Homeowner low-carbon retrofits: implications for future UK policy

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Abstract:

The promotion of low-carbon home retrofit among UK homeowners is widely recognised as an important strategy to reduce operational energy use in dwellings and mitigate climate change. The related predominant UK policy approach is to address various market failures and develop the market for low-carbon retrofit and innovation. The current low uptake rate of low-carbon home retrofit suggests that a complementary policy approach is necessary to increase it and support households in their change towards low-carbon living. This paper uses an innovation framework to analyse retrofit as an innovation-decision process of several stages. Low-carbon technology is conceptualised at three nested levels: product, design option and technological system. A multiple-case study approach is used to analyse eight home retrofit cases from the SuperHomes network, that achieved significant carbon emission reductions through retrofit activities. Case analysis shows that:
(i) homeowners collect information for each technology level through different communication channels, which are not interchangeable; (ii) homeowners develop a certain capacity to transform their environmental concerns into substantial retrofit activities; (iii) the positive retrofit experience of homeowners is crucial to develop such capacity and to convince others to retrofit their homes. These findings have important implications for energy policy on retrofit uptake in UK to support household transition to low-carbon living.

Keywords: home retrofit, low-carbon, decision process, innovation, socio-technical, system

Highlights:

- 3 levels of low-carbon technology: product, design option, technological system
- Homeowners collect information about low-carbon technology from different sources
- Homeowners develop a capacity to carry out significant retrofit works
- The capacity manifests in retrofit knowledge and pride of project results
- The positive retrofit experience of homeowners is crucial to develop such capacity

1. INTRODUCTION

The UK government considers the promotion of low-carbon home retrofit to UK homeowners as an important strategy to reduce operational energy use in dwellings, meet national targets for carbon emission reductions and mitigate climate change (*The Climate Change Act 2008 (2050 Target Amendment) Order 2019*, 2019; UK. BEIS, 2017a). Low-carbon retrofit in the owner-occupied housing sector is an important part of the effort to address the climate change challenge, as the domestic building sector, 70% of which is owner occupied (UK. MHCLG, 2019), accounts for just under a third of total energy use in the UK (UK. BEIS, 2019). Estimates show that one quarter to one half of energy use in dwellings could be cost-effectively saved by 2035 (Rosenow et al., 2018).

A range of policies has been implemented in the UK in an attempt to reduce operational energy use in owner-occupied dwellings and its associated carbon emissions (Abu-Bakar et al., 2013; Dowson et al., 2012). The governmental approach towards energy efficiency policy has historically alternated between the view that market forces on their own can deliver the targeted energy savings in a cost-effective way, and the view that government intervention and support is necessary to achieve the same targets (Mallaburn and Eyre, 2014). The UK clean growth strategy outlines the current policy approach to achieve national targets for carbon reduction (UK. BEIS, 2017b). It is predominately framed in terms of nurturing the market for low-carbon technology, to ensure that the UK is “the best place for innovators and new business to start-up and grow” (UK. BEIS, 2017b, p. 11).

The policy aim is to make the desired retrofit options seem more attractive than market alternatives to homeowners and increase their uptake rate. However, empirical evidence suggests that the rate has dropped sharply since 2013 (UK. BEIS, 2020), a trend commonly attributed to the Green Deal’s failure (Bergman and Foxon, 2020). It was the last governmental scheme that purposefully targeted low-carbon retrofit in the owner-occupied sector, and it was scrapped in 2015 for lack of uptake, only two years after its launch (Rosenow and Eyre, 2016). This suggests that the current policy focus might not be sufficient to support the desired low-carbon home retrofit uptake. Since 2015, the UK government has sought evidence and consultation on how to encourage homeowners to retrofit their homes to low-carbon standards (CCC, 2019; UK. BEIS, 2017a).

The policy for home retrofit framed only in market terms neglects important aspects of the challenge of reducing carbon emissions, particularly from a homeowner investor perspective (Bergman and Foxon, 2020). In particular, it neglects the processes by which homeowners build capacity to carry out low-carbon home retrofit activities. Renovation and refurbishment rates are estimated to be between 2.9% and 5% of existing stock for domestic buildings (Stafford et al., 2011), which is between about 790,000 and 1,365,000 dwellings per year. However, most of these renovations are amenity renovations, and homeowners often do not use them as an opportunity to carry out energy efficiency works (Stieß and Dunkelberg, 2013). There are no centralised records of how many sustainability-related renovations projects are carried out, but there is consensus among both practitioners and academics that the rate of such renovations is stubbornly low (Egger, 2015; Fawcett, 2014; Fawcett and Killip, 2014; Jenkins and Hopkins, 2019), likely “in the order of hundreds” annually (Fawcett, 2014, p. 487).

This paper takes a process perspective (Langley, 1999; Mohr, 1982; Van De Ven, 1992) to investigate the temporal sequence of various influences that operate between stages of household retrofit process, and how they could lead towards, or away from, a realisation of a sustainability-related retrofit solution. It investigates the potential for policy intervention in retrofit to increase the changes that energy-related retrofit activities are carried out when an opportunity is presented. Low-carbon retrofit is conceptualised as an innovation and the chosen theoretical lens integrates: (i) a socio-technical context of a dwelling that determines operational energy use; (ii) three nested levels of low-carbon technology: product, design option, technological system; (iii) the stages of retrofit-decision process.

The innovation lens is applied at eight successful, pioneering cases of low-carbon home retrofit, to analyse the dynamics of the retrofit process that lead this process to a sustained level of low post-retrofit energy use. The in-depth case analysis reveals some policy relevant insights: (i) the importance of information provision at different levels of low-carbon technology at different stages of retrofit-decision process; (ii) the importance of developing homeowner capacity, which helps to transform their sustainability-related intentions into energy-related retrofit activities; (iii) the importance of a positive retrofit experience to build such capacity, as well as to convince others to retrofit their homes.

The rest of the paper is structured as follows. Section 2 provides the theoretical underpinning for the conceptualisation of low-carbon home as an innovation. Section 3 provides the methodology for empirical data collection and the framework for qualitative data analysis. Section 4 describes the study findings. Section 5 discusses the insights drawn from the findings in line with current literature, derives possible implications for policy, considers the limitations of the study, and provides suggestions for future research. Section 6 concludes the paper.

2. THEORETICAL CONCEPTUALISATION

Innovation is a broad concept that is difficult to define, and related innovation typologies tend to be complex and challenging to structure (Crossan and Apaydin, 2010; Kotsemir et al., 2013). A content analysis on definitions of innovation in the literature, identifies six key attributes (Baregheh et al., 2009): (i) nature of innovation (e.g., something new or improved); (ii) type of innovation (e.g., product or service); (iii) stages of innovation; (iv) social context; (v) means of innovation (e.g., technology and financial resources); and (vi) aim of innovation.

