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Exploring time and cost optimization in energy retrofit programmes of traditionally constructed, owner-occupied UK dwellings

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ABSTRACT
Despite a step change in the social-rented sector in recent years, retrofitting homes in the owner-occupied sector is still slow and expensive. This applies particularly to the case of solid wall (and unfillable cavity wall) homes where staple energy efficiency measures cannot be applied easily. Drawing on interviews with owner occupiers of traditionally constructed dwellings who have completed or are in the process of retrofit projects, this paper explores the role of time and cost within one-off energy retrofit programmes. It is observed that a mix of one-go and long-term projects of varying depths are being completed. Projects completed in one go appear most likely to achieve a deep retrofit required for meeting emissions reduction targets, yet the associated costs remain significant and beyond affordability for most households. Opportunities for time and cost savings are identified in the combination of renovation and retrofit works and the use of government subsidies, however, the correct sequencing of these measures is essential to avoid the occurrence of shallow retrofits or investment lock-ins.

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Housing; retrofit; refurbishment; energy; time; cost

Introduction

Meeting the UK's legal commitment to net-zero emissions by 2050 requires significant decarbonization efforts, particularly in high-emitting sectors such as energy supply, transport, and buildings. Residential emissions remain consistently high and still make up the majority of emissions from the building sector (see Figure 1). This is largely due to 88% of homes being heated by gas boilers and the UK having the oldest and leakiest housing stock in Western Europe (Department for Levelling Up Housing & Communities, 2023, p. 14). Reducing residential energy demand has been identified as a key challenge in achieving net-zero in the built environment. There are currently close to 29 million homes in the UK, and it has been estimated between 70 and 80% of inhabited homes in 2050 have already been built (Boardman, 2007; Power, 2008; Ravetz, 2008). This figure shows reducing the energy demand from the domestic sector will primarily come from improvements to the existing building stock.

To date, most progress in the retrofit of the UK's domestic building stock has been within social rented housing (Wade & Visscher, 2021, p. 802), with this sector now containing the most properties above an Energy Performance Certificate [EPC] rating of C (DLUHC, 2023, p. 4). This progress can in part be explained by: the age profile of socially rented properties allowing for wider use of cavity wall insulation; social landlords owning property portfolios of similar or identical types that can benefit from repeat measures; and a history of strong regulation and legislation aimed directly at this sector (Webb et al., 2020, p. 12), with the most recent wave of projects facilitated by the Social Housing Decarbonisation Fund (Department for Business Energy & Industrial Strategy, 2022).

Decarbonizing the owner-occupied and private-rented sectors will require a more concerted effort. Currently, the responsibility for energy demand reduction in these sectors falls on the owner or landlord and is expensive. Research by Fuerst et al. (2015) found a positive correlation between energy efficiency measures and the subsequent improvement of EPC rating against house price value, however, a return on investment is unlikely while retrofit costs remain high. In the private-rented sector, the split incentive from most tenants to pay their own energy bills has also hindered progress. Findings by Adan and Fuerst (2015) show that while rental properties are in high demand (as is currently the case across the UK (Peachey, 2023)), landlords are not incentivized to improve thermal efficiency (beyond

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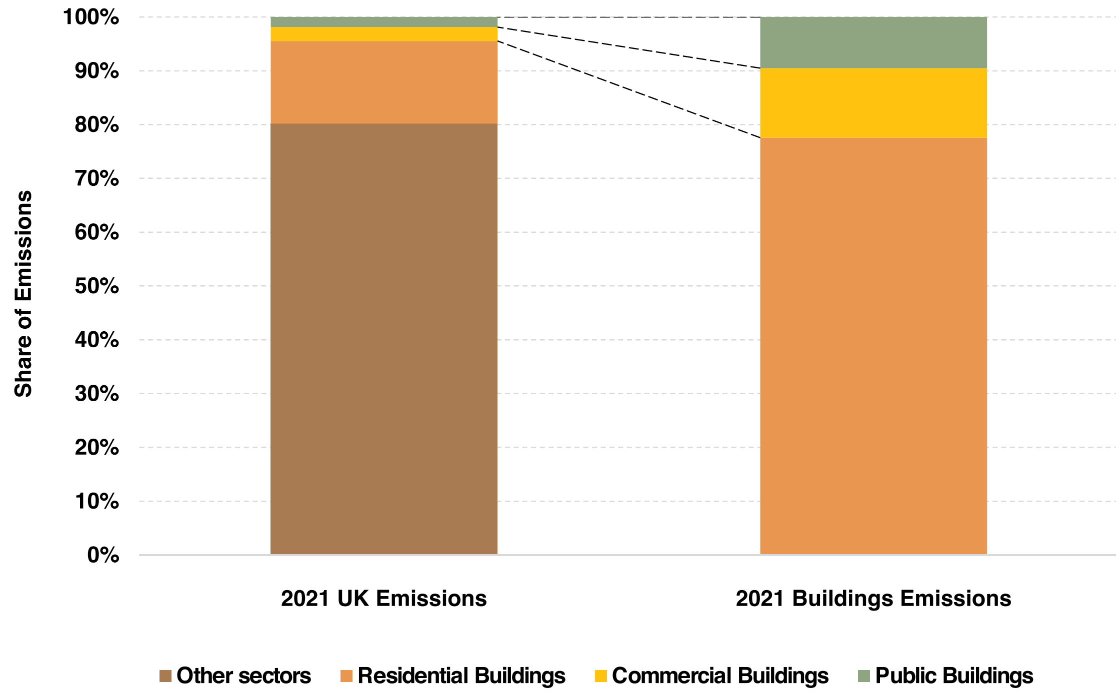


Figure 1 . UK building emissions share of overall emissions by sub-sector (data source: Climate Change Committee, 2022).

the minimum EPC rating of E required to let a property in the UK).

Historically, several government schemes have provided or subsidized the installation of ad-hoc retrofit measures in the private sector (see Table 1). These schemes have targeted easier measures such as loft and cavity wall insulation, however, they have aimed primarily at low-income households in an attempt to address fuel poverty (Ofgem, 2023). More recently, a small portion of government funding has targeted homes deemed 'hard to treat'. The effectiveness of this scheme, funded through the Energy Company Obligation [ECO] since 2013 can be questioned, with only 9% of eligible solid wall properties receiving external wall insulation (Department for Energy Security & Net Zero, 2023, p. 1). For a direct comparison, the percentage of eligible properties that have received cavity wall and loft insulation is 72% and 66%, respectively (Seifhashemi & Elkadi, 2022, p. 4).

For homes with cavity walls, an elemental approach can lead to notable savings. However, the law of diminishing returns applies strongly in retrofit projects beyond energy demand savings of around 30%. For homes starting from a low baseline, the first measures will always appear to be cost-effective as achieving these early savings is more straight forward (Bennadji et al., 2022, pp. 14–55).

Policies focused on one-off measures in the private sector to date have proven unsuitable for reaching the required demand reduction needed to meet net-zero emissions. The government's latest round of ECO funding (ECO4) now claims to take a whole-house approach to home upgrade measures yet does not provide a comprehensive retrofit package (DESNZ, 2023). As Morgan et al. explain,

> unless there is a fundamental change in how the issue is framed, the presumption is that households in the main will be paying for retrofitting and will be expected to come to decisions on an individual basis, which, in turn invites a focus on individual affordability. (2023, p. 9)

Affordability remains a significant barrier to progress in reducing emissions from buildings (Climate Change Committee, 2023, p. 158). This is particularly the case when trying to achieve the high carbon savings necessary for net-zero emissions in the domestic sector. Jones et al.'s (2013, p. 546) seminal study identified two types of 'fabric first' retrofit based on CO_2 reduction targets – shallow (10–30%) and deep (60–80%). They found that after emissions savings of 30–40%, costs begin to rise steeply and major costs begin to take effect beyond 60%. Johnston et al. (2005, p. 1657) posit that 'reductions greater than about 80% will be technically demanding' and this is furthered by Stafford et al. (2011) who suggest it may be technically possible to achieve a thermal performance close to zero-carbon new build homes, however in some cases this could approach a similar cost to demolition and rebuilding. If we are to get close to net-zero emissions, most properties will need to be removing somewhere between 60

Table 1. UK government mandated and funded schemes to improve energy efficiency of private sector housing (author's own).

