'Domesticating' low carbon thermal technologies: Diversity, multiplicity and variability in older person, off grid households

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Abstract

The uptake of low carbon heating technologies forms an important part of government strategies to reduce carbon emissions. Yet our understanding of why such technologies are adopted and how they are engaged with post-adoption, particularly by older adults living in off-grid areas, is limited. Drawing on a contextualised, socio-technical approach to domestic heating, we present findings from 51 in-depth interviews with a sample of 17 older person households with ages ranging from 60-89 years. Diverse and multiple configurations of heating devices and fuels were found that varied considerably, with some households using five different fuels. The design of the study ensured that approximately half the sample used some form of low carbon thermal technology, such as heat pumps and biomass boilers. Many factors were reported to influence the adoption of low carbon heating; environmental motives were not primary influences and the avoidance of financial risks associated with 'peak oil' was expressed. Low carbon thermal technologies were typically integrated into rather than replaced existing heating systems so that valued services provided by conventional technologies could be retained. Implications of the findings for policies to reduce carbon emissions, particularly in older adult, off-grid households, are discussed.

Keywords: low carbon thermal technologies, domestication, older people, off grid.

1. Introduction

Domestic energy use accounts for more than a quarter of carbon dioxide emissions in the UK and housing has been identified as a sector where energy use and associated carbon dioxide emissions may be cut (Palmer and Cooper, 2011). Understanding and reducing domestic energy use is not a new aspiration; research into energy consumption dates back several decades and has drawn on a range of disciplines (McDougall et al., 1981; Shove, 1998; Hazas et al., 2011). Increasing awareness of the impact of climate change and the importance of sustainability have highlighted the urgency with which energy consumption must be tackled (Hazas et al., 2011), reflected in the UK government target of cutting greenhouse gas emissions by four-fifths from 1990 levels by 2050. To achieve this, homes will not only need to become more energy efficient but there will be an increasing focus on householders using low carbon technologies for heat and power generation (DECC, 2011). The UK housing stock is old and government initiatives such as the Green Deal (DECC, 2012c) aim to help meet the 2050 target by providing funds to retrofit existing homes. Given that space and water heating totalled 60% and 18% respectively of UK domestic energy consumption in 2011 (DECC, 2012a), low carbon thermal technologies (LCTTs) such as heat pumps, biomass boilers and solar thermal provide an option for customers to change to ‘greener’, and potentially cheaper alternatives (OFT, 2011).

Gas is the main fuel used for domestic heating (83% of homes) in the UK; nevertheless 3.3 million homes are off the gas grid (Baker, 2011) and 51% of these are in rural areas (OFT, 2011). Off grid households rely on other fossil fuels such as oil, LPG, and solid fuels for heating, and often use other fuel sources in addition to their primary heating fuel (Baker, 2011; OFT, 2011); for example, wood or coal may be used to supplement the use of electricity for heating (SPA Future Thinking, 2011). Off grid rural householders are seen as ideally placed to take advantage of low carbon heating because of their reliance on more expensive fuels and their ability to house the ‘hardware’ associated with technologies such as ground source heat pumps and biomass boilers (DECC, 2012b). Uptake to date has been higher in rural areas (OFT, 2011); typically, early adopters of LCTTs have been middle class home owners, aged 45+, living in larger rural properties that are not connected to the gas grid (Roy et al., 2008). A field trial by the Energy Saving Trust suggested that households with heat pumps still commonly used supplementary forms of heating (Caird et al., 2012) but there was little emphasis in this study, and in the literature more generally, upon how LCTTs may be integrated, post-installation, into existing thermal comfort technologies and practices.

Research on domestic microgeneration has largely employed quantitative methods and concentrated on two areas: the adoption of LCTTs, drawing on innovation theory (e.g. Caird et al., 2008; ECL, 2008; Caird and Roy, 2010); and analyses of technical performance and system efficiencies post-installation (e.g. EST, 2010; DEE, 2011). Older person households will be an important consumer group for LCTTs, given that this social group is growing in size in the UK and other countries. It is estimated that the proportion of the UK population aged 60+ will increase from 14.4 million in 2012 to 21.6 million in 2050 (United Nations Population Fund and HelpAge International 2012). The development of an ageing society is forecast to increase residential energy demand because retired people spend more time at home and potentially have higher energy requirements (Roberts, 2008), but an emerging research literature involving older people suggests that they may be less likely to invest in renewable thermal technologies. Mahapatra and Gustavsson (2008) reported that the percentage of respondents planning to install a new heating system decreased with age. The authors suggested that older owners might be less likely to install a new heating system if they did not expect to recoup their investment. Willis et al. (2011) found that older person households were less inclined to adopt discretionary microgeneration technologies such as solar thermal, solar PV and wind turbines and Sopha et al. (2010) found that older age was statistically significant for choosing electric heating over either a heat pump or a wood pellet stove. Owen et al. (2013) concluded that older people in fuel poverty might prefer to be ‘late adopters’ or ‘laggards’ in adopting air source heat pumps. Given the wider contexts of an ageing society and efforts to decarbonise domestic heating, there is a need to better understand the extent to which, and how, older adults are engaging with these technologies both prior to and after installation. As Caird and Roy (2010) noted, adopting these technologies is not the same as making carbon savings with them.

We argue that understanding how LCTTs are engaged with requires a perspective that goes beyond linear, individualistic views of technology adoption. A co-evolutionary approach (Brand, 2005) views technological change as an inherently social and cultural process (Shove, 2010), involving the mutual shaping of material and non-material aspects. Moreover, we emphasise the importance of context, here pointing out important ways that LCTTs become emplaced within a particular kind of space - the home (Aune, 2007). ‘Low carbon homes’ have become a prevalent policy agenda over recent years, yet in ways that favour a narrow, technocentric perspective (Reid and Houston, 2013). In contrast, a contextualised, socio-technical approach to how LCTTs become adopted and used would view the home as more than a physical container into which technologies are installed (Easthope, 2004).

This socio-cultural conception of the ‘low carbon home’ is compatible with recent approaches to thermal comfort. Historically, thermal comfort research was informed by engineering-led approaches that focused upon measuring and producing ‘optimal’ thermal conditions for building occupants. The ‘new approach’ (Cooper, 2010) takes as a starting point the diverse, systemic and adaptive character of thermal comfort in which people respond to the environments and conditions they inhabit, and to the historical and cultural underpinnings of how comfort is played out in everyday life. Empirical research is accordingly less concerned with the experimental worlds of climate chambers, and more with capturing the ways that thermal comfort is experienced and adapted *in situ* by building occupants; how the ‘demand’ for comfort is socially and culturally produced (Wilhite, 2010) while being intimately wrapped up with its ‘supply’ through technologies, ideas and policies (Shove et al., 2010).