Retrofit can be juxtaposed to these attributes as an innovation. A wide array of actors, such as inventors, builders and homeowners use knowledge of building physics to utilise and transform technological ideas into context-specific, low-carbon retrofit solutions that may include a mix of products and services (points i-ii). Low-carbon retrofit is understood as a process with a series of stages (point iii) that take place in a complex socio-technical system (Wilson et al., 2013). Low-carbon retrofit as an innovation involves not only technology and market developments, but also includes the post-retrofit embedding of the low-carbon technology in the web of household domestic practices (point iv), such as cooling or heating (Gram-Hanssen, 2014a; Wilson et al., 2015). Various resources are necessary to complete a retrofit, such as technology, information provision and financial support (point v). The aim of low-carbon retrofit is to achieve and sustain low post-retrofit levels of energy use (point vi). In line with these characteristics, low-carbon retrofit innovation in this paper is understood as:

> *the multi-stage process whereby various actors transform building physics and systems engineering ideas into new or improved building products and their combinations, and embed them in the social context of everyday life to achieve and sustain low levels of operational energy use in a dwelling.*

2.1. Low carbon innovation in a socio-technical system

The technical and social aspects of the built environment must be jointly considered to understand its development patterns (Du Plessis and Cole, 2011; Hassler and Kohler, 2014; Moffatt and Kohler, 2008). The socio-technical systems approach investigates how society and technology influence each other, as different values specific to a particular societal context shape technological change, while technology constantly influences society (Bijker et al., 2012; Hughes, 1983). This approach is used in urban architecture, urban economics and environmental architecture (Rhodes, 2012), in studies of energy demand in the built environment (Jenkins and Hopkins, 2019; Sorrell, 2015), literature on low-carbon retrofit (Gram-Hanssen, 2014b; Karvonen, 2013; Tweed, 2013; Wilson et al., 2015), and to some extent in low-carbon home retrofit policy (BSI, 2020).

In line with socio-technical systems approach, an individual building is understood as a system of interactions that involves biophysical systems, the natural laws that govern them, and the behaviour of building occupants (Du Plessis and Cole, 2011). Operational energy use is understood to arise from homeowner adaptive interactions in this socio-technical system (Cole et al., 2013). This perspective does not attribute low-energy consumption solely to the physical structure of the house and its components, or to the behaviour of its occupants. The focus shifts to various services and practices that energy makes possible, conditioned by one's social context (Wilhite et al., 2000)

It is important to clarify what low-carbon retrofit technology is in relation to a socio-technical system of a house. The innovation diffusion literature focuses predominantly on diffusion of particular products or services. Owen and Mitchell (2015) show that the home retrofit-decision process often starts from an identification of a design option to address a specific design problem before it moves to an identification of a particular product, and therefore it is possible to differentiate between a diffusion of a particular product and a diffusion of a design option. Low-carbon retrofits typically require the installation of a collection of advanced energy savings measures (e.g., fabric insulation or airtightness membrane), energy saving technologies (i.e., AAA-rated appliances), and energy generating technologies (i.e., photovoltaics and solar thermal). However, a simple amalgamation of individual design options, even advanced ones, is unlikely to result in the desired energy use savings (Pickerill, 2016).

Instead, a building should be considered as a system, as optimising the operational energy use of a whole system might be more efficient than optimising its individual components and even yield increasing returns (Lovins, 2004). For instance, a conventional heating system is often completely eliminated in a Passivhaus as a result of its superinsulation and airtightness, and heating is instead supplied via the ventilation system (Passipedia, 2019). A systemic approach to low-carbon retrofit is also needed to avoid unintended consequences often associated with it, such as reduced air flow and a subsequent poor air quality (Shrubsole et al., 2019, 2014). Therefore, the diffusion of low-carbon home technology can be seen and analysed at three nested levels:

(i) A particular *product*, for instance, the Earthwool DriTherm 34 Super — glass mineral wool insulation, manufactured by Knauf Insulation (Knauf Insulation, 2021).

(ii) A *design option*, which is a solution to a particular design problem. For instance, an internal and an external wall insulation represent two design options to solve a problem of heat loss through walls. Either design option may be implemented with different products.

(iii) A *technological system*[1] of various design options, which is more effective to optimise its efficiency as a whole, rather than each design option separately, for instance a house retrofitted to Passivhaus standard.

[1] Note: a technological system of a low-carbon house is embedded in its broader socio-technical context, sometimes referred here as a socio-technical system

2.2. The innovation-decision process in a low-carbon home

The definition of low-carbon retrofit innovation, outlined earlier, is the basis on which to bring together different aspects of retrofit innovation. The focus of this paper is on the processes by which individual households build capacity to carry out significant energy-related retrofit activities. In line with this focus, Rogers' (2003, first published in 1962) innovation diffusion theory is used to conceptualise retrofit as an innovation-decision process. The theory explains how abstract ideas and concepts, technical information or actual practices spread over time through communication channels in a particular social system. The theory asserts that individual agents, through information collection, attempt to reduce the uncertainty inherent in a decision-making process associated with the adoption of a novelty.

Innovation diffusion theory draws on the notion of capacity building (Eade, 1997; Weidner et al., 2002), to explain the process in which actors become gradually able to determine their own priorities, and organise to act on these (Geroski, 2000). In particular, actor priorities coming from a pro-environmental attitude do not necessarily lead to coherent actor behaviour change and action such as low-carbon retrofit activities (Heiskanen et al., 2020; Kersten et al., 2015; Pelenur, 2018). Different strategies are necessary to support the capacity of people for action to transform their concerns into low-carbon retrofit activities (Kersten et al., 2015).

Innovation diffusion theory distinguishes information channels through which an actor becomes aware about something, is persuaded about it and acts on it (Rogers, 2003). For example, interpersonal communication channels of friends or colleagues help actors consider generic information in terms of the conditions they face (Coleman et al., 1955; Rogers, 2003). Such internal influences through world-of-mouth communication were mathematically shown to be crucial to form a critical mass to persuade others and, ultimately, increase the speed with which an innovation is adopted in a system (Bass, 1969; Geroski, 2000; Mahajan and Peterson, 1985).

Communication channels operate through five stages, during which an agent: (i) acquires *knowledge* and becomes aware of a particular novelty, (ii) forms a positive or negative attitude towards this novelty via a *persuasion* process, (iii) takes a *decision* to adopt or reject it, (iv) follows through with its *implementation*, and (v) seeks reinforcement or *confirmation* of the decision already made. Several scholars conceptualise stages specific to retrofit decision process, rather than rely on the generic stages of Rogers. However, in most of these cases the conceptualisation has no empirical basis, and it is done based on researchers' own understanding of the situation and existing literature (Broers et al., 2019; Nair et al., 2010; Pettifor et al., 2015). For this reason, these stages are not considered in this paper.

However, Owen and Mitchell (2015) provide empirical evidence of five stages, at which intermediaries have the potential to influence a household's retrofit decisions. There is an overlap with Rogers' generic stages, and it is clear that the generic *implementation* stage outlined by Rogers can be further subdivided into three phases, specific to retrofit: (a) *option formalisation*, when the household acquires specifications and quotes for particular options, gets planning permission and ensures compliance with regulations; (b) *installation*, when the new technology is installed; (c) *commissioning*, when the new technologies are switched on and tested to ensure they function as expected. As these phases of Owen and Mitchell (2015) are empirically grounded, they are used in the theoretical framework in this paper.

Altogether the theoretical framework of the paper conceptualises a dwelling as a socio-technical system, differentiates three nested levels of low-carbon home technology and five stages of retrofit decisions, with the generic *implementation* stage subdivided into three phases (Figure 1).