Scheme	Country	Scheme summary	Target households	Funded measures	Years active	Used by
Energy Company Obligation (ECO)	England Wales Scotland Northern Ireland	Places obligation on medium and large energy suppliers to promote measures that improve the ability of low income / fuel poor homes in Great Britain to heat their home	Low Income Fuel Poor Exact eligibility has varied from ECO1 – ECO4	Insulation Electric Heaters Boiler Repair/ Replacement Heating Controls Solar PV Draught Proofing Windows & Doors	2013 –	–
ECO + / Great British Insulation Scheme	England Wales Scotland	Funded by levy on energy bills as per ECO but wider target households	Low Income EPC D-G and Council Tax A-D (England) A-E (Scotland,Wales)	Insulation Heating Controls	2023 –	–
Warm Front	England	A tax-payer funded scheme designed to help vulnerable households benefit from energy efficiency improvements	Vulnerable households including those in fuel poverty	Loft Insulation Draught Proofing Cavity Wall Insulation Boiler Replacements	2000–2013	–
Green Deal	England Scotland Wales	Loans to make energy efficiency improvements with repayments attached to the electricity bill at a property	Any household with an electricity meter	Energy efficiency measures Low-carbon heat Renewables	2013–2015	Interview D
Green Homes Grant / Local Authority Delivery (LAD)	England	Provided grants to households and local auhorities to subsidise installation of energy efficiency improvements	All households (max. voucher £5000) Low-income households (max. voucher £10,000)	Insulation Low-carbon heat Draught Proofing Windows & Doors Heating Controls	2020–2021	Interview J
Home Upgrade Grants (HUG)	England	Funding for local authorities to improve energy efficiency of off gas grid homes in England	Low income, off-gas grid and EPC D-G	Energy efficiency and low-carbon heat measures	2023 –	–
Sustainable Warmth	England	Combination of HUG and LAD funding given to local authorities	LAD funded low-income homes heated by mains gas; HUG funded low-income households off-gas grid	Energy efficiency and low-carbon heat measures	2022–2023	–
Boiler Upgrade Scheme (BUS)	England Wales	Upfront grants to support installation of heat pumps and biomass boilers in homes & non-domestic buildings	Property owners replacing fossil fuel heating systems (oil, gas, electric or liquified petroleum gas)	Air Source Heat Pump Ground Source Heat Pump Biomass Boiler	2022 –	–
Warmer Homes Scotland	Scotland	Provides funding for home energy efficiency measures to households who are in or at risk of fuel poverty	Homeowners or private rental tenants who meet the 'household' and 'home' criteria	Insulation Draught Proofing Gas Boiler Replacement Air Source Heat Pump Renewables	2015–	–
Home Energy Scotland Grant and Loan	Scotland	Provides homeowners a grant, interest free loan or a combination of both to install clean heating and energy efficiency measures	Homeowners in Scotland (must live in property and be primary residence)	Energy efficiency and low-carbon heat measures	2022 –	–
Warm Home Nest Scheme	Wales	Free, impartial energy efficiency advice and a package of free home energy efficiency improvements (if eligible)	Low income and those living in deprived communities across Wales	Insulation Air Soure Heat Pump Solar PV	2022 –	–
Northern Ireland Sustainable Energy Programme	N. Ireland	Funds energy efficiency measures on vulnerable households funded through a public service obligation on NI electricity customers	96% of the funding is spent on 'priority' schemes aimed at low income and vulnerable households	Energy efficiency measures and boiler replacements	2010–	–
Affordable Warmth Scheme	N. Ireland	Grants for measures to address the effects of fuel povery and energy inefficiency in the private housing sector	Low income households	Insulation Heating Windows Solid Wall Measures	2014–	–

and 80% of emissions through building fabric improvements, with the remainder being offset by low-carbon heating technologies powered by non-emitting electricity. This required level of emissions saving will only be possible through a deep retrofit which takes a whole-house approach. Jones et al. identified in 2013 that whole house, deep retrofits are the most expensive to complete and the picture ten years on is still very much the same. In a recent report by Cambridge City Council (2022), the costs for deep retrofits to a level suitable to meet net zero emissions are estimated for five local house types (the estimates are formed from a combination of BEIS data (see Palmer et al., 2017) and information gathered from homeowners of local retrofit case studies). These costs vary from £98,500 for an end-of-century, mass-built house to £171,000 for a large semi-detached home built in the 1950s. Although housing ownership typically sits behind access to cheaper credit, accumulation of assets and the ability to save, these figures are still expected to be beyond affordability for most homeowners.

Individual decisions based entirely on affordability risk the continuation of swathes of shallow retrofits whereby measures installed may prevent a deep retrofit from being achieved at a later date. This is particularly the case for ‘hard to treat’ properties, with most dwellings only able to achieve 10–30% energy savings with shallow measures (Mohammadpourkarbasi et al., 2023). ‘Hard to treat’ homes have been defined as those properties featuring one or more of the following characteristics: solid wall construction; no gas connection; no loft space; or high-rise flats (Building Research Establishment, 2008, pp. 5–6). Solid wall properties make up more than half of ‘hard to treat’ properties and, as of 2020, there are 8.7 million dwellings in England with uninsulated solid walls (including dwellings constructed with cavity walls deemed unsuitable for insulation, e.g. a maximum cavity of 50 mm (DLUHC, 2023, p. 33)). Finding opportunities for retrofitting at scale in these properties will be key to reaching emissions reduction targets. This area has received less attention across literature in recent years, with the focus being on ‘easy win’ projects where disruption to properties and homeowners is limited (Raslan & Ambrose, 2022, p. 675).

This paper focuses on the energy retrofit of homes that are owner-occupied and of traditional construction (solid brick/stone, brick cavity or brick and block cavity walls) as opposed to all dwelling types included within the ‘hard to treat’ category mentioned in previous literature (Bros-Williamson & Reid, 2015; Building Research Establishment, 2008; DG Cities, 2023; Mohammadpourkarbasi et al., 2023). This is because only 2% of owner-occupiers live in purpose-built high-rise accommodation, whereas 89% live in detached, semi-detached, terraced or bungalow properties (DLUHC, 2022) – most of which are of traditional construction (Nicol et al., 2014). Although improving the retrofit turnover in all housing is imperative for an equitable net-zero transition, focusing on the sector covering the highest percentage of properties across the UK seems prudent to support as much future retrofit activity as possible. This is supported by an assumption that, due to most high-rise properties being within the social-rented sector, support for retrofitting the remaining 2% of properties under private ownership may stem from publicly funded initiatives to prevent any gaps within a given building or estate.

The primary component of this paper investigates how owner-occupiers have, or endeavour to, reduce time and costs in one-off energy retrofit projects of traditionally constructed dwellings. Based on a collection of interviews with owner-occupiers (and architects who are supporting the completion of retrofit projects in this sector), timelines for one-go and long-term projects and their associated measures are created. This data is supported by a thematic analysis of interviews to understand in more detail how phenomena relating to cost and time are being negotiated. On the basis of the data collected, six key findings are presented which explore the impact that time and cost negotiations are having on the implementation of energy retrofit projects in the owner-occupied sector.

Anatomy of one-off retrofit programmes in the owner-occupied sector

A decade ago, Fawcett (2014, p. 478) stated that ‘at present very little low carbon retrofit is undertaken in either the social or the private housing markets’. While the social sector has ramped up its efforts over recent years, the same cannot be said for the private sector (Climate Change Committee, 2023, p. 146). A study by the European Commission (2020, p. 2) found ‘deep renovations to reduce energy consumption by at least 60% are carried out in only 0.2% of the building stock per year and in some regions, energy renovation rates are virtually absent’. Data on where retrofits are taking place (and to what level of demand reduction) is scarce in the UK. Karvonen (2013, p. 566) explains ‘general statistics on energy and carbon performance of the UK housing stock are readily available, but detailed data on domestic retrofit activities are scarce due to the fragmented nature of refurbishment activities’. This responds to what Brown (2018, p. 1504) refers to as the ‘atomized market model’, which is the primary model for domestic retrofit delivery. The domestic retrofit market in the UK is strongly intertwined with the general repair, maintenance and improvement (RMI) market which delivers most home extensions and renovation works through an atomized network of sub-contractors. The nature of the market means each retrofit or renovation project is unique; the team of subcontractors formed for one project regularly differs from the next, even if the property characteristics and works installed are identical. The evident inefficiencies in this delivery model make for slow and expensive projects as there is little room for economies of scale to be achieved in labour or materials.

The high costs associated with retrofit to date have meant the delivery of projects in the owner-occupier sector is often driven by affordability. This has typically split projects into two groups – those with the funds to complete all retrofit works at once (sometimes referred to as whole-house, one-off (Fawcett, 2014) or one go (Maia et al., 2021)) and those breaking down the work into smaller projects over a longer period of time (referred to in literature as step-by-step (Maia et al., 2021) or over-time (Fawcett, 2014)).

A handful of studies have explored the anatomy of one-off retrofit projects in the owner-occupied sector (referring here to one house at a time) and how they are formulated in terms of project timeline, costs, and retrofit depth. In a qualitative meta-synthesis of case studies from previous literature, Bobrova et al. (2022) investigated the retrofit timelines of homeowner energy retrofits from a process perspective. Their study includes retrofit case studies from across Europe and Australia and explores the 'temporal dynamics' of drivers and barriers throughout a project. They concluded the depth of a retrofit project 'cannot be attributed solely to homeowner motivations, but can only be explained by the degree of goal alignment among different actors involved in the retrofit, pre-existing homeowners expectations, expertise of the building professionals and the maturity of the market' (2022, p. 10). This study provides a useful understanding of the complexity in one-off project delivery and the interplay of factors effecting the quality of the final outcome, yet their reference to time remains high-level, with projects only broken down into the stages of 'pre-retrofit', 'retrofit' and 'post-retrofit'.