We draw on the concept of ‘domestication’ to reflect the process whereby technologies become integrated into the ‘moral economy’ of a household (Silverstone et al., 1992). Here a process of technological change such as moving from fossil-fuel to low carbon domestic heating systems is not reduced to technological attributes such as cost or carbon emissions, or adopter attitudes and behaviour. Instead, the focus is to better understand how LCTTs become embedded within a complex assemblage (Latour, 1988) of people, artefacts, knowledge, practices and institutions (Sorensen et al., 2000). Pre-existing socio-cultural values, including notions of cosiness, sociability, status and autonomy, may play an influential role (Aune, 2007; Hards 2013; Petersen, 2008;

Wilhite and Lutzenhiser, 1999); and the physical/material setting, both internal and external to the home, will shape and constrain what options are considered practical or feasible in rural, off-grid contexts. Yet our current understanding of how novel low carbon thermal technologies become ‘domesticated’ into off-grid homes post-adoption, and how their use may be shaped by such values and meanings, is limited.

To address these gaps, this study aimed to deepen understanding of how low carbon heating technologies are accommodated within the household to provide thermal experiences which are valued by the occupants. Our focus is upon households off the gas grid inhabited by older adults, noting their reliance upon expensive fossil-fuels (Baker, 2011), suitability for LCTT installation (DECC, 2012b) and the findings of existing research suggesting that these are less likely to adopt LCTTs (Sopha et al., 2010). Taking forward the primarily quantitative and individualistic survey work undertaken in the UK to date (e.g. Caird et al., 2008; Caird and Roy, 2010; Caird et al., 2012), we chose to use qualitative methods to provide in-depth accounts of how and why householders engage with both conventional and low carbon energy technologies. The central questions are: (1) What assemblage of people, technologies and fuels feature in rural, off-grid households, including those containing LCTTs? (2) What factors are reported to underlie the adoption of LCTTs? (3) To what extent do low carbon technologies replace conventional, fossil-fuel technologies or become integrated within existing home heating systems?

2. Method

To recruit a mix of households with low carbon and conventional thermal technologies, a short survey was sent to members of three environmental groups based in

Devon in South-West England, asking about domestic low carbon thermal technology usage in people aged 60+. Eight households were selected covering a range of low carbon technologies[1] (heat pumps (n = 4), biomass log boilers (n = 2), and solar hot water (n = 2)) and asked if we could interview at least one occupant of the household. Six survey respondents agreed to participate; two people with heat pumps did not respond despite follow up emails and telephone calls. To recruit households with conventional thermal technologies, two short news items about the study were published in a local newspaper, inviting readers to participate in the research. Eleven responses were received from households using a variety of (mainly conventional) thermal technologies and all participated in the interviews.

Participants were aged from 60 – 89 at the time of recruitment; the median age (based on the older of the interviewees in a 'couple' household) was 69 years. All interviewees were retired (n = 15) or semi-retired (n = 2). The majority had sources of income in addition to that of the state pension (e.g. private pensions or income earning investments). Demographic details together with characteristics of the dwelling are shown in Table 1. Eleven households comprised couples, five were inhabited by sole female occupants, and the remaining household comprised a mother and daughter. Our sample primarily consisted of people occupying detached or semi-detached dwellings (Table 1). Eight (47%) had four or more bedrooms (although these rooms were sometimes adapted for other uses) compared with less than 20% of houses nationally (DCLG, 2011); almost all participants had large gardens or a landholding in conjunction

[1] We did not recruit solar PV users unless they also had an additional type of LCTT installed, on the basis that solar PV on its own does not alter the thermal environment.

with the dwelling. All properties were owned by the occupants except for the mother and daughter who rented their cottage. The length of time our participants had lived in their current home ranged from 2 to 33 years with almost half of the sample (n = 7) having lived in the same property for 14 years or more. Most participants had changed at least some aspects of their heating system during the time they had been in their current home.

Fifty-one interviews were conducted comprising three interviews with 17 households (winter, summer, and autumn or spring depending on when they were recruited) to understand heating practices across different seasons. As some households had recently had LCTTs installed, repeat interviews every three to four months enabled us to capture ways in which heating systems evolved with the introduction of the novel technology. In addition, repeat visits enabled a greater rapport with interviewees to be achieved, which could elicit richer data (Andersen, 2001). The data collection period commenced in November 2011 and was completed in August 2012. A semi-structured interview guide was used which was divided into areas reflecting the broad scope of the project as a whole: notions of the home, day to day activities/routines, characteristics of the dwelling, decision-making relating to choice of thermal comfort technologies, personal thermal comfort preferences, use of heating/cooling technologies across different seasons, other strategies used to achieve thermal comfort, and energy use. Interviews were conducted by the first author at the home of the householder/s and were digitally recorded. The initial interview typically lasted 80 – 90 minutes and subsequent interviews typically lasted 30-60 minutes. Interviewees received a £20 grocery voucher for the initial interview, and a £10 grocery voucher for each subsequent interview.

Table 1. Characteristics of participant households

ID	Occupants[a] ( ) = did not take part in interview	Group[b]	Age of oldest P	Location	Type of dwelling	Age of dwelling (yrs)[c]	Length of residence (yrs)	Number of bedrooms	Insulation[d]	Double glazing
1.	Scott & Rose	Primary	66	Hamlet	Farmhouse: detached (under renovation)	400+ (parts)	14	4	Partial	Being installed
2.	Keith (& Fran)	Primary	60	Isolated dwelling	House: detached (new build)	2	2	4	Yes	Yes
5.	Mark & Ann	Primary/SPV	65	Hamlet	House: detached	250+ (part)	30	6	Partial	Partial secondary
6.	Dave & Stella	Primary/SPV	62	Outskirts of village	Bungalow	28	7	5	Yes	Yes
17.	Phil & Carol	Primary/SPV	78	Village	Bungalow	47	4	2	Yes	Yes
3.	Martin & Gay	Partial/SPV	68	Outskirts of village	Bungalow	18	4	3	Yes	Yes
4.	Dan (& Joyce)	Partial/SPV	89	Village	House: detached	6	6	4	Yes	Yes
15.	Jeff & Clare	Partial	67	Village	House: terraced	200+	4	3	Yes	Yes
16.*	Paula	Partial	73	Hamlet	Cottage: detached	400+	17	3	No	No
7.*	Janet	Conventional	76	Village	Cottage: detached	140	33	3	Partial	Yes
8.	Mick & Anna	Conventional	69	Hamlet	House: detached	400+ (parts)	22	5	Partial	No
9.*	Joan	Conventional	76	Hamlet	Cottage: semi-detached	100+	15	3	Partial	Yes
10.*	Susan	Conventional	74	Village	Bungalow	36	6	2	Partial	Yes
11.	Trish (& Cliff)	Conventional/ SPV	66	Hamlet	House: semi-detached	170 + new extn	28	4	Partial	Yes
12.†	Sally & Karen	Conventional	75	Outskirts of village	Cottage: semi-detached	100+	4	2	Not known	Yes
13.	Neil & Diane	Conventional/ SPV	67	Hamlet	House: detached	200	2	4	Yes	Partial
14.*	Bella	Conventional	72	Village	House: detached	100+	9	3	Partial	Yes

