part I: introduction to the DNAs framework, Build. Environ. (May) (2016), https://doi.org/10.1016/j.buildenv.2015.02.019.

[29] T. Hongs, T. D’Oca, S.C. Taylor-Lange, W.J.N. Turner, Y. Chen, S.P. Corgnati, An ontology to represent energy-related occupant behavior in buildings. Part II: implementation of the DNAs framework using an XML schema, Build. Environ. 94 (2015) 196–205, https://doi.org/10.1016/j.buildenv.2015.08.006.

[30] V. Haines, V. Mitchell, B. Mallaband, Merging a practice-oriented approach with an engineering-driven product development: a case study on home improvement, J. Des. Res. 14 (101-12) (2012) 28–49, https://doi.org/10.1504/JDR.2012.046138.

[31] B. Mallaband, V. Haines, Blurred lines: how does cross-disciplinary research work in practice, Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Adjunct Publication, 2014, pp. 963–970. ACM.

[32] T. Hong, S.C. Taylor-Lange, S. D’Oca, D. Yan, S.P. Corgnati, Advances in research and applications of energy-related occupant behavior in buildings, Energy Build. 116 (2016) 694–702, https://doi.org/10.1016/j.enbuild.2015.11.052.

[33] R. Galvin, How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? J. Build. Eng. 1 (2015) 2–12, https://doi.org/10.1016/j.jobe.2014.12.001.

[34] A. Crabtree, T. Rodgers, Domestic routines and design for the home, Comput. Supported Cooperative Work (CSCW) 13 (2) (2004) 191–220, https://doi.org/10.1023/B:COUS.0000045712.26846.a4.

[35] V. Haines, V. Mitchell, B. Mallaband, Using a practice-oriented approach to inform the design of energy efficiency measures for older homes, ERSCP-EMSU Conference 2010: Knowledge Collaboration & Learning for Sustainable Innovation (2010) 315–322.

[36] A.M. Kanstrup, E. Christiansen, Selecting and evoking innovators: combining democracy and creativity, Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing roles (2006) 321–330.

[37] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2) (2006) 77–101, https://doi.org/10.1177/1478088706063001.

[38] C. Robson, Real World Research: A Resource for Social Scientists and Practitioner-Researchers, Blackwell Publishing, 2002, https://doi.org/10.1016/j.jclinepi.2010.08.011.

[39] Energy Savings Trust, Measurement of Domestic Hot Water Consumption in Dwellings, Retrieved from Energy Savings Trust, 2008, pp. 1–63, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/481883/3147_measure-domestic-hot-water-consum.pdf.

[40] T. Dietz, A. Dan, R. Shwom, Support for climate change policy: social psychological and social structural influences, Rural Sociol. 72 (2) (2007) 185–214, https://doi.org/10.1526/0013916512454730.