In *Exploring the time dimension of low carbon retrofit: owner-occupied housing* (2014), Fawcett explored two publicly available databases containing retrofit case studies to ascertain project timelines. They separated the collected samples into 'one-off' and 'over-time' categories, noting that higher carbon savings were evident amongst the 'one-off' projects, but believed there was potential in the 'over-time' route to increase the number of retrofits being completed that achieve 60% or more carbon savings. They explained that 'by elongating the time dimension … the profile of disruption and cost to the householders is also spread out over time' (2014, p. 480) and could be attractive to more homeowners. As cost data in this sector is scarce (particularly so in 2014), they add that 'it is not possible to estimate whether and by how much costs of an over-time approach would differ from a one-off low carbon retrofit' (2014, p. 483). Fawcett and Killip (2014) expand on this research into the time dimension of retrofit by surveying and interviewing homeowners from one of the databases previously explored. This provided one of the first detailed understandings of the anatomy of retrofits in the owner-occupied sector. Within this work, they build on Fawcett's 'one-off' and 'over-time' categories and divide the sample into 'planned' and 'emergent' projects, primarily due to the sample containing 'very early adopters' and the 'planned' category containing projects by homeowners who had relevant experience of retrofit through their own work (Fawcett & Killip, 2014, p. 440). In this more detailed study, Fawcett and Killip manage to explore costs in the one-off sector beyond that covered in Fawcett's earlier work. They do however caveat 'the certainty which can be attached to the estimates' due to a lack of record keeping by interviewees, and not being able to distinguish between retrofit and conventional renovation work which has been executed simultaneously (2014, p. 441). Of significance to the research supporting this paper, they conclude further research would be beneficial to 'investigate the complexities of retrofit costs [and] methods for assigning costs' in addition to strategies used by households to deliver lower costs in retrofit (2014, p. 443). A deeper assessment of one-off retrofit projects in the owner-occupied sector, outside of the 'very early adopters' group explored by Fawcett & Killip, appears to be beneficial to this research area. This is particularly important in understanding if any of the successful methods of achieving sufficient carbon emissions savings by this group have assimilated to current retrofit activity.

Examining the role of time and cost in domestic energy retrofit projects of owner-occupied, traditionally constructed dwellings.

An interview-based methodology was developed to examine the timelines of one-off retrofit projects of traditionally constructed dwellings in the owner-occupied sector. A call for interviewees was sent out via two networks (Cambridge Carbon Footprint's Eco Homes Network and the Architects Climate Action Network [ACAN]) requesting to interview any owner-occupiers of traditionally constructed dwellings who had completed or were in the process of a retrofit project. This method has been used to gain a wider understanding of the role time and cost play in the completion of projects and how events within the timeline are considered, negotiated, and reflected upon in relation to these two key factors. Interrogating how these projects are currently being completed in more detail is proposed as a necessity to enable suitable optimization opportunities, both in terms of practical applications and policy recommendations, to be identified.

Previous studies have applied interview-based methodologies to domestic energy efficiency research to gain a greater understanding of retrofit activity and decision making. Sunikka-Blank and Galvin (2016) interviewed homeowners in Cambridge (UK) to identify how aesthetic qualities and heritage values influenced decisions regarding the installation of retrofit measures. Some of the interviewees in this study are members of the same Eco Homes Network in Cambridge as Sunikka-Blank & Galvin's sample. The aim of this research, however, is to reflect a breadth of society and construction methods. It was therefore important to extend the call for interviewees to ACAN who have a UK-wide network to ensure the sample could also include homeowners of traditionally constructed properties outside of Cambridge (for example in Northern England where solid stone wall dwellings are more common).

As previously touched upon, Fawcett and Killip (2014) interviewed 'Superhome' owners (homeowners who have completed retrofit projects to reduce CO_2 emissions by 60% or more and subsequently opened their homes up to the public as case studies). Their paper contributed substantially to understanding the anatomy of one-off retrofit projects, however, the authors recognize that 'Superhome owners could be characterized as very early adopters of low carbon retrofit' and '… are a small and specific group of the population, who have both undertaken low carbon renovation and are prepared to open up their homes to the public' (2014, p. 443). They add 'it would be instructive to repeat this research with a group of owner-occupiers who have done the former, but not the latter, to see whether the findings are the same' (2014, p. 443). Locating suitable interviewees for research into retrofit that are not part of an early adopters network was challenging and some of the samples for this study have at some point opened their home to the public as a case study, however, the majority have not. Although a side to the focus of this study, the motivation for undertaking a retrofit within this sample is also noteworthy. Emissions reduction was not deemed a sole focus, with many interviewees also mentioning the importance of reducing energy bills and creating a more comfortable and healthier living environment.

Method

A combination of structured and semi-structured questions was used to conduct in-depth interviews with owner-occupiers to explore the timeline and details of their retrofit projects, with a particular focus on time and cost. This sample was supplemented by interviews with three architects; two speaking in detail about retrofit projects on behalf of their owner-occupier clients (A, G) and one discussing the pilot project for their retrofit start-up company through which they aim to expedite the retrofit programme of Victorian terraced dwellings (B) (Figure 2).

The aim of this research was to investigate the role of time and cost in one-off retrofit projects for a target population which previous literature has so far not explored in detail. The use of a qualitative methodology not only allows us to understand what is happening in this sample but more importantly how and why this is the case (Crouch & McKenzie, 2006). Qualitative research allows us to 'scrutinise the dynamic qualities of a situation under investigation, rather than its constituents and the proportionate relationship between them' (Crouch & McKenzie, 2006, p. 489).

Acknowledging the difficulty in discussing costs directly in this research area, as highlighted by Fawcett and Killip (2014, p. 444) and within the present climate of high construction costs and inflationary pressures, the interview questions were framed around time as a proxy for cost. Exact figures were not collected as it was identified in an earlier study that most interviewees did not feel comfortable providing this information or they could not easily separate out retrofit costs from other renovation work. It was identified that during discussions relating to the time spent on retrofit projects, interviewees commonly expanded further to discuss expense without added inquiry, particularly where a piece, or series of works, resulted in a significant saving or cost. Furthermore, there is an inherent interplay due to the additional labour cost associated with an increase in programmed time and this approach was therefore used to gain a broader indication of the assignment of costs within projects.

The mixture of question types in the study (see Appendix B) was intentionally structured to allow for data on the property type, specific retrofit measures, and sequencing of a project to be collected in each interview before providing the opportunity for interviewees to expand on the time spent in pre-construction and construction stages. This resulted in interviews that began structured (in order to collect key details) and became less so with the introduction of the remaining semi-structured questions. The exact form of the second half of each interview was dependent on where the

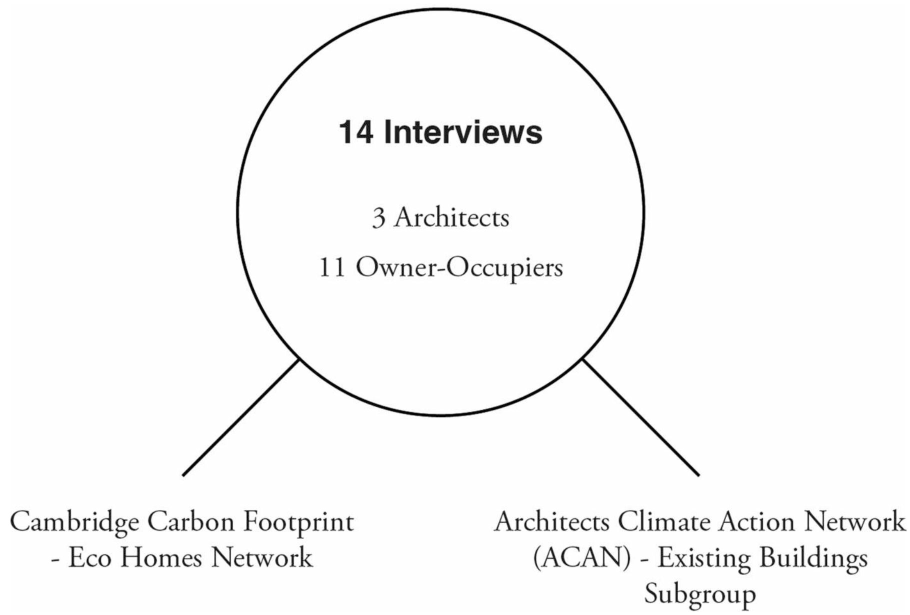


Figure 2. Breakdown of interviewee roles and recruitment locations (author's own).

interviewee was more focused, and this was often influenced by the stage of retrofit they were currently in.

In total, 14 interviews were carried out during the month of July 2023. These were all conducted online, lasting between 30 minutes and 1 hour. All interviewees were provided with a project information sheet (Appendix A) and gave their informed consent for inclusion before they participated in the study. The study was approved by the Research Ethics Committee of the Department of Engineering, University of Cambridge.

Table 2 lists the interview sample and their associated characteristics. All of the data in Table 2 was collected during the interview stage with the exception of the final column which categorizes projects as 'Deep' or 'Shallow' retrofits. This was deciphered during the interview analysis stage as it transpired none of the samples had collected data on their exact emissions savings. The retrofit measures implemented in each project were cross-checked against the measures listed in Table 3 to develop a preliminary understanding of the depth of each project.