LOW-CARBON HOME INNOVATION

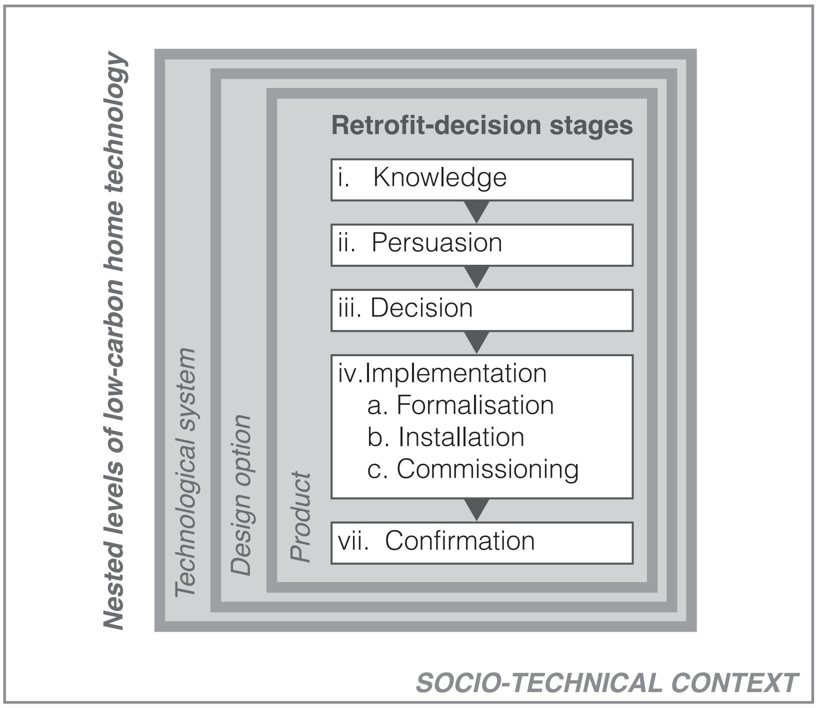

Figure 1. The theoretical framework of low carbon home innovation: (i) a socio-technical context of a dwelling that determines operational energy use; (ii) the nested levels of low-carbon technology: product, design option, technological system (iii) the stages of retrofit-decision process.

3. METHODS AND DATA

This research uses a multiple case-study design with a qualitative approach for data collection and analysis (Yin, 2018). The unit of analysis is the household retrofit journey, and each one is considered a case. The focus on the household is justified, as recent research suggests that household occupants with committed relationship are likely to share their viewpoints towards energy use (Pelenur, 2018). The literature on multiple case-study research suggests a range of 4 to 10 cases to generate enough complexity for theory development, while at the same time keeping the volume of the data manageable (Eisenhardt, 1989; Miles et al., 2014). Purposive sampling strategy was used to select eight cases with potentially rich information to explore theoretical insights into phenomenon of successful domestic retrofit to low-carbon standards (Miles et al., 2014). The cases were selected from the SuperHomes network, a voluntary UK network with about 200 homeowners. Other databases of low-carbon dwellings are available, such as Low Energy Building Database and Passivhaus UK Buildings Database, however the SuperHomes network has a greater representation of owner-occupiers and a greater variety of retrofit experiences.

The network awards a SuperHomes label to houses, that achieve at least 60% carbon reductions as a result of a retrofit (NEF 2015; SuperHomes, 2011). Pre-retrofit emissions are estimated based on a model basis, and post-retrofit emissions are based on either a model or monitored data. A Standard Assessment Procedure (SAP) is currently used as an estimation tool (UK. BEIS, 2014), which substituted the previously used National Home Energy Rating (NHER) (Brownhill and Chapman, 1995). The data, which serve as an input for an energy assessment tool, is collected at one point in time, post-retrofit. In the rest of the paper the phrase 'low-carbon retrofit' refers to retrofit activities that were granted a SuperHomes label.

A SuperHomes representative was approached to establish contact with potential participants. Eight of those showed interest and formed the study sample. An attempt was made to sample more cases the following year, however, the response of the representative was that no more assistance can be provided due to a lack of funding for the network (Project Director SuperHomes, *pers. comm.*, 7th March 2018). The retrofit cases fall in three categories (Figure 2), consistent with those observed by Fawcett and Killip (2014). The first category includes cases A, E, F, and G, where the retrofit was planned from the outset and took place largely at one point in time. Retrofit work in these cases took up to a year to complete. The second category includes cases B, C, and D, where the retrofit was planned at the start, but the works took place as separate pockets of intense activity over a period of time: cases. The works spanned 2–4 years for these cases. The third category includes case H, in which the retrofit was not planned from the beginning, but rather emerged over time and resulted in a low-energy house. The overall retrofit work in this case spanned over three decades.

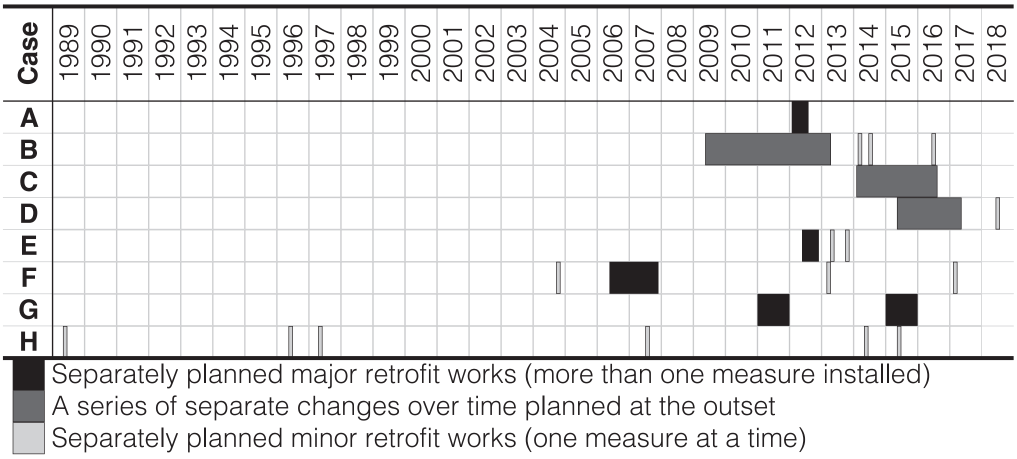

Figure 2. Summary of the purposeful sampling strategy: retrofit timelines

3.1. Case profiles

The selected cases range from Victorian terraced houses, through an early-20th-century terraced and semi-detached houses, to a mid-20th-century detached house (Table 1). The houses are located in London, Hertfordshire and Buckinghamshire, and half of them are in heritage conservation areas. At the time of data collection, the households in the study ranged from a couple to a family of five. Where there were children, they ranged from very young to late teenagers. Two out of eight households had tenants living in their houses. Most adult occupants in the sample were professionally active. In cases A and B, at least one of the owners was a professional architect/ builder; in cases C, D and E, at least one of the owners worked in an area related to sustainable construction; in cases F and G, at least one of the owners had non-construction specific engineering background; both owners in case H had non-technical background.

Table 1. Profile of sample households

Case	House age/ type	Location	Conservation area	Occupants	Professional background
A	Victorian, four-bed, former mews house	London	Yes	Four adult tenants	Professional architect
B	1920, three-bed, mid-terrace	London	Yes	Family of four	Professional builder
C	1930s, three-bed, semi-detached	Buckinghamshire	No	Young couple	Sustainable-construction-related
D	Edwardian, three-bed, mid-terrace	Buckinghamshire	Yes	One adult, one child	Sustainable-construction-related
E	Victorian, five-bed, mid-terrace	London	No	Family of four and an au pair	Sustainable-construction-related
F	1967, five-bed, detached	Hertfordshire	Yes	Family of five	IT-engineer
G	1925, three-bed, semi-detached	London	No	Family of four	IT-engineers
H	1933, three-bed, semi-detached	London	No	Retired couple, one tenant	Non-technical

Low-carbon retrofit projects typically require the installation of a collection of energy-saving measures and appliances, and often require the installation of energy-generation technologies such as photovoltaics (PV). Indeed, a variety of fabric, ventilation, heating and energy generation measures were installed by the homeowners in the sample, which helped them to achieve significant carbon savings (Table 2).