[a] Names have been changed to preserve anonymity.
[b] These groups are explained in the Results section. "SPV" are those households with solar photovoltaic panels.
[c] Parts of some older properties were of different ages; the age of the oldest part is included in this column. Where the age of the property is not known; the householder's best estimate has been used.
[d] "Yes" means the roof and walls were insulated; "Partial" means either the roof or walls were insulated or only parts of one or both these areas were insulated.
* Sole female occupant; † Mother and daughter; All other occupants were couples.

Each interview was transcribed verbatim and imported into Atlas.ti (version 6.2). In analysing the data, a thematic approach was undertaken (Braun and Clarke, 2006). That is, the interview dialogue was coded into categories and sub-categories guided by the conceptual approach and the interview topics.

3. Findings

3.1 Diversity and multiplicity

A key finding of the study is that our households indicated a complex assemblage of heating technologies and fuels (see Tables 2 and 3) that we have interpreted using the overlapping concepts of 'diversity' and 'multiplicity'. By 'diversity' we mean the range of heating technologies and fuels used, whereas 'multiplicity' refers to the use of a number of different technologies which perform the same function. Although the focus of our research was on space and water heating systems, heating was often provided by a kitchen range or other cooking appliance, such as an oven, when in use. We therefore also draw on data in relation to cooking to illustrate the variety of heating technologies and sources utilised in any one, off-grid household.

3.1.1 Diversity

Our households fell into three categories: *primary* households were reliant upon LCTTs for space and/or water heating ($n = 5$); *partial* households were those with some form of LCTT but were only partially reliant on such technologies ($n = 4$); and the *conventional* group were those with conventional thermal technologies ($n = 8$). Three households from the *Primary* group and two households from each of the other two groups (total $n = 7$) had solar photovoltaic panels installed. A household was determined to be primarily reliant on a certain space heating technology when that technology was identified by the householders as their principal space heating system. Some households used two space-heating technologies in tandem to achieve a satisfactory level of comfort. The characteristics of each group are briefly described below (see also Tables 1-3).

The *Primary* group consisted of five households, each comprising a ‘couple’ and, in two cases, additional family members. Two households had ground source heat pumps (GSHP), one had an air source heat pump (ASHP), and two had biomass (log) boilers (BB).

Example: Keith and Fran had 18 months previously moved into a new build house adjoining their farm. A ground source heat pump provided primary space heating (under floor heating downstairs, radiators upstairs) and water heating; there was a supplementary wood burner in the lounge, and the cooker was electric. (P2)

The *Partial* group comprised four households, three of which comprised a ‘couple’ and the fourth household a single female occupant. One household had an ASHP, one had wood burners, and two had solar thermal.

Example: Martin and Gay had an oil fired boiler with radiators throughout the house to provide primary space heating although, due to an under-sized radiator in the lounge, on colder days in winter a wood burner was used in addition to the central heating to ensure an adequate level of comfort in the living area; solar thermal, boosted when necessary by the boiler, provided hot water. Supplementary electric heaters were used occasionally in bedrooms, and LPG was used for cooking. (P3)

The *Conventional* group comprised eight households with half of the households having single female occupants, three households comprising a 'couple', and the final household comprising the mother and daughter.

Example: Joan had a Rayburn range[2] in the kitchen fuelled by wood and coal that provided background space heating and water heating and was used as a cooker in winter. An open fire in the sitting room, using wood and coal, also formed part of the primary space heating system. Water heating in summer was provided by an immersion heater. Supplementary electric heaters were occasionally used and there was an electric cooker for use in summer. (P9)

In terms of diversity, the average number of different fuels/energy sources used by all households for space/water heating and cooking was three; the maximum was five, used by two households for various heating functions (Table 2: P3 & P12, *Partial* and *Conventional* groups respectively). Diversity across our *Primary* and *Partial* groups can partly be attributed to our sampling rationale, whereby we purposively recruited households with specific LCTTs. This is not a complete explanation, however, as the heating systems in the LCTT households often incorporated additional technologies (e.g. wood burning stoves), either through necessity or through choice.

[2] A range is an old type of cooker, with one or more ovens and cooking surfaces, that is traditionally heated with wood, coal or oil and is kept hot all the time in the colder months. Popular makes are 'Aga' and 'Rayburn'.

Table 2. Diversity of technologies used by participant households for main space heating and water heating

ID/ Grp	Main space heating[a]									Water heating[b]							
	Biomass boiler	Wood/ Multi-fuel burner	GSHP	ASHP	Oil fired boiler	Electric heaters	Gas heaters	Range	Open fire	Solar Thermal	Biomass boiler	Wood/ Multi-fuel burner	GSHP	ASHP	Oil fired boiler	Immersion heater	Range
$1^{(1)}$			●										●				
$2^{(1)}$			●										●				
$5^{(1)\,S}$	●				□					●	●				□	●	
$6^{(1)\,S}$	●				□						●				□		
$17^{(1)\,S}$				●										●			
$3^{(2)\,S}$		●			●					●					●		
$4^{(2)\,S}$					●					●					●	●	
$15^{(2)}$								●						●		●	●
$16^{(2)}$		●						●				●				●	
$7^{(3)}$						●		●								●	●
$8^{(3)}$							●	●								●	●
$9^{(3)}$								●	●							●	●
$10^{(3)}$						●										●	
$11^{(3\,S)}$					●										●		
$12^{(3)}$						●			●								●
$13^{(3)\,S}$		●			●										●		
$14^{(3)}$					●			●							●	●	●

(1) = *Primary* group; (2) = *Partial* group; (3) = *Conventional* group. S = Solar photovoltaic panels.

a Where two technologies are included for a household, both were required or were regularly used to achieve thermal comfort in the main living area/s on a typical winter's day.

b Where more than one technology is included for a household, these were often used in different seasons.