Interview analysis

A common interview analysis method in qualitative research is 'grounded theory' which was first developed by Glaser and Strauss (1967). The pair defined the approach as 'the discovery of theory from data systematically obtained from social research'. The approach typically involves the objective analysis of interview transcripts with the assumption that the researcher has no preconceptions regarding their content in order to locate theory 'from the ground up' (Crouch & McKenzie, 2006, p. 489). However, due to the research questions being pre-conceived in this study, in addition to the author's existing knowledge of the research area, a 'realist' method was chosen for interview analysis (Crouch & McKenzie, 2006). In the 'realist' method, 'the researcher approaches the analysis with specific, pre-formed research questions in mind, and examines the data with a view to seeing how these might be addressed or enlightened by the interview data' (Sunikka-Blank & Galvin, 2016, p. 102).

The transcriptions from each interview were imported into qualitative data analysis software (ATLAS.ti) for analysis and coding. Due to the focus on cost and time in this study, a top-down coding approach was utilized to reveal how these themes were addressed within each interview. During interview analysis, further themes of *DIY* and *Retrofit Sequencing* emerged in transcriptions and additional codes were added in response to this (Figure 3 shows the breakdown of codes used across the analysis). The coding of interview transcripts was used to support the creation of one-go and long-term project timelines from the sample (Figures 4 & 5) and develop key findings based on the identification of common themes and characteristics within the retrofit projects.

Results

The key findings from the interviews are summarized in Table 4. These were developed during the thematic coding of the interview transcripts and the creation of timelines showing the timing and sequencing of retrofit measures for the projects completed in one go (Figure 4) and over a long-term programme (Figure 5).

Table 2. Characteristics of interview sample (author's own).

Interview Label	Position / Role	Location	Property Type	Constructed (Year)	Retrofit Stage	One Go / Long Term	Technical Advisory	Shallow / Deep Retrofit
A	Architect	Edinburgh	Detached Bungalow	~1930	Completed	One Go	Architect	Shallow Retrofit
B	Architect / Entrepreneur	Leeds	End Terrace (Prototype)	1979	Construction	One Go	Architect & Retrofit Coordinator	Deep Retrofit
C	Owner-Occupier	Central London	Flat in Converted Terrace House	1895	Design / Construction	Long Term	None	Shallow Retrofit
D	Owner-Occupier	Cambridge	Detached	1962	Mostly Completed	Long Term	Architectural Technician	Deep Retrofit
E	Owner-Occupier	Norwich	Terraced	1880	Design	One Go	Architectural Designer	Deep Retrofit
F	Owner-Occupier	St Ives	Detached Bungalow	1957	50% Completed	Long Term	Architect	Deep Retrofit
G	Architect	Wiltshire	Detached	~1900	Construction	One Go	Architect	Shallow Retrofit
H	Owner-Occupier	Cambridge	Semi-Detached	1945	90% Completed	Long Term	Architect	Deep Retrofit
I	Owner-Occupier	Cambridge	Semi-Detached	~1930	Completed	One Go	None	Shallow Retrofit
J	Owner-Occupier	Cambridge	Semi-Detached	1935	Completed	Long Term	None	Shallow Retrofit
K	Owner-Occupier	North Warwickshire	Detached	1850 / 1970	75% Completed	One Go	Architect & Retrofit Coordinator	Deep Retrofit
L	Owner-Occupier	Derbyshire	Detached	~1830	Completed	One Go	Architect & Retrofit Coordinator	Deep Retrofit
M	Owner-Occupier	Cambridge	End Terrace	~1930	Mostly Completed	Long Term	Architect	Shallow Retrofit
N	Owner-Occupier	Derbyshire	Detached	~1974	Construction	One Go	Architectural Technician	Deep Retrofit

As the interview sample was limited to owner-occupiers of traditionally constructed dwellings who have completed, or are in the process of, a retrofit project, the findings of this study are robust only for this target population. By applying Galvin's (2015) work on the validity of small-sample qualitative research, we can find a reliable indication of the likelihood of findings in this data being present amongst the wider target population. Galvin (2015) conducted a survey of 54 papers that applied interview methodologies within the research area of building energy consumption. In this paper, he presents a statistical approach to estimate the reliability of findings and inferences in small-sample qualitative research produced through semi-structured interviews. By using Galvin's equation, and based on the sample of this study being truly random, his approach indicates there is a 100% probability of a theme that exists in 60–100% of the target population appearing in at least one interview in this study. Moreover, we could be 91.41% confident that a theme found in 20% of the target population being present in at least one of the 11 owner-occupier interviews.

Long-term retrofits require at least one major installation package to achieve a deep retrofit

In this sample, six projects were completed over a longer time period – these are shown in Figure 5. The confirmed and expected timelines across these projects vary from 5 to 12 years in total. It is important to

Table 3. Breakdown of low-cost, shallow and deep retrofit measures as identified within the Cambridge City Council Retrofit Guide (2022) (author's own).

Low-Cost Measures	Shallow Retrofit (incl. Low Cost Measures)	Deep Retrofit (incl. Low Cost & Shallow Measures)
Low-Energy Lighting & Applicances	Top-up Loft Insulation	External Wall Insulation
Basic Draught Proofing (Cracks & Gaps)	Ground Floor Insulation (dependent on solid or suspended floor)	Triple Glazed Doors and Windows
Improved Heating Controls	Internal Wall Insulation	Fastidious Air Tightness Measures
Loft Insulation	Cavity Wall Insulation	MVHR (Mechanical Ventilation Heat Recovery)
Extractor Fans	Eaves Insulation	Air Source Heat Pump
Sealing Floorboards	Insulated Loft Hatch	Solar Photovoltaic Panels
Sealing Holes in Outside Walls	Mechanical Extraction (Kitchen & Bathroom)	Removal of Chimney Thermal Bridge
Chimney Balloons	Demand Control Ventilation	
Pipe Lagging (Insulating)	Secondary Glazing or Double Glazing	

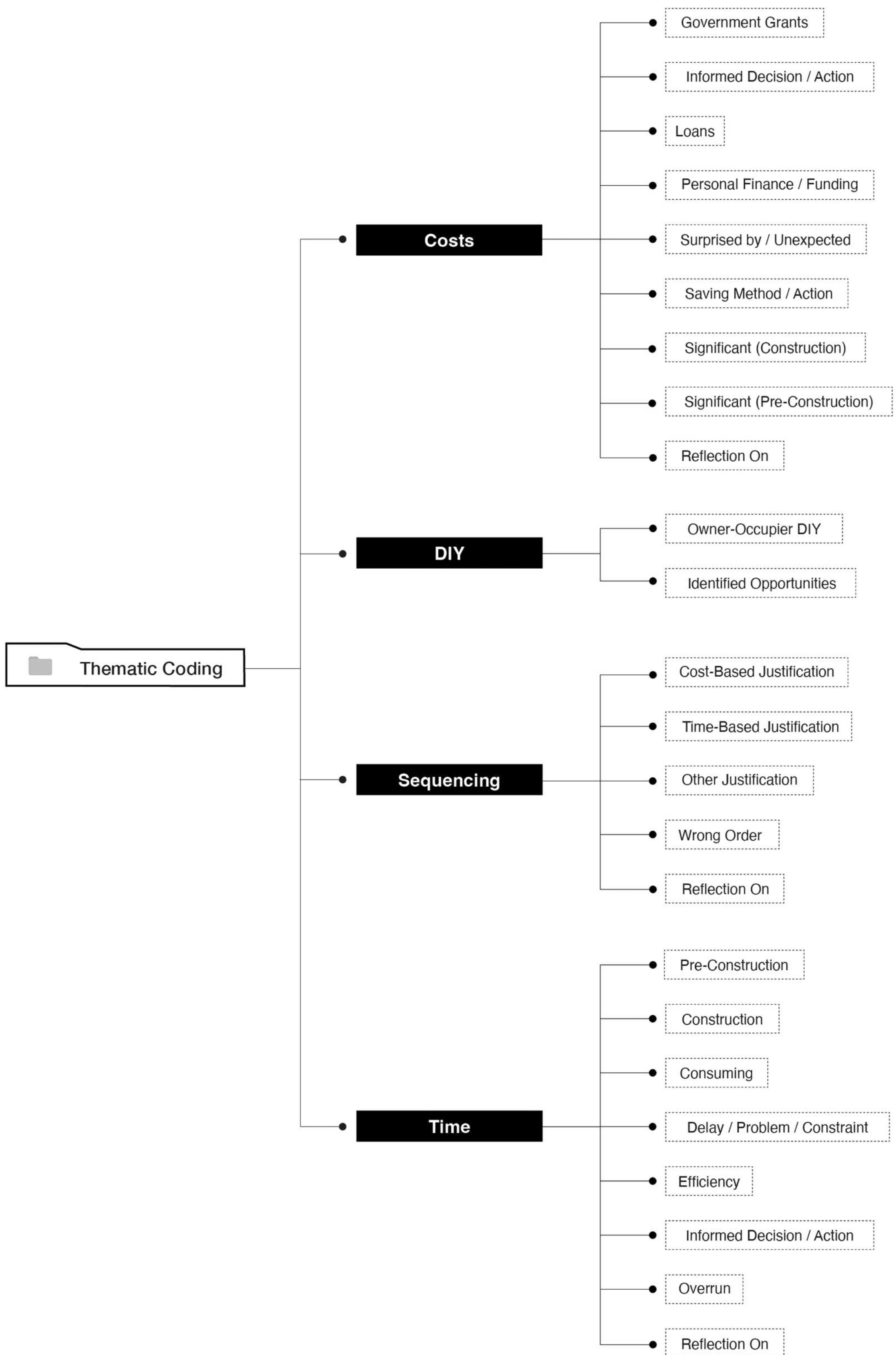
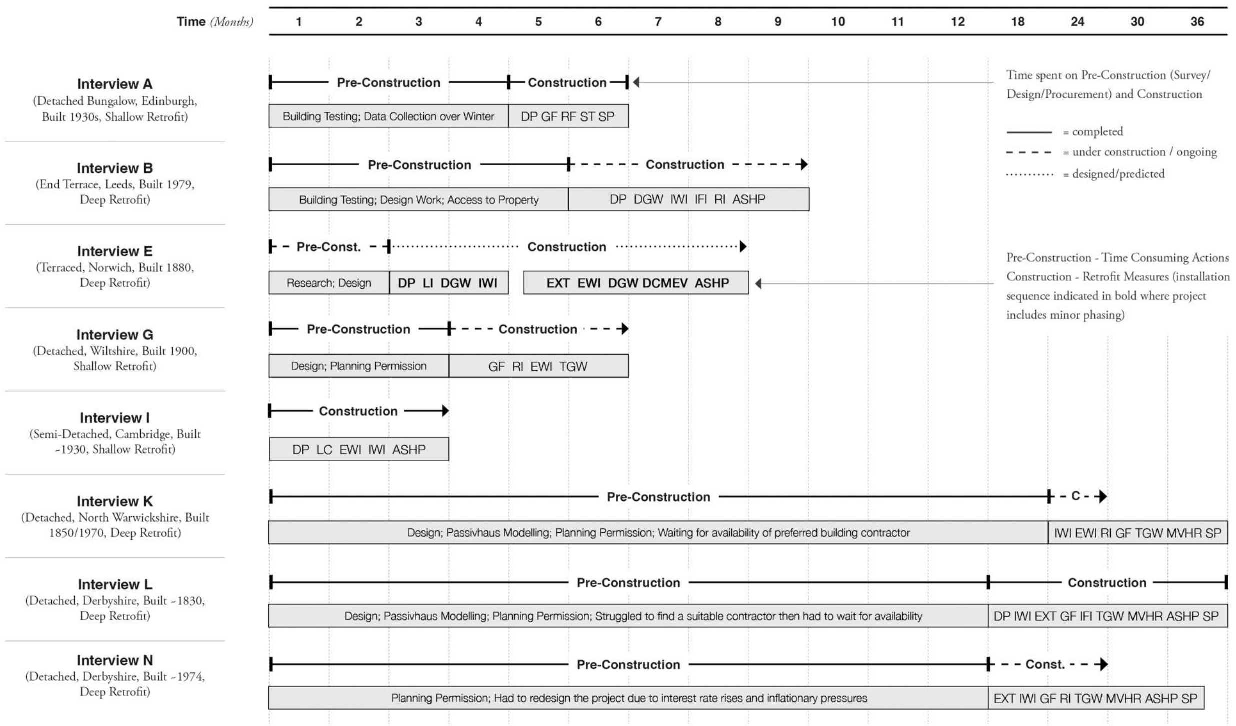