Table 2. Summary of dwelling characteristics post-retrofit and level of measured carbon reductions

Case	Wall Insulation	Air-tightness *	Ventilation	Heating	Energy Generation	Carbon savings measured
A	All internal	Low leakage	MVHR	Condensing boiler	Solar thermal	75%
B	All internal	Intermediate leakage	Natural	ATA heat pump, underfloor heating	Solar PV, battery tank	67%
C	Front internal, back external	Low leakage	PVHR	Condensing boiler	none	70%
D	Original house internal, extension uninsulated	Intermediate leakage	Natural	Condensing boiler, multi-fuel stove	Solar PV, solar thermal	78%
E	Original house internal, extension external	Intermediate leakage	Natural	Condensing boiler	Solar PV, solar thermal	68%
F	Cavity wall	Low leakage	MVHR (heating switched off)	Wood pellet boiler, wood burning stove, underfloor heating	Solar PV, solar thermal	92%
G	External envelope	Low leakage	MVHR	Condensing boiler	Solar PV, solar thermal	80%
H	External envelope	High leakage	Natural	Condensing boiler, wood burning stove, underfloor heating	Solar PV	90%

Note: Floor insulation, loft and/ or ceiling insulation, high performance windows and low-energy lighting were installed in all cases.

MVHR = mechanical ventilation heat recovery; PVHR = passive (stack) ventilation heat recovery; ATA = air to air (heat pump); PV = photovoltaics. *A visual assessment of the airtightness of the properties was done by the first author.

3.2. Post-retrofit interviews of homeowners

The choice of the number of interviews for each case was driven by the emerging conceptual understanding of the phenomenon (Miles et al., 2014). 15 semi-structured interviews were carried out for eight case studies during two rounds of interviews: 8 in spring/ summer 2018 and 7 in summer/ autumn 2019. In case F only the first round of interviews was carried out. The interviews were usually carried out with one of the owners, normally the one who was more involved in the retrofit project. In case H, both owners participated in the interviews. The interviews lasted between 50 and 90 minutes and took place at interviewees' homes. Interviews incorporated a walk-through procedure, which is spatial-visual technique that allows the interviewee to evoke memories about the retrofit experience. Photographs of different aspects of the retrofit were taken, to retain visual information for future analysis. All interviews were digitally recorded and transcribed verbatim for analysis.

In the first round of interviews, information was collected on general household characteristics, dwelling characteristics prior and post retrofit, and the retrofit process itself. The homeowners were asked about the scope of the retrofit work, the sustainability motives and the rationale of their choices, the sequence of events in their decision-processes and possible influences at each stage of the process. The retrofit timeline was documented together with the homeowners. During the second set of interviews, further information was gathered on households' emotional experiences related to their retrofit journeys. At this point, preliminary results on the evidence of retrofit decision stages for each case were shared with the participants for review as part of the member checking strategy (Creswell, 1998). All of the interviewed homeowners agreed with the evidence on retrofit stages presented to them, which deepens trustworthiness of the research results. Their feedback and comments were incorporated in further analysis.

3.3. Analysis

The transcripts, the corresponding photographs and retrofit timelines were sorted into cases and reviewed. Notes and memos taken during the interviews, and those arising from the interview reports were kept for further analysis. The interviews were coded by the first author, the analysis and results were continuously reviewed by all authors to raise further the confidence in data interpretation. First, the data was arranged into a chronological account for each case. This included a description of the household, the state of the house before and after the retrofit, and the order of events for each retrofit case. The description served as a basis for a written report for each case. Second, the theoretical framework was used thematically to identify the diversity of information types and sources at different retrofit-decisions stages for three aspects of low-carbon home technology: a product, a design option and a technological system (Braun and Clarke, 2006). Third, the chronological accounts were used to identify concepts and dynamics relevant to the development of a capacity necessary to transform one's environmental concerns into significant retrofit activities. Through several iterations between the raw data, the summaries and theory, three core themes were generated: (i) processes relevant to a successful capacity development; (ii) manifestations of a successful capacity development; (iii) implications of a successful capacity development. The analysis incorporated matrices as an analytical display tool to structure the cross-case comparison and further direct the analysis (Miles et al., 2014). The full coding scheme can be found in Appendix A. The matrices together with associated reports, notes and memos provided a systematic way to display the information and go through the iterative process of qualitative analysis and building a theoretical explanation from case studies.

4. RESULTS

4.1. Information types and sources at different retrofit-decision stages: evidence of diffusion as a persuasion process

The interview analysis confirmed the existence of stages in retrofit-decision processes described in section 2.2. The owners received information from different sources and channels at different stages of the decision process (Table 3). An extended, more detailed list of information sources at different retrofit-decision stages for three aspects of low-carbon home technology for each case can be found in Appendix B.

It took a long time for the owners in the case studies to go from becoming aware of retrofit options to installing them. For instance, the owners in case H completed their low-carbon retrofit in six independent retrofit steps, which took about 25 years. For some steps the owners were able to recall quite precisely how long it took them to form an idea, develop and implement it. For example, the external wall insulation took three years, the loft conversion and insulation took two years, and the solar PV took five years. In each of these steps, the actual construction works ranged from a couple of days to a couple of weeks. Both mass media and interpersonal communication channels were important sources of information for all homeowners in the case studies at the **knowledge** and **persuasion** stages. Nevertheless, there was an evident difference between the process of gathering information at an early stage and the process of persuasion at a later one. For instance, the owners in case H report:

> We read papers. We read the Times, we read the Observer. They all have sections on homes. We read what people have done and if we think we can do it, then we seek out an expert.

The owners in the case studies sought quotes and specifications for various products, design options, or combinations thereof. They subsequently made their **decisions** on whether to proceed with these options after an evaluation of their benefits and drawbacks. The three phases of the **implementation** stage, outlined by Owen and Mitchell (2015), are also evident in the case studies. All the owners in the sample had to obtain planning permission at least for part of the works, and some owners (e.g., case E) also engaged in a formal tendering process, which is indicative of the option *formalisation* phase. Homeowners gathered further information when it was required at the time of *installation* of measures and technologies, e.g., in cases C and D the owners used specialised magazines and YouTube videos to learn the tricks of the trade; in cases A, G and F the owners relied on the construction team as a source of information; in case E the owner hired a sustainability consultant to transfer practical knowledge regarding low-carbon retrofit to the builder, who had no previous experience in low-carbon construction. The *commissioning* phase was visible in cases A and G, where a pressure test was carried out to receive the level 4 of the Code for Sustainable Homes, and the Passivhaus label respectively.

At the **confirmation** stage the homeowners in the sample joined the SuperHomes network to share their experience with other people who may consider a home retrofit to low-carbon standards. Some owners did it also to acquire the information on the amount of carbon reductions they achieved and validate the decisions they made. For instance, the owner in case F was "blown away" to find out that they had achieved 92% of carbon reductions.

Table 3 Information sources at different retrofit-decision stages per level of low-carbon home technology

<table>
<tr><th rowspan="2">Retrofit-Decision Stages</th><th colspan="3">Level of low-carbon home technology</th></tr>
<tr><th>Product</th><th>Design option</th><th>Technological system</th></tr>
<tr><td rowspan="3">i. Knowledge</td><td colspan="3">Internet, specialist sources</td></tr>
<tr><td></td><td colspan="2">Personal experience, Open home events</td></tr>
<tr><td></td><td>Non-specialist sources</td><td>Norms</td></tr>
<tr><td rowspan="2">ii. Persuasion</td><td colspan="3">Specialist sources</td></tr>
<tr><td></td><td>Personal experience, non-specialist sources, Internet, sales team, trusted specialist sources, governmental regulations and incentives</td><td></td></tr>
<tr><td rowspan="4">iii. Decision</td><td colspan="3">Specialist sources</td></tr>
<tr><td colspan="2">Personal experience</td><td>Building structure</td></tr>
<tr><td>Internet</td><td colspan="2">Sales team</td></tr>
<tr><td></td><td>Building team</td><td></td></tr>
<tr><td rowspan="5">iv-a. Formalisation (implementation)</td><td colspan="3">Governmental regulations and incentives, specialist sources</td></tr>
<tr><td colspan="2">Internet</td><td></td></tr>
<tr><td></td><td colspan="2">Building team</td></tr>
<tr><td colspan="2">Sales team</td><td></td></tr>
<tr><td></td><td>Building structure, non-specialist sources</td><td></td></tr>
<tr><td rowspan="3">iv-b. Installation (implementation)</td><td colspan="2">Building team</td><td></td></tr>
<tr><td></td><td colspan="2">Internet, specialist sources</td></tr>
<tr><td></td><td>Building structure</td><td></td></tr>
<tr><td>iv-c. Commissioning (implementation)</td><td></td><td>Building team</td><td>Airtightness test</td></tr>
<tr><td>v. Confirmation</td><td colspan="3">Personal experience, non-specialist sources, Open home events, specialist sources, data monitoring</td></tr>
</table>