□ Means back-up system which would be used in place of a primary space heating technology rather than in addition to it.

Table 3. Diversity of fuels used by participant households for space and water heating, and cooking[a]

ID/ Grp	**Main and supplementary space heating**						**Water heating**							**Cooking**						
	Wood	Elect. (LC)^2	Elect.	Oil	LPG	Coal	Solar	Wood	Elect. (LC)^2	Elect.	Oil	LPG	Coal	Wood	Elect. (LC)^b	Elect.	Oil	LPG	Coal
$1^{(1)}$	Δ	●							●							●			
$2^{(1)}$	Δ	●							●							●			
$5^{(1)\ S}$	● Δ		Δ	□			●	●			□			●		●			
$6^{(1)\ S}$	●		Δ	□	Δ			●			□							●	
$17^{(1)\ S}$		●	Δ						●							●			
$3^{(2)\ S}$	●		Δ	●			●				●							●	
$4^{(2)\ S}$			Δ	●			●			●	●					●			
$15^{(2)}$	Δ					● Δ			●	●			●			●		●	●
$16^{(2)}$	●		● Δ					●								●			
$7^{(3)}$	Δ		● Δ	●						●	●					●	●		
$8^{(3)}$	Δ		Δ	●	● Δ					●	●					●	●		
$9^{(3)}$	●		Δ			●		●		●			●	●		●			●
$10^{(3)}$			● Δ							●						●			
$11^{(3)\ S}$				●							●					●		●	
$12^{(3)}$	●		● Δ			●				●	●						●	●	
$13^{(3)\ S}$	●		Δ	●							●					●			
$14^{(3)}$	●			●						●	●					●	●		

[a] This table includes only fuels actually used, rather than fuels householders had capacity to use (e.g. if a household owned supplementary electric heaters but did not use them, their usage of electricity for supplementary space heating would not be included above).

(1) = *Primary* group; (2) = *Partial* group; (3) = *Conventional* group. S = Solar photovoltaic panels.

[b] We have separated out technologies which use electricity to produce heat but are more energy efficient (and are therefore "low carbon") than conventional technologies using electricity.

● Main space heating/water heating/cooking fuel; Δ Supplementary space heating fuel; □ Fuel used by back-up system.

A wide range of technologies and fuels were also represented in the *Conventional* group households. Oil fired boilers and ranges fuelled by oil, wood or coal were the most common space heating technologies found in the *Partial* and *Conventional* households and were also often used for water heating. Our participants reported that, as temperatures became milder in spring and summer months, ranges were generally turned off and electric immersion heaters in hot water tanks were commonly used.

3.1.2 Multiplicity

A second key finding of the study is that none of our households were solely reliant upon the primary space and water heating technologies that are listed in Table 2 - supplementary and/or back-up space heating devices were found in every household. Our households contained complex arrays of technologies and fuels that were used across different home spaces at different times of the day or year to achieve thermal comfort (see Table 3). We define 'supplementary' space heating as heat sources used in addition to primary space heating technologies. 'Back-up' systems, on the other hand, were held in readiness to be used in place of primary space heating technologies. All interviewees (apart from the mother and daughter renting their cottage) considered that they achieved a satisfactory level of warmth but some households, most often those in the *Partial* and *Conventional* groups, required a number of devices distributed across home spaces to achieve desired comfort levels in the coldest spells in winter. In these cases, supplementary heating was used in rooms which were less frequently utilised, such as a 'study' or home office, especially where there was no central heating system. In addition, many of our participants lived in older dwellings and, although the majority had at least some insulation and double glazing (Table 1), almost all households used draught proofing methods such as curtains and draught excluders.

Our *Primary* group households reported they did not often need to use supplementary devices to their installed LCTTs as radiators could be thermostatically controlled to provide warmth as and when necessary in different spaces. Nevertheless, in these households, as well as in the other groups, considerable value was placed upon having a focal point of heat or cosy ‘glow’, an experience that heat pumps with under floor heating failed to provide. Wood burners or multi-fuel burners (which we will call ‘wood burners’ for simplicity) were very popular; approximately half of our householders (n = 8) had this type of heat source as either part of their primary heating system or, more commonly, as a supplementary form of heating. Remaining households had an open fire or an electric heater with a flame effect. These devices provided ‘visible’ heat to the householders and added to the multiplicity of technologies and fuels used.

A third key finding is that our households indicate considerable variability - only two of the 17 households shared the same combination of primary space and water heating technologies (Table 2: P1 & P2, *Primary* group). In our sample of rural, off-gas grid households therefore, we found little indication of a ‘normal’ configuration of heating technologies and sources.

3.2 Explaining adoption of LCTTs

Participants with LCTTs acknowledged that their previous ‘conventional’ heating system performed adequately; however, ageing heating systems, a new build or renovations, and the increasing price of oil were reported to be triggers for investigating alternative options. The most commonly mentioned reasons for considering LCTTs, as opposed to choosing an alternative conventional system, were reducing fuel costs, an interest in technology, and an aim of being environmentally "friendly". Environmentalism did not, however, appear to be a principal motivating factor; it was unlikely to be sufficient on its own to incentivise a householder to adopt LCTTs.

Participants' responses concerning their choice of technology can be categorised into physical/spatial, financial, technical, and social factors (Table 4), and often multiple reasons were cited. This explanation from Scott and Rose, who had changed from electric night storage heaters to a GSHP, traverses a typical array of reasons for investing:

> *Scott: We were spending about £3000 a year on electricity but we do cook with it um but the night store heaters were grossly inefficient. … And we didn't want to go down the oil route because obviously it was never going to get any cheaper, it was only going to get more expensive, and electricity will get more expensive but not at the same rate as oil I don't think.*
> *Rose: The banks are not paying very much in the way of interest at the moment so -*
> *Scott: We had the funds available -*
> *Interviewer: So you might as well invest in something that will give you a better return.*
> *Rose: That's going to save us money in the future.*
> *Scott: Yes and certainly we've always been interested in low carbon technology … And we've been to the shows and things and we were interested in making this place as efficient as possible - mostly because it's more comfortable you know for our own benefit but it also helps [environmentally] as well you know.* (P1-Primary)

The characteristics of the land and the house were most commonly reported to affect the technology chosen. Seven out of the eight households who had recently invested in an LCTT reported that the physical environment had constrained or affected their choice in some way. Smaller landholdings generally eliminated the option of GSHPs and BBs, and some LCTTs were considered to be more suited to houses which were new builds or having renovation work undertaken. Internal space also influenced participants' decisions. Solar thermal, for example, requires a large hot water tank which may mean the loss of space elsewhere:

> *Gay: There's a huge [hot water] tank. I was aghast. I lost a lot of the airing cupboard*. (P3-Partial)

In other cases, LCTTs provided an aesthetic or practical advantage indoors:

> *Rose: And they love it [under floor heating], the Listed [Buildings] people love it because it gets the radiators off the walls.* (P1-Primary)

The financial cost of a particular technology or the cost of the work that needed to be carried out to accommodate a system affected the choice for some households. The cost of some systems, such as GSHPs, could be reduced if the householder had some do-it-yourself expertise, and could undertake some of the preparatory or installation work themselves. The idea of 'free' fuel was a drawcard for some; for example, both our biomass boiler households had their own woodland, which made pellet systems less attractive (although it was acknowledged there were still costs involved such as electricity to power a chainsaw to cut the 'free' timber).