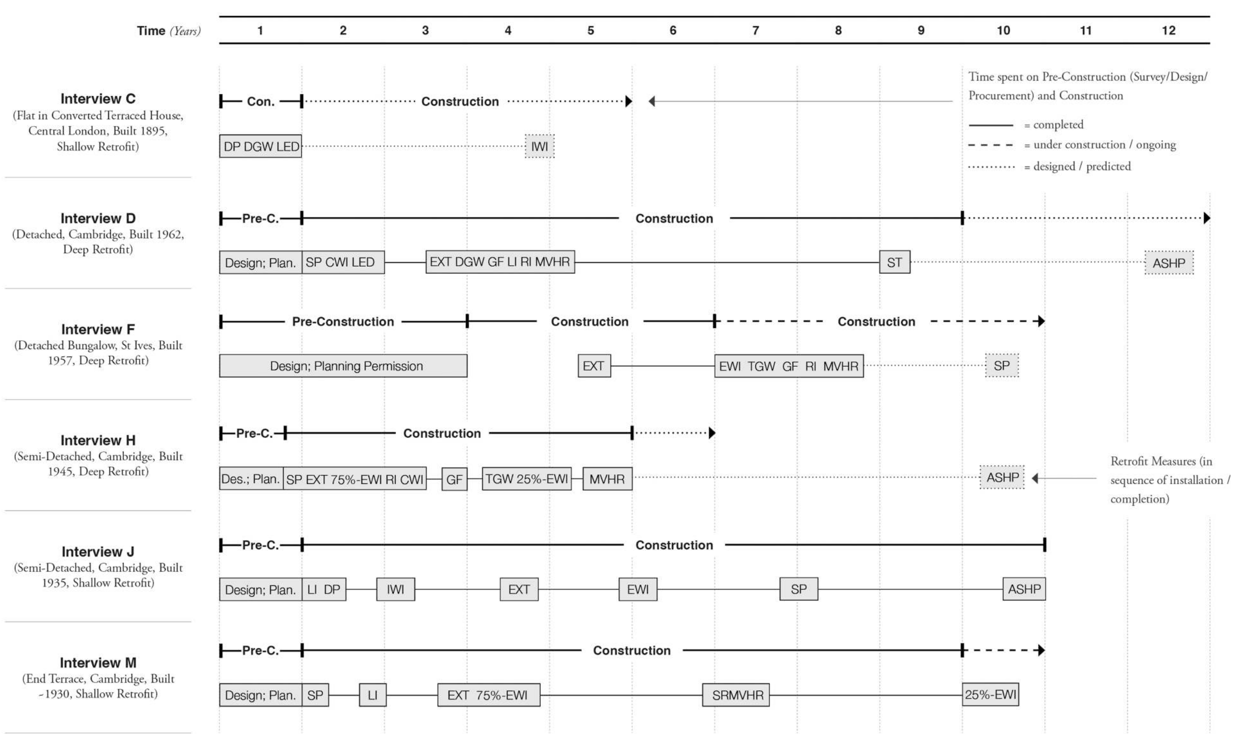
Figure 3. Coding tree of thematic codes for interview transcripts (author's own).

note that the timeline shown for construction in Figure 5 is intended to show the time lapsed from the first measure being installed to the completion of the final measure (or to what the interviewee deemed to be the final measure) and does not suggest works were being completed every day throughout this period. It is common for long-term, or over-time, projects to have lull or idle periods, as Fawcett (2014, p. 486) identifies: 'time passing allows for people to recover from the impact of disruption of earlier works, to accrue savings for



Note - EWI (External Wall Insulation), IWI (Internal Wall Insulation), LI (Loft Insulation), RI (Roof Insulation), GF (Ground Floor Insulation), IFI (Intermediate Floor Insulation), DGW (Double-Glazed Windows), TGW (Triple Glazed Windows), DP (Draught Proofing Measures), ST (Solar Thermal), SP (Solar Photovoltaic Panels), MVHR (Mechanical Ventilation Heat Recovery), DCMEV (Demand Controlled Mechanical Ventilation), ASHP (Air Source Heat Pump), EXT (Extension), LC (Loft Conversion)

Figure 4. Retrofit timelines of projects completed in one go from interview sample (author's own).



Note - EWI (External Wall Insulation), IWI (Internal Wall Insulation), CWI (Cavity Wall Insulation), LI (Loft Insulation), RI (Roof Insulation), GF (Ground Floor Insulation), IFI (Intermediate Floor Insulation), DGW (Double-Glazed Windows), TGW (Triple Glazed Windows), DP (Draught Proofing Measures), ST (Solar Thermal), SP (Solar Photovoltaic Panels), LED (LED Lighting) MVHR (Mechanical Ventilation Heat Recovery), DCMEV (Demand Controlled Mechanical Ventilation), SRMVHR (Single Room Mechanical Ventilation Heat Recovery), ASHP (Air Source Heat Pump), EXT (Extension), LC (Loft Conversion)

Figure 5. Retrofit timelines of long-term projects from interview samples (author's own).

Table 4. Key findings from the interview sample and their implications (author's own).