Note: Highlights same information sources for different aspects of low-carbon home technology

'Specialist sources' describe information sources on low-carbon technology that provide general, expert information. 'Building team' — sources that provide expert context-specific information (e.g. building surveyor, builder). 'Sales team' — sources that provide expert product-specific information. 'Non-specialist sources' provide information in a form of local situation (e.g. family, friends). 'Open home events' include events organised by the SuperHomes network. Examples of 'governmental regulations and incentives' are planning control and the Green Deal scheme. 'Building structure' refers to information afforded by the structure of the building, sometimes discovered through the retrofit. 'Norms' describe formative social and cultural environment for a household. 'Personal experience' describes previous household living and retrofit experiences. 'Data monitoring' includes monitoring energy use and energy generation.

The interview data analysis reveals two categories of information sources and two categories of information provided: (i) expert vs non-expert sources, (ii) general vs context-specific information (Table 3 and Table 4). During the *knowledge* and *persuasion* stages the owners gathered information from specialist sources that provide general expert information on low-carbon retrofit, such as specialised conferences (case G), trade fairs (cases B, F, H), lecturers (case B) and literature (case A). At the same time, the owners gathered information from non-specialist sources that had the capacity to consider such general information in light of the local situation, such as neighbours (case H) and SuperHomes Open home events (cases C, E, F, G). During the *decision* and *formalisation* stages all the owners in the sample got quotes and specifications for various options from sales people, who were able to provide product specific information. At this stage some of the owners paid for an expert to receive tailored advice and specific information, such as an advice from an environmental consultant (case A) or a building surveyor (case E). During the *implementation* phase, the construction team was the main source of expert context-specific information (case A, B, G, F, H).

The analysis reveals that expert and non-expert sources are both necessary and cannot be substituted by one another (Table 4). Expert knowledge is essential to make an informed decision regarding a complex technical system for a low-carbon dwelling. Non-expert knowledge is also essential to consider the newly obtained general information in the context of the local conditions that homeowners face at the early stages of the retrofit-decision process. As the owners in case H highlighted: “it is a big incentive to see that other people are doing it and it worked for them”.

Table 4. Typology of information sources and types of information

		Types of information	
		General	**Context/ product specific**
Information sources	**Expert**	Intermediaries (Passivhaus institute, UK Green Building Council), specialist newsletters and literature, trade fairs, conferences, training courses.	Context specific: building surveyor, environmental consultant, building construction team. Product specific: manufacturer’ return on investment quotes, quotes and specifications for various options.
	Non-expert	Internet, stories in non-specialist newspapers and magazines.	Friends, neighbours, local community, Open home events at low-carbon home networks (e.g., SuperHomes.)

The interview analysis revealed that the owners understood the difference between different aspects of low-carbon technology: a product, a design option and technological system. The interviewees in cases B, C, D and E highlighted that they were aware of the **design options** before starting the retrofit and did not learn anything new about them. However, they took their time to familiarise themselves with new **products** on the market, which were available at the time of retrofit works. The explicit choice of **technological systems** in the case studies include Passivhaus retrofit in case G and a whole house retrofit with passive ventilation strategy in case C, which followed a fabric first approach. The owners with no prior experience in low-carbon construction admitted that "they didn't understand [the] dependencies" (case G) inherent to low-carbon technological systems that are underpinned by building physics. However, without an understanding of such dependencies there is a greater chance to deliver a solution that compromises the building integrity of the thermal envelope or indoor air quality. Subsequently, there is a greater chance of unintended consequences such as thermal bridges and low ventilation rates (Shrubsole et al., 2019). The owners in the case-studies emphasised that they could find very little information about technological combinations and interdependencies that should be taken into account, when carrying out a low-carbon retrofit. The owners could not rely on tradespeople to provide such information either. For instance, the owner in case C reported his futile attempts to discuss his plans of internal insulation behind the radiators with a plumber, who just wanted to "stick radiators on the wall, and then get out of there".

4.2. Developing capacity for low-carbon retrofit

All owners in the study sample achieved a significant reduction in energy use and associated carbon emissions as a result of retrofit activities (Table 2). It is safe to claim that all of them built a certain capacity, which allowed them to transform their environmental concerns into retrofit activities. The manifestation of a successful development of such capacity across all cases is twofold (Figure 3). First, all the interviewees showed a remarkable level of knowledge regarding the complexity of the technological solutions for their low-carbon dwellings and how to operate them, regardless of whether they had a technical background or not. Second, all homeowners in the sample were very satisfied with the results they achieved.

Two processes were identified that contributed to the capacity development (Figure 3): (i) the processes of building confidence that the chosen retrofit solutions are the right ones and that they are installed correctly; (ii) the processes of maintaining the balance between the retrofit experience and the dynamics of everyday life. They are presented in more detail further.

The owners felt more confident in their decisions if they had time to "mature" them (case H). One of "the hardest part of it [retrofit]" was the amount of learning required to make an informed decision, as noted by the owner in case C. This was observed for all cases. The owners in all cases, except of case G, had time flexibility to allow for necessary research and learning on the project. None of the owners had strict deadlines for project completion. Where the nature of the project allowed for incremental retrofit, the owners benefitted from the possibility to pause in-between the projects and make the necessary research for the next steps. The owners in case G decided to retrofit to Passivhaus standard two months before construction works began. They decided to learn themselves as the team they hired had no expertise on Passivhaus construction. The owners were interested to finish the project as soon as possible to avoid having to pay for the extra time of the construction team. One of the owners in case G recalled the difficulty of project planning and logistics under conditions of limited time:

> We were building the house in the day, and we were trying to plan for the next week in the night, so we didn't sleep. We just tried to be ahead a little bit for the works to happen.

Another important aspect of low-carbon retrofit is confidence that the technologies have been installed correctly. The owners, who carried out works as part of do-it-yourself retrofit (cases C, D), reported confidence that the measures are installed correctly, precisely because they did it themselves. Other owners noted the importance to have appropriate knowledge to judge whether a job was done properly. Some owners (cases A, E) felt they had the knowledge necessary to check the work of their builders. In cases F and H the owners relied on the assessment by their building team, whom they trusted.

The owners in the sample gradually built a sense of pride of and satisfaction with the project. As the owner in case G explained that “a different relationship to your house” is formed in the process of retrofit, during which the house becomes “your baby” as you grow to “know every corner” in it. Confidence building regarding the retrofit decisions helped to build such sense of pride and satisfaction. The analysis also revealed that dynamics between the retrofit experience and the flow of the everyday life was also important to shape such feelings.