Technical factors concerning adoption relate to the characteristics of the technology and its operation, although these factors were often of less consequence than the characteristics of the property in determining the available options for a particular household.

Table 4. Factors reported to underlie adoption of LCTTs

Reason for selection	Example of participant comment	Reported by which participants
	Physical/Spatial	
Properties of land/buildings	Under floor heating is great for cob because it doesn't get the house too hot and it doesn't get the walls hot. (P1) … but um when the representative came he said "Oh we couldn't get our machinery between your neighbour's fence and the house to do the work" [to install a GSHP] … So he said "What I'd recommend for you is the air source heat pump". (P17)	1, 2, 3, 5, 6, 15, 17
	Financial	
Cost of technology and/or ability to reduce cost	… that [loft insulation] would all have to come out so it would have been a hell of a lot more of a job and no doubt more expensive [to install solar panels than a heat pump]. (P15) … so we did all that ourselves [digging the trenches for the GSHP] with our own labour and that obviously cut the cost (P2)	2, 3, 5, 15
Availability of 'free' energy	It's quite nice to know you're getting free hot water isn't it when the sun's shining brightly and er like today it will be pumping up the hot water. (P3) We went away from that [pellet boiler] because we had our own wood. (P5)	3, 5, 6
	Technical	
Efficiency of technology	We found out during the you know our investigations that they [heat pumps] don't really work on an old poorly insulated property. You need a small, *extremely* well insulated house. (P5)	1, 5
Security of fuel supply	There's also the factor that wood pellets are manufactured and as such you're at the mercy of whatever they want to put the price at. (P5)	5, 6
Characteristics of system	We actually have got ours [heat pump] in the house but it is in a sound proof box. (P1)	1, 3
	Social	
Networking to gain knowledge	… not just a couple of nights on the computer but talking to people you know, going to events and really getting your head around it and working out you know how the system actually works. (P2)	1, 2
Confidence in supplier	[I contacted the supplier because of] an advertisement. Then he came round and talked what I thought was a lot of sense. (P4)	2, 4

In terms of social factors, researching LCTTs online was a common way of gathering information about technologies and suppliers, as was going to exhibitions relating to building and heating products, and, if possible, talking to people who had a similar system installed. Establishing a rapport with and having confidence in the supplier was important in ensuring potential plans were acted upon. Advice from the installer could encourage a potential customer to change the planned type of technology.

> *Phil: He [the supplier] said 'You've only got a small garden there and it [a GSHP] would make an awful mess of it.' So he said 'What I'd recommend for you is the air source heat pump'. So we said 'Righto, fair enough, we'll go for that', so that's what decided us on that.* (P17-Primary)

It is notable that five out of the six households moving from conventional to low carbon space heating had previously had an oil fuelled system (Table 5). The cost of oil was a common factor in the desire to change and two of our participants noted the potential shortage of oil in the future, suggesting that the discourse of 'peak oil', prevalent in media reporting, may have had an influence on householder decision-making.

> *Keith: I think I was aware that the price of oil would ... oil would one day run out and that if you invest a lot of money in oil boilers and stuff then you'd have to replace the lot another day.* (P2-Primary)

Table 5. Tracing change in heating configurations

	Change in fuel		*Change in technology*	
ID/ Grp	**Original primary heating fuel/source**	**LCTT fuel/source**	**Replacement**	**Integration**
1[(1)]	Electricity	LC Electricity	✓	
2[(1)]	Oil fired boiler (previous home)	LC Electricity	n/a	
5[(1) S]	Oil fired boiler	Wood, solar thermal		✓
6[(1) S]	Oil fired boiler	Wood		✓
17[(1) S]	Oil fired boiler	LC Electricity	✓	
3[(2) S]	Oil fired boiler	n/a (solar thermal only)		✓
4[(2)]	Oil fired boiler	n/a (solar thermal only)		✓
15[(2)]	Oil fired boiler	LC Electricity		✓
16[(2)]	n/a[a]		n/a	

[(1)] = *Primary* group; [(2)] = *Partial* group. [S] = Solar photovoltaic panels.
[a] P16 had always used wood burners in her current property and had not invested in new LCTTs

Our analyses indicate that the relationship between age and willingness to adopt LCTTs is complex, and that beliefs about age often interacted with financial issues. The majority of our LCTT participants were aged over 60 years, with our oldest participant in his mid-80's when the initial investment in an LCTT was undertaken, suggesting that age is not necessarily a barrier to adoption. Nevertheless, analyses of interviews with the *Conventional* group indicated that age was sometimes cited as a reason for not installing these technologies. Solar PV was not a focus in the current study but it was often used by participants as a proxy for any kind of low carbon technology, presumably because of the high profile it has received due to the Feed in Tariff. Whereas the *Primary* and *Partial* groups seemed less concerned about dipping into their savings to invest in LCTTs, or whether they would recoup the cost of the technology, for the *Conventional* group the payback period detracted from any perceived advantages. In addition, this group were cautious about spending resources when they did not know what might lie ahead, suggesting that their financial means may have been lower than the other two groups:

> *Susan: Even if I had the money I wouldn't have solar panels … ecologically I don't give a stuff and at seventy-four I'd never pay them off by saving my electricity. For me it's more economical not to have them.* (P10-Conventional)
>
> *Bella: I'm just really wary of spending too much money in case I need it because that much is quite a significant amount [to invest in LCTTs]. If I need a new hip and I can't get it done on the NHS for example - and I've got a dodgy hip - I could use that money.* (P14-Conventional)

Avoiding unnecessary physical challenges and complexities in life were also mentioned as a reason not to invest in LCTTs:

> *Joan: I don't think it would have occurred to me to investigate a heat pump. I mean I'm getting to the time of life I want to simplify.* (P9-Conventional)

3.3 Evolving heating systems: replacement or integration

All but one of our participants ("Jeff and Clare", who we discuss later) were satisfied with their investment in low carbon heating technologies and considered that they were having a positive effect on their fuel costs. However, we wanted to ascertain whether the installation of LCTTs replaced existing technologies or whether these were integrated into existing heating systems. Table 5 shows that only two of our participant households fully replaced conventional forms of heating with LCTTs, while five integrated LCTTs into existing systems. Two of the latter households had installed solar thermal which is almost always added into systems rather than completely replacing technologies. The remaining three households, however, chose to add LCTTs to current systems, partly to provide a back-up in case of technical failure or human failure to keep the LCTT system going but also, in one case, to achieve what was considered to be the most economic way of managing the space and water heating system. In Figure 1, we profile three exemplar households from our sample, selected to show diversity of evolving technologies and contexts.

The three *Primary* households with heat pumps as their primary thermal comfort technology tended to have fewer different technologies as they relied solely on the heat pump to deliver their main space and water heating across all seasons. Scott and Rose (P1) originally had night storage heaters for space heating, boosted by two wood burners, and an immersion heater for water heating (Figure 1a). They replaced the night storage heaters with a borehole GSHP which provided both space heating (via under floor heating downstairs and radiators upstairs) and water heating. While the heat pump provided the thermal comfort our participants required, it did not provide a physical 'fireplace'. As a result, the wood burners were retained for supplementary heating and to provide a hearth-like experience:

> *Rose: But I mean I can see that we will run the wood burning stove really because they're nice to sit round, it's nice to sit round a fire.* (P1-Primary)

A thermal comfort focal point also played an important role as a hub for social interaction. A number of our participants did acknowledge, however, that because they were often used at the same time as the LCTT was running, overheating could occur:

> *Keith: … because in the lounge as a feature we put in a wood burner … but it doesn't take a lot to warm the place till it's too hot and you've got to try to gasp for breath like you know it gets so hot.*
> *Interviewer: So would you do that [use the wood burner] even if you were here on your own for example?*
> *Keith: No, it's when we're all sitting around together and you think well perhaps on a Saturday night or Sunday night or something when everybody's in we might decide to put the wood burner on in there, yeah.* (P2-Primary)

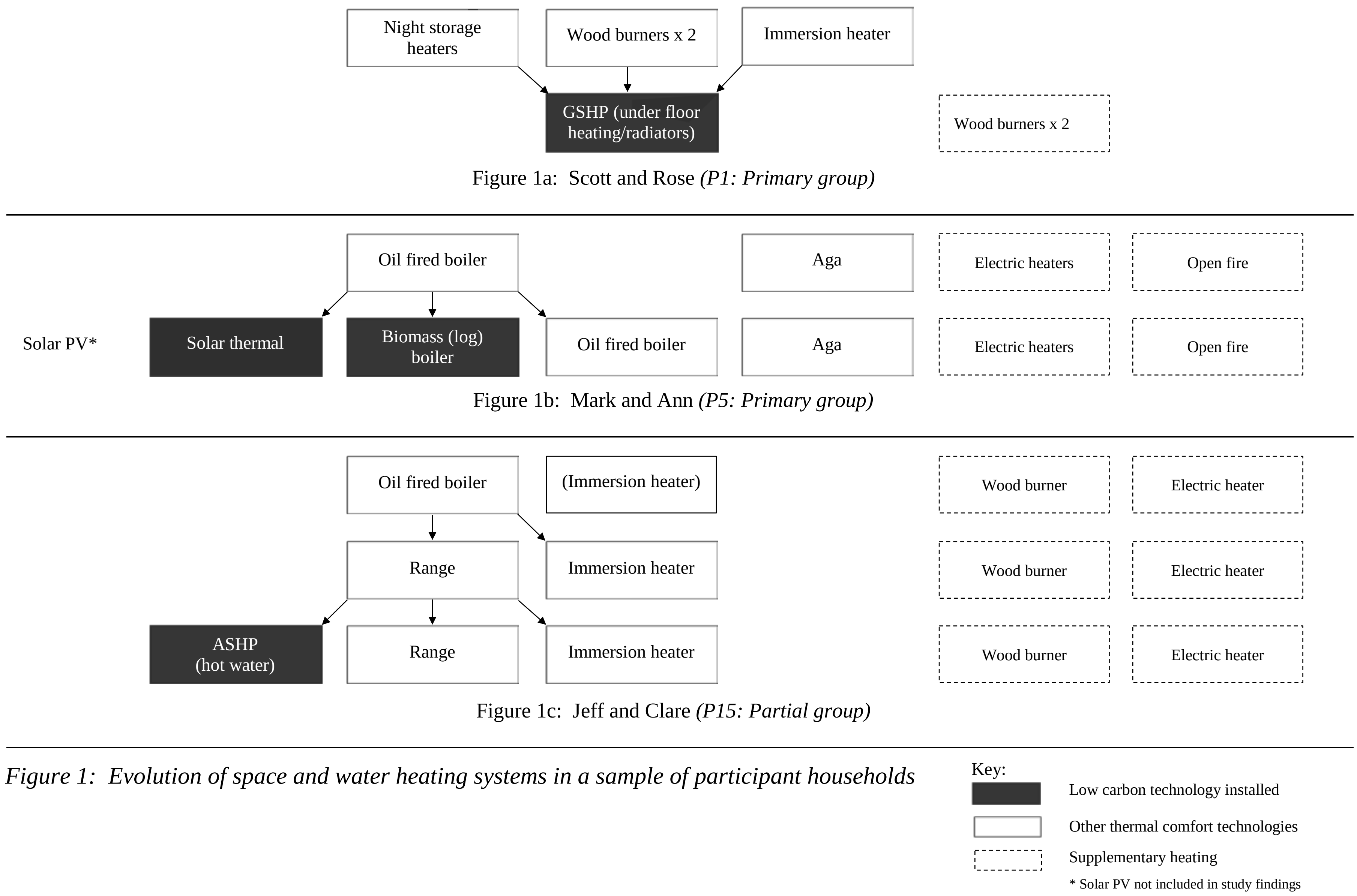

Figure 1: Evolution of space and water heating systems in a sample of participant households

In contrast to our heat pump participants, our two BB households – Mark and Ann (P5) and Dave and Stella (P6) - added to their technologies rather than replacing one with another because both retained their old oil boilers after installing their new biomass boiler, and Mark and Ann also installed solar thermal. Figure 1b shows how Mark and Ann's original system of an oil fired boiler for space and water heating, together with a wood fuelled Aga for background heat in the kitchen, evolved into a BB and solar thermal system in addition to the oil fired boiler and Aga. The addition of the new technology provided a sense of security if the wood boiler was not lit on a particular day:

> *Mark: If for some reason I don't fire the wood burning boiler when it needs to be fired there's an automatic system whereby if the temperature at the top of the thermal store drops below forty-five degrees centigrade it will fire up the oil fired system automatically.*
> *Interviewer: And what would be the circumstances that would make you not fire it?*
> *Mark: If I wasn't here, if I was ill or ... you know... I would normally fire it every day.* (P5-Primary)

Both before and after installation of the LCTTs, the heating system also included occasional use of electric heaters in otherwise unheated rooms and an open fire was sometimes lit in an infrequently used sitting room for added cosiness and a social hub when visitors came.