Key findings	Implications
Long term retrofits require at least one major installation package to achieve a deep retrofit	2050 emissions figures are unlikely to be met without deep retrofits and the best way to achieve this over a long time needs to be determined from the start to prevent shallow retrofits. Whole house plans could identify timings of major projects to enable savings to be made.
Predetermined plans for extensions and refurbishment works are frequently triggering retrofit projects	In this sample, owner-occupiers with pre-determined plans for extensions or kitchen/bathroom refits were advised by their architect or construction professional to combine works. This advice needs to be accessible to those who cannot afford an architect i.e. at the point-of-sale, to prevent investment lock-in.
Pre-Construction time delays are primarily rooted in planning applications and engagement of a suitable contractor	Identifying retrofit opportunities which do not require planning permission has proved to save time, however, planning policy is starting to catch up. Improving the technical skills of the workforce and / or removing the need for skilled labour from retrofit installation will alleviate the costs associated with specialist labour.
New construction methods and materials are increasing costs due to a lack of technical knowledge / skills and the novelty of some solutions	Lack of previous experience using a product/construction method results in contractors learning on the job and pricing by the hour which drives up time and cost significantly. Some products are suited to particular construction types which may be vernacular to an area i.e. sandstone wall construction. Specializing the skillset of the workforce in these areas would be beneficial to the local supply chain.
Cost savings from government schemes incentivised some retrofit works, however future schemes must consider sequencing to be successful	Pre-installed measures from government schemes can add time and cost (i.e. raising the roof height for additional insulation where solar panels are already installed) therefore more thorough assessment and considered sequencing must support future measures.
DIY viewed as a cost saving action – scope of DIY options could be explored further	DIY saved costs but added significantly in time on projects where DIY made up a large share of the works. Personal time was not viewed as a cost amongst this sample and the scope of how much DIY could be done to be 'retrofit ready' could be explored further.

future retrofit works and to enjoy the benefits of measures already installed'.

Of the six interviewees completing their projects in a longer time period, four mentioned this was either purely, or partly, driven by costs associated with the work and the need to spread these out (C D J M). Interview C explained:

> We've chosen to do it long term as that's the only way we can afford to do it really – we're spreading the cost over a long period of time and also trying to work out how we can limit the disruption at any one stage so that the flat can remain inhabited as moving out would be an extra cost. (Interview C)

While stretching a retrofit project out over a number of years has allowed for costs to be staggered in this sample, an additional finding here is that this could be hindering the depth of the retrofit achieved. Interview C is not a great example as the retrofit of flats within a converted terraced house will be a very difficult type to tackle due to a mixture of tenures within a single building. However, Interview M exemplifies how spreading the project out to save costs has appeared to have an impact on retrofit depth. Some measures such as ground floor insulation have not been completed in this property, despite there being an opportunity during the construction of a ground floor extension to do this. In this particular case, the owner remained in the property during the extension works which would likely have prevented the ground floor from being insulated. Although there is a benefit of combining these works, it is unknown if the additional cost of ground floor insulation was outside of the owner's affordability and the shallow depth is a result of a lack of available funds.

Of the long-term projects in this sample, it is evident there is still at least one phase of major works involved to achieve a 'deep retrofit' and this appears to centre on the disruption caused by ground floor insulation. This is evident in Interviews D, F and H where the owners combined some works into one significant package. The interviewees explained that this was to avoid multiple windows of disruption, to save on labour costs and also stemmed from an awareness that some measures need to be completed together. This key finding raises the importance of whole house planning, particularly when deciding to complete a project in the long term. Interview E, which has been placed into the one-go category in this study, but actually sits somewhere in the middle, provides further insight into the importance of whole house planning. The following quote shows the consideration required for the interplay between measures and getting this correct from the start:

> We're mainly doing it all one-go to ensure that any partially completed works don't compromise the performance of the building. Also, we're aware that some tasks must be done together. The heat pump cannot be housed in the existing building so the construction of the extension is necessary for this. The external wall insulation can't be done until the extension is built, and it makes

> sense to replace windows when we're doing this work. (Interview E)

Although not a primary focus of this study, a notable finding in terms of determining the likelihood of a deep retrofit being completed has been the procurement of technical advice; all the projects achieving a deep retrofit in this sample included an architect, architectural designer and/or retrofit designer at some stage of development. Further research into the role technical advising has on the depth of retrofit achieved could be beneficial for determining the importance of this factor.

Predetermined plans for extensions and refurbishment works are frequently triggering retrofit projects.

As the Energy Saving Trust highlighted in their report *Trigger points: a convenient truth* (2011), and as expounded by Fawcett (2014, p. 486), there are 'particular points in people's live where for practical and financial reasons, improving the energy efficiency of their home is less costly / less disruptive / more attractive / more important than it would be at other times'. Among the interview sample, the desire to undertake other renovation works has also triggered energy retrofit measures. It is understood that by combining renovation or extension works with energy retrofit measures, a labour and material cost saving can be found. Interview B (an architect completing a pilot retrofit project of a Victorian house for their start-up retrofit company) explained how they are taking advantage of this in their business model:

> We're really trying to use retrofit as a way of really renovating the property, so like rewiring it, repainting it, new bathroom, new kitchen – basically everything that you'd need to add in at that stage. The cost of retrofit is not too dissimilar if it's a knackered property or a good condition property, so you get way more value for your money if you're doing both. (Interview B)

> … the project we're doing has about £25k worth of renovation work that needed doing anyway, so we can hide the retrofit costs within a lot of that, especially in terms of labour. (Interview B)

Of the owner-occupiers interviewed, a number mentioned that new kitchens, bathrooms, loft conversions and extensions were proposed before deciding to commence with energy retrofit works. Interview K mentioned they had planned to have a new kitchen, but after speaking to their architect about doing this, the project soon snowballed into a whole house deep retrofit:

> … something worth mentioning is that we've got a new kitchen and we've also redone a bathroom as part of this project. This project actually started as a new kitchen believe it or not. The kitchen is 50 years old, and it was falling apart so for a number of years we'd talked about doing it so that's how it started. (Interview K)

Other interviewees focused on the disruption caused by renovation projects as a motive to complete energy retrofit work (D, I, H). Interview D mentioned:

> The decision to retrofit the house was made once we started on the extension because we realised while we've got all this mess we might as well do those works. (Interview D)

Only interviewees who had appointed an architect, or were trained in construction/architecture, seemed aware of the benefits of combining works; these cases were a minority within this sample. As extensions, new bathrooms and kitchens are disruptive works regularly involving interactions with the building envelope, ensuring the benefit of combining these with retrofit measures is promoted at the point of sale seems to be an area for future development. This finding is important in ensuring that investment lock-in does not occur and resultantly delays or deters the implementation of deep retrofits.

Pre-construction time delays are primarily routed in planning applications and engagement of a suitable contractor

In the pre-construction phase of retrofit projects in this sample, most time was spent in waiting for planning approval (where needed) and in appointing a suitable contractor. Amongst the sample experiencing long delays in waiting for contractor availability, there was an evident time vs. cost decision to be made. In recent years, there has been an increase in contractors specializing in retrofit work, however as they are a niche within the market, their pricing tends to be at a premium. For more than one interviewee in the sample, the additional cost associated with specialists, or 'retrofit champions' was not deemed to be affordable:

> It might be worth mentioning that there is one construction company nearby who we knew specialised in these types of projects but the extra that we would be paying for them just couldn't really be justified. (Interview L)

There was an evident time penalty involved in waiting for contractor availability when deciding not to appoint a retrofit specialist in this sample. As noted in the next key finding, there can also be an added cost in using contractors with little experience in retrofit (particularly deep retrofit) due to the additional labour costs associated with novel or technically challenging solutions. Interview K lost time in finding a suitable contractor and they put this down to the technical demands associated with their project:

> We found it really hard to find a builder who would take us on. The site is slightly inaccessible and it's not a straightforward project, so the 6 months this project might take, they could have done say 4 extensions without any of the risk of not knowing what we're going to find when we start. (Interview K)

Time delays associated with planning permission are typically out of the control of homeowners, however, the decision as to whether to avoid planning altogether was raised in the sample and was a driver behind some decision-making. Interview H was an example where time was saved by avoiding planning and instead utilizing Permitted Development Rights (a scheme that allows you to extend/renovate your home without the need for a full planning application):

> The funny thing was the north facing side of the house, that is the side that is visible from the road, that was done last. That was because I had to make my mind up about whether to go in for a planning application and do EWI [External Wall Insulation] and render or to have a brick slip finish. In the end I went for a brick slip finish because it doesn't need planning and looks nice. (Interview H)

New construction methods and materials are increasing costs due to lack of technical knowledge / skills and novelty of some solutions

The time vs. cost scenario previously mentioned is also of relevance to this finding. Where interviewees in the sample chose not to proceed with a specialist retrofit contractor, there were added costs associated with the time it was taking for other contractors to learn how to use and install new materials or to locate suitable sub-contractors. Interview L (the retrofit of a solid stone barn in Derbyshire) is an example of how new construction methods and materials added significant cost. Due to their contractor having little experience in the area, they refused to provide a whole job price (due to the risk this placed upon them) and instead had to provide a price per hour. In this case, it resulted in the homeowners paying for on-the-job training for the contractor at a significant expense. They explained:

> I think if we take the top storey which we are particularly pleased with in insulation terms, the labour demands for the joiners to actually get the work done properly and for the Velux to go in at the correct angles to maximise the light, well all of these things have to be individually made and therefore there's a huge cost associated with it. We found that because a lot of the contractors we were using didn't have much retrofit experience, they were refusing to charge by the job and we ended up paying them by the hour. (Interview L)

> I mean obviously once they've done one, they'll be able to do more and get quicker and more skilled, but unfortunately it's been the case where we've had to be that one which they've been training on and there's a cost involved with that. (Interview L)

The use of Diathonite (a breathable lime-based insulating plaster applied to the inside of walls) in Interview L's project also added significant cost as the only suitable sub-contractor to do the work was based 90 miles away:

> … we did have a few headaches with the Diathonite and in the end we got a team that came up from Northampton, in a minibus with about 5 or 6 plasterers who knew how to do Diathonite … in terms of getting someone local it was very, very difficult to monitor. (Interview L)

This situation puts a particular spotlight on the immaturity of parts of the retrofit market, particularly regarding materials, products, and technical knowledge. However, this does highlight that in locations such as the North of England where solid stone buildings are prevalent, there is an obvious market for specializing in the retrofit of these types and a one-stop-shop focused on these types of homes could eventually reduce time and cost in this situation.