The interview analysis shows that the satisfaction with retrofit experience and its outcome is also subject to influence by the interaction between the retrofit process and the level of comfort achieved in everyday household life. The owners who lived in their properties during the retrofit works (cases B–D, F–H), reported some negative experiences. The owner in case D, who was in full time employment during the retrofit, emphasised that “life is pretty full on doing it [retrofit] and working”, and recalled her experiences as “living in chaos”. The owner in case G noted “… we lived within building works; we couldn’t leave the house… Going this way, I think it [project] probably would have broken a few marriages”. Where the nature of the project allowed for incremental retrofit, the owners benefitted from taking small breaks to restore. The owner in case B recalls:

> Well, it was really few occasions when it was really bad. We literally just went on holidays, just took a weekend off. Just to not see the building site, … , just to be physically removed a bit… that kept us both going, kept me going, absolutely.

Overall, the dimension of *time* emerges from the analysis as an important factor in the formation of positive retrofit experience and satisfaction with retrofit outcome. Time allowed the owners to gain the necessary knowledge to operate their building in a low-carbon manner, and to gain confidence in individual retrofit solutions. Time availability was also crucial to balance retrofit works and everyday household life, and ensure that the satisfaction with retrofit outcomes is not tinted by the memory of the overwhelmingly difficult retrofit experience.

A successful capacity development has several implications (Figure 3). First and foremost, it helped the owners to translate their environmental concerns into successful retrofit projects. Second, the owners accumulated knowledge necessary to operate successfully their homes in a low-carbon manner. Third, the developed capacity, manifested in a sense of pride with the retrofit outcomes, helped them to accept and adapt to the suboptimal outcomes of their retrofit choices. It should be noted that, with the exception of case A where the homeowner is a professional architect, all of them reported unintended consequences or suboptimal outcomes that were energy or non-energy related. Suboptimal outcomes included slight overheating problem during summer months in case B; low ventilation rate in case C; leaky doors or windows in cases D and E; the adoption of several heating technologies with overlapping functions in case F, which the owners retrospectively found were not necessary to meet households needs; partial lack of daylight accessibility in case G and persistent draughts in case H. Nevertheless, the interviewed homeowners adapted to these issues and thought they were not of major concern. Last, but not least, the owners created a positive word-of-mouth regarding low-carbon retrofit process and its outcomes during SuperHomes Open house events.

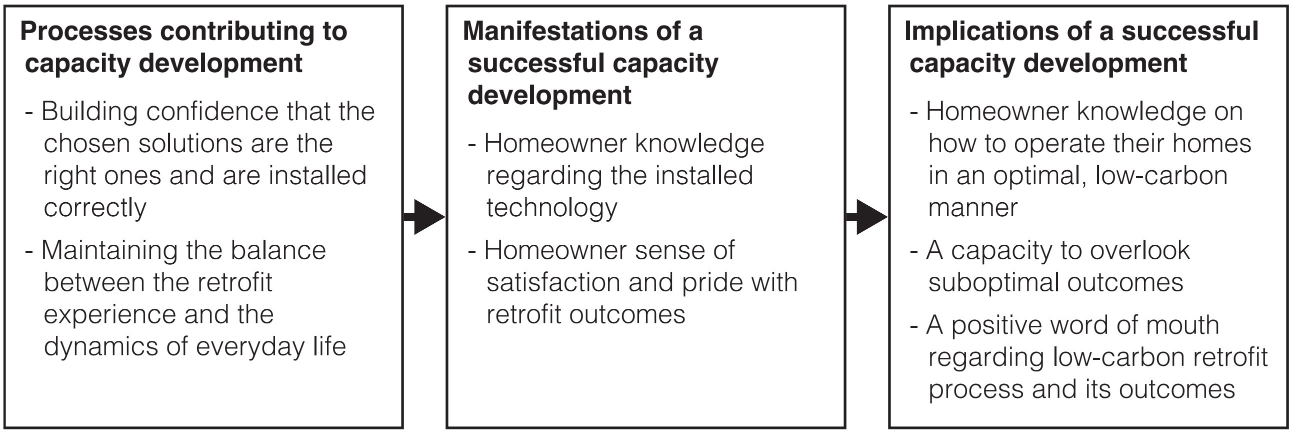

Figure 3. Capacity building for a successful low-carbon retrofit project

5. DISCUSSION

This discussion reflects on the use of the framework for the analysis and the insights it yielded on homeowner retrofit decisions. The analysis revealed that the concepts related to the chosen theoretical framework are evident in the case studies. First, the analysis shows how the owners in the study gained the knowledge and skills necessary to successfully operate the technology in the *socio-technical context* of their dwellings. This result highlights the role of human agency in realising the potential of low-carbon technology (Pickerill, 2016; von Hippel, 2005). Second, the results reveal that information sought by the homeowners could be framed from the perspective of three *levels of low-carbon home technology*: product, design option, and technological system as set in the framework. Third, it appears that all the owners in our study sought information from different sources, at *different stages of retrofit decision process*. The differentiation of information sources per stage indicates the potential utility of framing retrofit as an innovation-decision process with stages based on innovation diffusion theory (Rogers, 2003). The time that has taken these owners from an initial idea about a low-carbon technology to its implementation further suggests that retrofit-decision may be more of a process of persuasion rather than simply a process of knowledge provision.

The analysis generates two groups of insights about low-carbon home retrofit. The first group relates to the information sources used at different retrofit stages and the information types sought by the homeowners. The owners in the sample used expert and non-expert information sources for different and sometime specific purposes. These sources of information were not interchangeable. Expert sources, such as trade fairs and specialist literature, provide necessary generic technical information. Non-expert sources, such as friends and neighbours, help to understand such generic information in relation to the local conditions that homeowners face. Indeed, non-expert interpersonal communication sources are found to be important in ‘open home’ events and can have a positive impact on homeowner retrofit decisions (Berry et al., 2014; Gupta et al., 2014; Mcmichael and Shipworth, 2013). The results also show that the owners lacked an understanding of a house as a technological system, especially at early stages of the retrofit-decision process. This is because the owners in the sample struggled to find the information on technological systems of a low-carbon dwelling. They found that local authorities and building professionals were of little help, as the approach to a house as a technological system is still not widespread in modern construction (Hoicka and Parker, 2018).

The second group of insights relates to the capacity the owners developed during the retrofit decision process that helped them to transform their environmental concerns into actions and carry out significant retrofit works. The results show how important a positive retrofit experience was for these owners to build such capacity. Such capacity manifested in the homeowner knowledge regarding the installed technology, as well as a sense of pride regarding their projects and achieved results. The accumulated knowledge helped the owners operate successfully their low-carbon technology in post retrofit. The developed capacity helped the owners to accept and adapt to retrofit outcomes even if they were suboptimal. Similar results were found in Owen and Mitchell (2015), who report that occupants with positive retrofit experience build “affectionate feelings” (Owen and Mitchell, 2015, p. 931) towards the technology and are willing to overlook some operational problems. In contrast, a negative retrofit experience results in an occupant impression that the technology itself is substandard and does not operate as it should (Owen and Mitchell, 2015). A positive experience of retrofit was also found to be crucial in the creation of a positive word-of-mouth effect about low-carbon retrofit, as the owners in the sample shared enthusiastically their experience with others interested in such retrofit. On the contrary, an overly demanding retrofit experience, even if the homeowners are happy with the retrofit results themselves, might mean they discourage others to do similar works (Mlecnik, 2010). The finding is consistent with innovation diffusion literature, which highlights the importance of negative word-of-mouth on the diffusion of an innovation in a system (Mahajan and Peterson, 1985).

The analysis of low-carbon home retrofit among UK homeowners paves the way for two recommendations on energy policy: (i) support information provision through appropriate non-expert channels at different retrofit stages for different levels of low-carbon home technology: product, design option and socio-technical system; (ii) support homeowners to develop the necessary capacity for a successful retrofit implementation. Such capacity manifests in the homeowner's knowledge of operating installed technology. The resulting sense of satisfaction and pride with their SuperHomes could generate a positive word-of-mouth necessary to persuade others to retrofit their homes to low-carbon standards.