Of the *Partial* group, two households had solar thermal as their sole LCTT and, as these systems, even under optimal conditions, produce only 60% of an average household's annual hot water consumption (EST, 2011), they still relied on their present boiler for the balance. Consequently the solar thermal technology was added to rather than replacing existing devices. The installation of an ASHP by another household in this group provided an interesting example of how newer technologies become integrated into pre-existing systems and fashioned to meet householders' thermal comfort requirements. Jeff and Clare's system (Figure 1c) originally consisted of an oil fired boiler but a desire to have a range saw the replacement of the boiler with an anthracite-fuelled Rayburn. This provided space and water heating in winter, and an immersion heater (which had not previously been needed with the boiler) delivered hot water in summer. Finding the immersion heater to be an expensive option, the householders sought a cheaper alternative leading to the installation of an air source heat pump in the loft to provide hot water during the summer months. The wood burner was retained to provide the ambience and visual effect of comfort that was prized by all our participants.

Undertaking repeat interviews enabled us to ascertain changes to system use over the course of different seasons. For LCTT households with recently installed systems, there was some tweaking to ensure that the correct temperature was set for thermal comfort for all occupants; but for Jeff and Clare (P15), an economic issue was at the heart of efforts to run their system effectively. They had been advised by the heat pump installer to run the loft air source heat pump (to provide hot water only) at night, using a cheap rate of electricity. However, as the heat pump took much longer to heat water than the immersion heater, Jeff tried to gain the maximum from the integration of these low carbon and conventional heating systems:

> *Jeff: … I've got a temperature sensor there down into the airing cupboard where everything's monitored so I keep an eye on the temperature in Spring and Autumn and when it falls below say about 15 degrees in the air temperature in the loft when to my mind it's just not worth putting the heat pump on, I'll bang the immersion heater on.* (P15, first (winter) interview-Partial)

Managing a heating system consisting of multiple technologies was a complex task, challenged by unseasonable weather, sometimes necessitating adjustments for a short time before the weather changed back again. What emerges is a picture of older adults evolving sophisticated heating practices to juggle an idiosyncratic configuration of technologies that had accumulated in their homes over time:

> *Jeff: … and then of course the cold weather came back in so the Rayburn went back on, the heat pump and immersion became redundant again um but then followed a few weeks of real - real juggling … the Rayburn was running at a very minimal level which is not always easy. … so it meant that sometimes the Rayburn wasn't heating the water satisfactorily enough to um to avoid using the immersion, but just sparingly - just have it on for twenty minutes and um obviously with this- this weather here [very warm in early spring] um the loft temperature's gone up. ... I mean like now it'll probably be thirty-ish so the heat pump has been on and functioning.* (P15, second (spring) interview-Partial)

At the summer interview, Jeff was still juggling the use of his ASHP with other devices to achieve what he considered was an effective way of operating the heating system; by this stage he was expressing doubt as to whether the ASHP was really that efficient because of the time lag between switching it on and achieving hot water, when compared to the immersion heater. However, he was the only participant amongst our sample to have reservations about the performance of an LCTT.

4. Discussion

Policy goals to reduce carbon emissions in domestic settings rely upon householders not only adopting these technologies but also using them in a way that maximises their home's low carbon capability. Instead of viewing such outcomes in terms of user behaviour or technical performance, this study argued for the value of a contextualised, socio-technical approach to the adoption and use of LCTTs. With little research having been undertaken into how LCTTs are configured in a residential retrofit context, particularly in rural, off-gas grid areas, this study contributes to two under-researched areas: first, how older people engage with novel low carbon technologies; second, how multiple technologies are used together in the home (Shove, 2003) and how these become integrated into household thermal comfort systems.

The findings from the study indicate that there is no ‘standard’ domestic heating system in rural, off-gas grid households - the majority of households have a blend of several different technologies and fuels. Diverse and multiple heating fuel usage by off-gas consumers has been reported previously (Baker, 2011) but our findings contribute to the literature by demonstrating the fusion of fuels and technologies used in rural households, and providing evidence that, contrary to what one might expect, heating systems often do not become more streamlined and minimalist following the installation of LCTTs. Rather than directly replacing conventional heating technologies and fuel sources, LCTTs are more often integrated into an existing set of technologies, resulting in an accumulation of thermal comfort ‘hardware’, sometimes with unexpected configurations. This then leads to complex ‘software’ (Walker and Cass, 2007) – the juggling practices required to manage diverse and multiple heating systems across the seasons of the year. These findings illustrate how LCTTs become ‘domesticated’ (Aune, 2007), embedded within pre-existing thermal comfort expectations and practices, as well as configurations of technologies and devices.

Technologies such as solar thermal are primarily additions to existing systems because they are unable to provide sufficient low carbon energy to meet demand. However, the ways that some households added LCTTs to their existing arrangements, rather than substituting them when the new system has the technical potential to fulfil all space and water heating requirements, suggests that some LCTTs do not provide all of the features or do not fulfil all of the needs that households desire from their heating system. Research has indicated how thermal comfort is more than just providing an indoor temperature that is satisfactory to the inhabitants; multiple factors contribute to a person's enjoyment of environmental conditions, including physiological, psychological and contextual factors (Cole et al., 2008). Warmth and cosiness are attributes that are considered to be an important part of the ideal home experience (Allan and Crow, 1989). The perception of cosiness and 'hominess' has been found to be enhanced with the use of different types of lighting technologies (Wilhite and Lutzenhiser, 1999; Bille, 2012). Other researchers have found that devices which provide radiant heat or a 'flame effect', are commonly used as supplementary heaters because they provide a localised heat source and there is a perception by householders that a visual sensation of heat adds to an actual feeling of warmth (Petersen, 2008; Day and Hitchings, 2009). A partiality for devices that produce a visible 'glow' was confirmed in our sample, which participants saw as enhancing the experience of thermal comfort over and above what was provided by the installed LCTTs. Ranges are also popular with rural dwellers because they are perceived to provide warmth and character to a kitchen, and they perform more than one function. Such strong attachments to particular thermal comfort features and practices, already provided by conventional heating systems, illustrate how low carbon alternatives must not only replicate satisfactory temperature levels, but also contribute to the cosiness of domestic 'atmospheres' (Bille, 2012) that householders demand.