Cost savings from government schemes were incentivising some retrofit works, however future schemes must consider sequencing to be successful

Currently, publicly funded retrofit schemes must follow guidance set out in PAS2035 which states a fabric-first approach to retrofit must be followed to ensure the thermal fabric of a building is improved prior to the installation of any renewables or alternate heat sources (The British Standards Institution, 2020). To date, this stance has not been pushed in the private sector, where solar panels and air source heat pumps have been installed before any energy-saving measures. Most of these installations have been driven by government-funded schemes or incentives and can create challenges and additional costs when starting retrofit projects. For example, previously installed solar panels may need to be removed during roof insulation works when a roof height needs to be raised. Interview D was an example where solar panels were installed as a first measure due to the availability of the Green Deal:

> It was mainly driven by cost – we completed what we could as and when money became available. When we first moved in, we got solar panels installed through the government scheme. We then did the big project of the main house and extension which involved some borrowing to complete. (Interview D)

It is evident within the sample that government funding has influenced the uptake of retrofit measures, particularly when significant cost savings are attached. In response to receiving external wall insulation through the Green Homes Grant scheme, Interview J explained:

> The one thing I should add is that we paid virtually nothing for this. It was obviously not a successful scheme, but they were so desperate to spend the money. I think the quoted price was well over £7000 and we ended up paying £700 pounds – it was virtually nothing. It was a no brainer really and I must say out of everything we've done that has been spectacular. (Interview J)

Interview J is an interesting case study in this research as the retrofit project was steered by government incentives and all funded or subsidized measures available to them were installed at some point. Despite this, the property has not been completed in a way that would make one believe it has reached a deep retrofit level. Complaints made by the interviewee regarding the poor performance of their recently installed air source heat pump through the Boiler Upgrade Scheme (BUS) add to this concern.

It is clear from the cases in this sample that government-funded schemes can be a good way to rollout retrofit measures, however, it is arguable that these need to be part of a whole house plan which enables the achievement of a deep retrofit. The installation of renewables prior to any thermal efficiency measures could remove any homeowner incentive to retrofit. As the Climate Change Committee has stressed, 'any short-term scheme should clearly fit with the Government's long-term plans' (2022, p. 200).

DIY is viewed as a cost saving action – scope of DIY options could be explored further

There was a spectrum of DIY completed amongst all projects in the sample. This ranged from basic draught proofing such as filling gaps in floorboards and window reveals (I, J), through to the installation of external wall insulation and a brick-slip finish (H).

The ease at which quick wins could be achieved early in the retrofit process (which does not hinder deeper works) emerged in the sample. Interview J explained:

> We got Cambridge Carbon Footprint to come in and do some thermal imaging and that was really good at identifying some quick wins we could do ourselves. The loft hatch for example came up as a massive patch of red so we plonked insulation on that which cost next to nothing. We discovered there were a few kind of gaps between windows and walls which just needed some simple sealant. (Interview J)

For some interviewees, DIY was used as a way to ensure they achieved the quality of retrofit they desired, but at a cost they could afford. Where a cost saving was achieved here, an increase in time was added, yet the loss of personal time did not appear to be viewed as a cost in this regard. Interview H was an example of this:

> I wanted to have a very high standard so then you can't really get builders who you can trust to deliver that so I DIY'd it mostly. And that then makes it limited by weekends, days off, holidays, that kind of thing. So it's a combination of those. Of course, these builders who do high spec retrofits do exist but if you specified what I now have you would pay an absolute fortune to get it and I just can't afford that. (Interview H)

With the view of personal time essentially being cost-free, further research into how much DIY owner-occupiers would be willing to complete would be worthwhile. Of those measures listed in Table 3, the majority in Low-Cost Measures and Shallow Retrofit are already being completed by homeowners, yet nearly all measures in the Deep Retrofit column are still installed by specialists. The development of products that could be installed by homeowners more easily without causing unintended consequences could also be explored.

Discussion

The Climate Change Committee has expressed that 'energy efficiency in non-fuel poor homes is the most significant policy gap in the buildings sector' (2023, p. 155). The sample in this study can all be considered non-fuel poor homes; however, it is evident from this research that this covers a wide range of households. Some could afford to complete very expensive, one-off projects and others required support from government subsidies or the spreading of costs. A handful of interviewees who completed deep retrofits in this sample reflected on the significant costs that occurred to complete their project:

> … we went into it recognising that, whilst the work we have done will improve the value of the property significantly, it won't improve it to the extent that we will make back all of what we have spent. We'll definitely have a net loss. (Interview K)

> In terms of reflections, it's been a very demanding but exciting process and we're very pleased with the end

> results. I think financially, we've been in a privileged position, and I think a lot of people would just not have been able to do this. I would guess that approximately a third of what we've spent we won't recoup in terms of value of the property. We're almost paying off what we owe to the environment and it's not a value driven thing. (Interview L)

> Ok, the energy prices now have helped, but if you look at how much I spent on insulation and products for the EWI [External Wall Insulation] and I did it all myself – it still has a payback time of 10 years at least and that's factoring in the energy price crisis. So that's never going to be worthwhile if you're looking purely at a return-on-investment scenario. (Interview H)

These interviewees all reflect on the lack of a return on investment in their projects and how this factor has not been a driving force for their retrofit. In an attempt to scale retrofit activity in this sector, this group who have the capital to afford to retrofit without concern for a return-on-investment just yet are worthy of further research. Locating similar homeowners may not be easy, but they could provide a market for the completion of deep retrofit pilots across a range of house types in the UK. Through completion and thorough documentation of these projects, diagnosis of the most efficient route to deep retrofit across a wide range of properties could be explored. This could subsequently support those without the funds to take risks with new materials and construction methods who need to be able to identify the quickest and most affordable route to retrofit their home.

The interplay between time and cost in domestic retrofit projects highlighted in previous literature also emerged in this study, with most households who decided to complete their retrofit project over a longer time period doing so in the view of saving, or staggering costs. In the current economic landscape of high construction costs and interest rates, it is plausible to assume that most retrofit projects by homeowners with less available capital will be completed in the long-term. With this in mind, and supported by the findings in this study, it is evident that intervention in this sector is required to prevent the completion of further shallow retrofits. This study highlighted, for those projects that do not involve an architect, retrofit professional or significant amounts of research by an enthusiastic homeowner (beyond what could generally be expected), there is a lack of guidance and management for long-term projects to ensure the works implemented are contributing to a future deep retrofit of 60% or more emissions reductions. In the private sector, enabling retrofit at a scale beyond shallow measures implemented by central government funding has proven challenging. Some researchers have identified the 'community' or 'neighbourhood' as an ideal scale for the execution of retrofit in this market (Arup, 2013; Gupta et al., 2014, 2015; Karvonen, 2013; Saffari & Beagon, 2022), however when considering that not all homeowners on a given street will be able to afford the same amount of work, implementation of this proves difficult to envisage. The rise in one-stop-shops delivering one-off retrofits in the private sector seems likely to be a future area of progress (Marmolejo-Duarte et al., 2022). In their study comparing the operation of public and private-driven one-stop-shops in Europe, Pardalis et al. (2022, p. 10) explain that

> since their [private-driven one-stop-shops] viability depends on the payments for each delivered renovation, they focus on customers who have the financial capability to pay for such a renovation. As a result, a large share of potential customers cannot have access to such a service.

As the one-stop-shop model scales, it is imaginable that costs will fall and open up this service to a wider market. However, as Pardalis et al. (2022, p. 10) suggest, further research into the collaboration between private-driven one-stop-shops and commercial banks offering low-interest loans to customers would be beneficial. Notably, some progress has recently been made in this area in the UK through some of the pilot phase projects funded through the Department for Energy Security and Net Zero's Green Home Finance Accelerator (DESNZ, 2024)

Moving forward, further research into the emissions reduction limits of specific house types and the measures required to reach a deep retrofit of 60% or more carbon savings is proposed. It is evident from Interviews I and H in this study that the selection and design of measures impact the overall depth of retrofit. Both properties were 1930s semi-detached dwellings in Cambridge of comparable size, yet the decisions made by one homeowner have led to a deep retrofit whereas the other has not. This research into the design considerations in achieving a deep retrofit feeds into the need for households to understand the implications involved in the retrofit of their home, particularly when this is done over a longer timeline. The Climate Change Committee explains that 'many homeowners lack even the most basic information about the efficiency of their homes' and EPCs currently do not provide detailed enough information (2022, p. 200). Increasing homeowner knowledge regarding property information could begin to shift with the implementation of Digital Building Logbooks, however, this has been driven with regard to digitizing property transactions and they are still very much in their infancy with only 450,000 logbooks across the UK in December 2023 (Residential Logbook Association, 2024, p. 6). Notably, since January 2024, the National Retrofit Hub (2024) in the UK has hosted a working group to begin to decipher how a whole house plan and single measure record could be integrated into a Digital Building Passport.