The first recommendation has partially found its way to UK policy. The PAS 2035 document (BSI, 2020) specifies that different information sources should be considered to deliver retrofit-related advice: web forums, open home events and community meetings. However, there is currently no official support for non-commercial information channels and networks, even though they might not be self-sustainable without external support. For instance, the withdrawal of official support for intermediaries in low-carbon retrofits in recent years (Kivimaa and Martiskainen, 2018), led National Energy Foundation to withdraw funding from the SuperHomes network (Project Director SuperHomes, *pers. comm*., 7th March 2018).

The PAS 2035 document also sees a house as a technological system. PAS 2035 requires a building team to propose an integrated retrofit plan to improve energy efficiency and reduce carbon emissions for all retrofit projects, even if only small improvements are carried out in the short term (BSI, 2020). Therefore, PAS 2035 outlines a pathway to provide expert context-specific information for the household at the implementation stage of the retrofit decision-process. However, there is still a need for general expert information on technological systems of low-carbon dwellings at the earlier stages of retrofit. A promising route seems to be for local authorities to proactively deliver such information (Vlasova and Gram-Hanssen, 2014).

The second recommendation relates to the ways to help homeowners build the knowledge necessary to operate the installed technology, ensure a positive retrofit experience by homeowners and their satisfaction with retrofit outcomes. The dimension of *time* emerged from the analysis as an important factor in these dynamics. Time allowed the owners in the study to gain the necessary knowledge to operate their home in a low-carbon manner, and to gain confidence in individual retrofit solutions. Time availability was also crucial to balance retrofit works and everyday household life, and ensure that the satisfaction with retrofit outcomes was not tainted by the memory of the overwhelmingly difficult retrofit experience. Therefore, this paper encourages support of a step-by-step-retrofit approach, for which there seem to be a market preference (Fawcett, 2014; Galvin and Sunikka-Blank, 2017; Killip, 2011) and evidence that most retrofit works are carried in this manner anyways (Huber et al., 2011). Fawcett (2014) reports that an overtime retrofit approach was taken in roughly half of the SuperHomes cases (18 cases), for which it was possible to ascertain timing of retrofit works.

The analysis revealed that, besides time availability, a high level of confidence in retrofit decisions was afforded in cases, where the owners carried out the works themselves (DIY retrofit), which is consistent with prior research (Darley and Beniger, 1981). This points to a potential DIY niche for low-carbon home-retrofit, which would fit in the UK context with its strong tradition of DIY home improvement and supply chains to support it (Fawcett and Killip, 2014). However, the current policy direction does not favour DIY retrofit for safety and quality reasons (BSI, 2020). The interview analysis shows that confidence in retrofit decisions was also facilitated through a high level of trust between the construction team and the owners, which is also consistent with the literature (Fawcett and Killip, 2014; Laan et al., 2011). Further research on construction team-homeowner relation is suggested.

The work described in this paper has a number of limitations. Data collection through post-retrofit interviews, allows the possibility that interviewees make sense of their experiences retrospectively (Kahneman, 2012). A longitudinal data collection in real time can mitigate this issue, however, this may not be feasible, especially when the retrofit is intermittent and takes decades, as in case H. To partially mitigate the recall bias, the interviewees were asked to draw their retrofit timelines, which helped them to remember the sequence of events. A second limitation concerns generalisability of findings. In qualitative research, generalisations are done on the basis of a match to the underlying theory based on conceptual grounds, not on representative grounds to a larger population (Miles et al., 2014). It is possible to make the findings more robust, by showing that a finding that holds in one setting also holds in a comparative setting, but does not hold in a contrasting one. This could be achieved by extending this study to different groups, that have different characteristics from the study participants, e.g., unsuccessful cases of low-carbon retrofit, owners from different socio-demographic and economic backgrounds or with different levels of education, etc. To partly overcome this limitation, the findings were extensively positioned in the broader literature.

Future research can investigate the mechanisms to ensure a positive retrofit experience among homeowners. A related research issue is to investigate the pace of step-by-step retrofit to consider whether a desirable number and order of steps exists in which to install retrofit measures. The steps should be sufficiently small to reduce negative homeowner experience, and sufficiently big to complete the retrofit relatively quickly and thus, facilitate the formation of a critical mass of people that live in such houses. The positive word-of-mouth from this critical mass contribute to accelerating the transition of the housing stock to a low-carbon state. We recognise that any theoretical lens emphasises only a part of reality. Some important aspects of the homeowner retrofit experience were not covered by the constructed framework. A different theoretical lens is necessary to look at the role of motivational priorities in such decisions; the dynamics between energy and non-energy-related retrofit intentions and its influence on retrofit outcomes; or the role of everyday routinised experiences in shaping retrofit decisions, such as in Fyhn and Baron (2017).

6. CONCLUSIONS AND POLICY IMPLICATIONS

UK governmental policy aims to encourage low-carbon home retrofit among UK homeowners and has historically focused on nurturing the market for low-carbon technology. Such a focus can neglect important aspects of the challenge of reducing energy use in the housing sector, such as embedding of the technology in the social context of a household. This paper has taken an innovation approach and investigated retrofit as a process, by which homeowners achieved significant energy and carbon reductions through retrofit. This paper contributes to the innovation literature by drawing attention to: (i) the disaggregation of a unit of analysis for an innovation technology into three nested levels: a particular product, a design option and a technological system; (ii) the importance of a good implementation experience for the formation of a positive homeowner attitude to the retrofit innovation, and a subsequent positive word-of-mouth for the innovation.

The paper documents the diversity of information types and sources used by the homeowners at different stages of retrofit process. It appears that this diversity is necessary to the homeowners in the study as they move through the decision process. The findings also suggest that the owners developed a certain capacity during the retrofit process that helped them to realise their retrofit intentions. Such capacity manifested in the knowledge the owners accumulated about their technologies during the retrofit process, as well as in a sense of pride and satisfaction with their projects. The findings also suggest that the homeowners' positive experience of the retrofit process was paramount to develop such capacity and was also necessary to create a positive word-of-mouth regarding low-carbon retrofit.

The results from the analysis could provide the basis for recommendations on low-carbon retrofit policy in the UK private residential sector. First, a policy to encourage low-carbon retrofit should diversify its effort to target households at different stages of the retrofit process, and support information provision for all aspects of low-carbon retrofit technology: a product, a design option and a technological system. The results suggest that it may be important to support decision process at its early stages, in particular support non-expert networks as sources on information, as well as support information provision regarding technological systems though local authorities. Second, policy should focus on capacity-building among homeowners to enable them to move towards low-carbon living. Time availability is necessary to build such capacity, and therefore a step-by-step retrofit approach may be a way forward to facilitate such capacity-building. Homeowner confidence in their retrofit decisions appear to be paramount to build such capacity. A do-it-yourself retrofit could also help develop confidence in retrofit solutions and outcomes for some homeowners.

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APPENDIX A

Table A illustrates the coding scheme. Retrofit stages correspond to stages in Figure 1.