In addition to providing shelter from the elements, the home also performs a significant social function (Sixsmith, 1986), affording an important setting for people to interact with each other, especially with family members (Werner, 1987; Saunders and Williams, 1988). Devices that provided a focal point for social interactions were considered by our participants to be an important aspect of their heating system. The spatial arrangement of rooms and their contents have traditionally relied on the placement of the hearth, and our householders showed a preference for congregating around a hearth type device when socialising. In Petersen's (2008) study, wood burners were considered by some participants to be a piece of furniture, and even "applied art", features that were not ascribed to LCTTs by our participants. Given that some LCTTs do not have a visible presence for householders within living spaces (e.g. bore-hole ground source heat pumps, under floor heating systems), a desire for 'visible warmth' may be one reason for the multiplicity of heating technologies found in the participating households.

In the context of policy goals to reduce carbon emissions, and particularly initiatives in the UK such as the Green Deal and the Renewable Heat Incentive to encourage adoption of low carbon technologies, multiplicity might be viewed in negative terms as affording the potential for profligate energy use. Our findings show some evidence that over-heating of rooms or spaces could occur when supplementary devices are used. Multiplicity may not be considered a significant problem if wood burners, which are considered to be a renewable energy option, are used as an additional heating source. However, if households that adopt low carbon systems also run them in conjunction with devices operating on fossil fuels, expected carbon emission savings are unlikely to be realised. Our findings highlight the need for policy makers and low carbon technology designers to strongly consider the 'cultural energy services' (Wilhite et al., 1996) that are valued by householders. A narrow focus on the economic and environmental benefits of such systems does not take into account the full range of services home heating systems provide.

A more positive perspective on multiplicity is that, rather than being tied into one way of heating the home or particular spaces, multiple heating devices and a range of heating fuels provide options which promote flexibility and resilience. For rural dwellers, who may be more at risk of power outages than urban residents, having additional heating options may be an important safety net, and particularly so for older people in winter as they are more likely to be at risk of ill-health from cold homes than younger people (Department of Health, 2011).

Having the space to install novel systems or access to 'free fuel', the prospect of reducing fuel costs, and having an interest in the technology were major factors in the adoption of LCTTs, as has also been found in research involving a younger demographic (Caird and Roy, 2010). The volatility of oil prices was a particular concern to some of our participants, as shown by the numbers of households that switched from oil to low carbon systems. However, decisions to invest in LCTTs are rarely made on one factor alone. Environmentalism was not as important to our participants as saving money on fuel costs, as has been found in some studies investigating adoption of energy efficiency measures (e.g. Caird et al., 2007) but not in others (e.g. Caird and Roy, 2010). Exterior and interior factors of a dwelling affect its suitability for certain LCTTs and a greater range of technologies with more flexibility to meet the demands of different dwelling contexts may need to be developed than are currently available.

Our study has certain limitations. The sample comprised a small number of rural households. Whilst we recognise this as a limitation, we suggest that if the research had been conducted with a larger sample, it is likely that the multiplicity and diversity of heating technologies and fuels found would be increased rather than reduced. An increased sample size would most likely further demonstrate that domestic heating systems in rural households are complex and that the introduction of LCTTs does not necessarily simplify them. That said, future research with a larger sample would help to identify potential patterns in heating configurations across households, building upon the diversity, multiplicity and variability shown in this study. It could also help to further understanding of the ways in which age is perceived to be a barrier towards the adoption of LCTTs, currently an issue with somewhat contradictory findings.

The findings may also be limited by a self-selection bias, given that some participants were recruited through groups interested in environmental issues. However, environmentalism was not reported to be a major factor in the investment decision. Although the financial outlay was a deterrent to investing in microgeneration for some of our *Conventional* group, our *Primary* and *Partial* groups had enthusiastically embraced the opportunity to invest in LCTTs. The majority of our *Primary* group were at the younger end of the older age spectrum but our research shows that even people in their 80's may invest in LCTTs, contradicting the consensus that older people may not be amenable to adopting new low carbon technologies (e.g. Sopha et al., 2010; Willis et al., 2011; Owens et al., 2013). Those older people who are still leading an active life may feel less pressure to preserve resources than those who are starting to feel the effects of age and have concerns about having sufficient financial resources to meet their future healthcare needs.

The findings from our research suggest the value of going beyond the adoption stage to investigate how LCTTs become 'domesticated' within pre-existing assemblages of thermal comfort technologies, fuels and practices (Aune, 2007). Older people's efforts at keeping warm are influenced by past experiences as well as their attitudes and values (Tod et al., 2012); younger people may have weaker ties and demonstrate less attachment to conventional systems and the services they are perceived to deliver. In a study investigating user satisfaction with heat pumps (Caird et al., 2012), it was found that supplementary heaters, from choice rather than need, were sometimes used in cold weather but it is not clear how common this was within each of the retrofit and new build groups. Our findings indicate that even in new build homes, the introduction of supplementary heating devices may occur (although we only had one such installation in our sample). Follow-up research focussing on potential design modifications to space heating LCTTs to meet consumer requirements for 'cultural energy services' (Wilhite et al., 1996) such as cosiness and sociability is therefore warranted.

Effective strategies to encourage people to assume low carbon, sustainable lifestyles requires policy-makers to comprehensively understand how novel energy technologies become embedded within existing thermal systems and practices. Scenario modelling has been used to estimate potential emission savings from the widespread uptake of a range of low carbon energy sources (DECC, 2013) but the predictions of these models are based on certain assumptions being made. Taking a rational approach to home heating, system designers/engineers may use models which assume that investment in one technology will result in the neat replacement of another, rather than the evolution of diverse, multiple and variable systems. The low importance given to environmentalism in our sample provides a setting in which households may combine different energy sources without concern that one may be ideologically incompatible with another. Policy makers need to take into account that householders may persist with conventional heating devices because they offer other kinds of valued services that may not be provided by LCTTs and therefore the expected carbon emission savings may not be realised.

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