Table A.1. Coding scheme *(continued}*

Themes and codes	Description	Reference
Retrofit decision stages		
i. Knowledge	The first stage of the retrofit-decision process, at which a which a household becomes aware of one or another low-carbon retrofit technology.	Rogers (2003)
ii. Persuasion	The second stage of the retrofit-decision process, at which the household forms positive or negative attitude towards the technology via a persuasion process.	Rogers (2003)
iii. Decision	The third stage of the retrofit-decision process, at which the household decides whether to adapt of to reject the technology.	Rogers (2003)
iv. Implementation	The third stage of the retrofit-decision process, at which the household follows through with the implementation of the technology. This stage is further subdivided into three phases: (a) formalisation, (b) installation, (c) commissioning. See below for further details.	Rogers (2003); Owen and Mitchell (2015)
a. Formalisation	The first phase of the implementation stage of the retrofit-decision process, at which the household acquires specifications and quotes for particular options, gets planning permission and ensures compliance with regulations.	Owen and Mitchell (2015)
b. Installation	The second phase of the implementation stage of the retrofit-decision process, at which the technology is installed.	Owen and Mitchell (2015)
c. Commissioning	The third phase of the implementation stage of the retrofit-decision process, at which the new technologies are switched on and tested to ensure they function as expected.	Owen and Mitchell (2015)
v. Confirmation	The final stage of the retrofit-decision process, at which the household reflects on the experience and communicates messages about his/ her experience to others, thus influencing their decisions through persuasion.	Rogers (2003)
Aspects of low-carbon technology		
Product	A particular item, which can be used in low-carbon retrofit, is mass produced and commercially marketed. For instance, Earthwool DriTherm 34 Super — glass mineral wool insulation, manufactured by Knauf Insulation.	Oxford English Dictionary (2020a); Knauf Insulation (2021)
Design option	A collection of possible solutions for a particular design problem. For instance, an internal and an external wall insulation represent two design options to solve a problem of heat loss through walls. A design option can be realised with different products.	Design option feature in Revit Autodesk (2017)
Technological system	A combination of various design options forming a connected complex whole. The manifestation of the integra-	Oxford English Dictionary (2020b);

Table A.1. Coding scheme *(continued}*

Themes and codes	Description	Reference
	tion into a complex whole is twofold. First, a technological system is more efficient to optimise as a whole, rather than optimising efficiency of each design option separately. For instance, a conventional heating system is often completely eliminated in a Passivhaus as a result of its superinsulation and airtightness, and heating is instead supplied via the ventilation system. Second, a technological system is optimised to eliminate unintended consequences that could result from the installation of individual options. For instance, high levels of insulation and airtightness not only reduce heat loss through fabric, but also reduce air penetration in the building. Therefore, an appropriate ventilation strategy should be considered to compensate for an increased airtightness and ensure good air quality.	Lovins (2004); Passipedia (2019); Shrubsole et al. (2014); Shrubsole et al. (2019)
Capacity development (CD) for low-carbon retrofit		
Capacity for low-carbon retrofit	A household ability to transform their pro-environmental concerns into low-carbon retrofit activities. Capacity development denotes a process in which actors become gradually able to determine their own priorities, and organise to act on these.	Eade (1997); Geroski (2000); Kersten et al. (2015); Weidner et al. (2002).
Processes of CD	Processes that contribute to the capacity development. Capacity development is a process and several mechanisms can contribute to the process.	Derived inductively from the data
Manifestations of CD	Visible expressions of developed capacity. Capacity is an intangible phenomenon and cannot be directly observed. Therefore, manifestations serve as a proxy to indicate that sufficient capacity is developed.	Derived inductively from the data
Implications of CD	Effect of capacity development. The most obvious effect is the ability to transform one's pro-environmental concerns into low-carbon retrofit activities. Other effects are also possible.	Derived inductively from the data

APPENDIX B

The table presented in this appendix shows differentiation of information sources and communication channels at different retrofit-decision stages for three aspects of low-carbon home technology: a product, a design option and a technological system, for each case in the sample.

Table B.1. Information sources at different retrofit-decision stages for 3 aspects of low-carbon home technology

Retrofit- decision stages	Aspects of a low-carbon home technology		
	Product	**Design option**	**Technological system**
Stage i. Knowledge	Internet (B,C,F)	Internet (F)	Internet (H)
	Passivhaus organisation (G)	Passivhaus organisation (G)	Passivhaus organisation (G)
	Sp. newsletters (H)	Sp. newsletters (H)	Social and cultural norms (H)
	Sp. trade fairs (B,F,H)	Sp. trade fairs (B,F,H)	Common sense (D)
	UK Green Building Council (A)	Non-sp. literature (H)	Nurturing environment during formative years (F,H)
		Previous living experience (H)	Previous living experience (F,G)
		Sp. conference (G)	Sp. conference (G)
		Sp. lectures (B)	Sp. lectures (B)
		Sp. literature (A)	Sp. literature (A)
		Sp. training course (A,G)	Sp. training course (A,G)
		SuperHomes and other networks (C,E,F,G)	SuperHomes and other networks (E,G)
		Work (B,C,D,E)	Work (A,C,E)
Stage ii. Persuasion	Sp. trade fairs (F)	Sp. trade fairs (F)	Passivhaus org. (G)
	Work (B)	Work (B,C,D,E)	Work (A,C,E)
		Building regulations (A,C,E,F,G,H)	
		Governmental incentive schemes (F,H)	
		Internet (H)	
		Friends/ neighbours (H)	
		Manufacturers' return on investment quotes (C,F)	
		Previous living/ retrofit experience (B,D,F,H)	
		Salespeople (A)	
		Trusted experts (H)	

Table B.1. Information sources at different retrofit-decision stages for 3 aspects of low-carbon home technology

Retrofit- decision stages	Aspects of a low-carbon home technology		
	Product	**Design option**	**Technological system**
Stage iii. Decision	Passivhaus organisation (G)	Passivhaus organisation (G)	Passivhaus organisation (G)
	Previous living experience (B)	Previous living experience (B,F)	Existing building structure (E)
	Internet (F)	Quotes and specifications for various options (A,B,C,D,E,F,G,H)	Quotes and specifications for combining or phasing out various options (A,B,C,D,E,F)
		Environmental consultant (A)	
		Construction team/ builder (E)	
Stage iv-a. *Formalisation* **(implementation)**	Building regulations (F)	Building and building systems' regulations (D,F)	Building control and planning permission (A,B,C,D,E,F,G)
	Internet (C)	Internet (H)	Sp. training course (G)
	Quotes for particular products (C,D)	Construction team/ builder (F)	Construction team/ builder (F)
	Passivhaus organisation. (G)	Building surveyor (E)	
		Discoveries through retrofit (D,E,F)	
		Friends/ neighbours / local community (D,H)	
		Governmental incentive schemes (C,D,H)	
		Reputation ratings (C,F)	
		Tender process (E)	
		Work (D)	
Stage iv-b. *Installation* **(implementation)**	Contractors (D)	Construction team/ builder (A,B,G,F)	
		Internet including YouTube videos (C,D)	Internet including YouTube videos (C,D)
		Sp. literature (C.)	Sp. literature (C.)
		Retrofit itself (G)	
		Sustainability consultant (E)	
		Work (A)	
Stage iv-c. *Commissioning* **(implementation)**		Construction team/ builder (F,H)	Airtightness test (A,G)
		Household existing knowledge or lack thereof (A,B,C,D,E,G,H)	

Table B.1. Information sources at different retrofit-decision stages for 3 aspects of low-carbon home technology

Retrofit- decision stages	**Aspects of a low-carbon home technology** **Product**	**Design option**	**Technological system**
Stage vii. Confirmation	Living experience (E)	Living experience (E,G)	Living experience (G)
	Meter on energy generation (D)	Meter on energy generation (D)	Monitoring data (G)
	Neighbours / local community (B)	Neighbours / local community (B,H)	Neighbours / local community (B)
	Open House London (B)	Open House London (A,B)	Open House London (A,B)
	Sp. lectures (B)	Sp. lectures (B)	Sp. lectures (B)
	SuperHomes network (B,C,E)	SuperHomes network (A,B,C,D,E,F,G,H)	SuperHomes network (A,B,C,D,F,G)
			Annual energy use and energy generation figures (B)
			Architectural portfolio (A,G)

Note: [shaded box] Highlights same information channels for different aspects of low-carbon home technology

Sp. stands for 'specialised'; Specific cases are given in brackets.