Conclusion

The key findings identified in this study further our understanding of how retrofit projects are currently being approached and implemented on traditionally constructed homes in the owner-occupied sector in the UK. For the first time, this paper has painted a picture of how economic, political and market forces are impacting the implementation of retrofit projects beyond the 'very early adopter' sector and shows how actors are negotiating time and cost within the current landscape.

It is acknowledged that the fuel poor in the UK is a priority in attacking energy efficiency as a means to achieving emissions reduction. However, in the current economic climate of high construction costs and interest rates, in addition to a lack of focus on efficiency improvements and demand management across the government, it is hypothesized that the scaling of retrofit in the private sector is likely to rely on the 'able-to-pay' market. This research opens the door for further exploration into how this sector could help to address some of the immaturities in the market at present. It is envisioned that further opportunities for time and cost optimization will be found through the implementation of more deep retrofit projects, with the aim of removing some of the additional costs identified in this study, particularly with regard to retrofit skills and supply chain.

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References

Adan, H., & Fuerst, F. (2015). Modelling energy retrofit investments in the UK housing market: A microeconomic approach. *Smart and Sustainable Built Environment*, *4*(3), 251–267. https://doi.org/10.1108/SASBE-03-2013-0016

Arup. (2013). *Delivering and funding housing retrofit*. https://www.arup.com/perspectives/publications/research/section/delivering-and-funding-housing-retrofit.

Bennadji, A., Seddiki, M., Alabid, J., Laing, R., & Gray, D. (2022). Predicting energy savings of the UK housing stock under a step-by-step energy retrofit scenario towards net-zero. *Energies*, *15*(9), 3082. https://doi.org/10.3390/en15093082

Boardman, B. (2007). Examining the carbon agenda via the 40% house scenario. *Building Research & Information*, *35*(4), 363–378. https://doi.org/10.1080/09613210701238276

Bobrova, Y., Papachristos, G., & Cooper, A. (2022). Process perspective on homeowner energy retrofits: A qualitative metasynthesis. *Energy Policy*, *160*. https://doi.org/10.1016/j.enpol.2021.112669

The British Standards Institution. (2020). *PAS2035:2019 - Retrofitting dwellings for improved energy efficiency - Specification and guidance*.

Bros-Williamson, J., & Reid, A. (2015). Improving the thermal performance of "hard to treat" historic buildings in Edinburgh's new town. *Anales de Edificacion*, *2*(1), 26–33.

Brown, D. (2018). Business models for residential retrofit in the UK: A critical assessment of five key archetypes. *Energy Efficiency*, *11*(6), 1497–1517. https://doi.org/10.1007/s12053-018-9629-5

Building Research Establishment. (2008). *Energy analysis focus report: A study of hard to treat homes using the English House Condition Survey*. www.communities.gov.uk/ehcs

Cambridge City Council. (2022). *Cambridge City Council: Retrofitting your home*. https://www.cambridge.gov.uk/media/11677/retrofitting-your-home-report-non-accessible-version.pdf

Climate Change Committee. (2022). *Progress in reducing emissions: 2022 Report to Parliament*. www.theccc.org.uk/publications

Climate Change Committee. (2023). *Progress in reducing emissions: 2023 Report to Parliament*. https://www.theccc.org.uk/publication/2023-progress-report-to-parliament/

Crouch, M., & McKenzie, H. (2006). The logic of small samples in interview-based qualitative research. *Social Science Information*, *45*(4), 483–499. https://doi.org/10.1177/0539018406069584

Department for Business Energy & Industrial Strategy. (2022). *Social housing decarbonisation fund wave 2.1: Competition guidance notes*.

Department for Energy Security and Net Zero. (2023). *Statistical release 30 March 2023: Household energy efficiency*. https://www.gov.uk/government/collections/green-home-grant-statistics

Department for Energy Security and Net Zero. (2024). *Green home finance accelerator: Details of Pilot Phase projects - GOV.UK*. GOV.UK. https://www.gov.uk/government/publications/green-home-finance-accelerator-discovery-phase-projects/green-home-finance-accelerator-details-of-pilot-phase-project

Department for Levelling Up Housing & Communities. (2022). *English Housing Survey 2021 to 2022: Headline report - GOV.UK*. GOV.UK. https://www.gov.uk/government/statistics/english-housing-survey-2021-to-2022-headline-report/english-housing-survey-2021-to-2022-headline-report

Department for Levelling Up Housing & Communities. (2023). *English Housing Survey: Energy Report, 2020-21*. https://www.gov.uk/government/collections/english-housing-survey-technical-advice#technical-reports

DG Cities. (2023). *DG Cities - Hard to treat homes*. DG Cities. https://www.dgcities.com/hard-to-treat-homes

Energy Saving Trust. (2011). *Trigger points: A convenient truth - Promoting energy efficiency in the home*

European Commission. (2020). *A renovation wave for Europe - Greening our buildings, creating jobs, improving lives*. https://eur-lex.europa.eu/resource.html?uri=cellar:0638aa1d-0f02-11eb-bc07-01aa75ed71a1.0003.02/DOC_1&format=PDF

Fawcett, T. (2014). Exploring the time dimension of low carbon retrofit: Owner-occupied housing. *Building Research & Information*, *42*(4), 477–488. https://doi.org/10.1080/09613218.2013.804769

Fawcett, T., & Killip, G. (2014). Anatomy of low carbon retrofits: Evidence from owner-occupied Superhomes Anatomy of low carbon retrofits: Evidence from owner-occupied Superhomes. *Building Research & Information*, *42*(4), 434–445. https://doi.org/10.1080/09613218.2014.893162

Fuerst, F., McAllister, P., Nanda, A., & Wyatt, P. (2015). Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. *Energy Economics*, *48*, 145–156. https://doi.org/10.1016/j.eneco.2014.12.012

Galvin, R. (2015). How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? *Journal of Building Engineering*, *1*, 2–12. https://doi.org/10.1016/j.jobe.2014.12.001

Glaser, B., & Strauss, A. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Aldine de Gruyter.

Gupta, R., Barnfield, L., & Hipwood, T. (2014). Impacts of community-led energy retrofitting of owner-occupied dwellings. *Building Research & Information*, *42*(4), 446–461. https://doi.org/10.1080/09613218.2014.894742

Gupta, R., Gregg, M., Passmore, S., & Stevens, G. (2015). Intent and outcomes from the Retrofit for the Future programme: key lessons. *Building Research & Information*, *43*(4), 435–451. https://doi.org/10.1080/09613218.2015.1024042

Johnston, D., Lowe, R., & Bell, M. (2005). An exploration of the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the year 2050. *Energy Policy*, *33*(13), 1643–1659. https://doi.org/10.1016/j.enpol.2004.02.003

Jones, P., Lannon, S., & Patterson, J. (2013). Retrofitting existing housing: How far, how much? *Building Research & Information*, *41*(5), 532–550. https://doi.org/10.1080/09613218.2013.807064

Karvonen, A. (2013). Towards systemic domestic retrofit: A social practices approach. *Building Research & Information*, *41*(5), 563–574. https://doi.org/10.1080/09613218.2013.805298

Maia, I., Kranzl, L., & Müller, A. (2021). New step-by-step retrofitting model for delivering optimum timing. *Applied Energy*, *290*, 116714. https://doi.org/10.1016/j.apenergy.2021.116714

Marmolejo-Duarte, C., Biere-Arenas, R., Spairani-Berrio, S., Spairani-Berrio, Y., & Perez-Lamas, C. (2022). One-stop-shops as a model to manage housing energy retrofit: A general approach to Europe and Spain. In W. Bustamante, M. Andrade, & P. Ortiz (Eds.), *PLEA 2022 Santiago: Will cities survive?* (pp. 979–983). Pontificia Universidad Catolica de Chile.

Mohammadpourkarbasi, H., Riddle, B., Liu, C., & Sharples, S. (2023). Life cycle carbon assessment of decarbonising UK's hard-to-treat homes: A comparative study of conventional retrofit vs EnerPHit, heat pump first vs fabric first and ecological vs petrochemical retrofit approaches. *Energy and Buildings*, *296*, 113353. https://doi.org/10.1016/j.enbuild.2023.113353

Morgan, J., Chu, C. M., & Haines-Doran, T. (2023). Competent retrofitting policy and inflation resilience: The cheapest energy is that which you don't use. *Energy Economics*, *121*, 106648. https://doi.org/10.1016/j.eneco.2023.106648

National Retrofit Hub. (2024). *Digital Building Logbooks - An Introduction to Logbooks and Retrofit*. https://nationalretrofithub.org.uk/wp-content/uploads/2024/05/NRH-Logbooks-Explainer-2.pdf?vgo_ee=cFvBshM%2BAVqyrRNv3HN%2FV8mQXLKZ19w59TSITalS7nsSI2l9F1CISw%3D%3D%3A7eE%2BbXjv4ryEQbBFGtO5JuAv4BIKrfVe

Nicol, S., Beer, C., & Scott, C. (2014). *The age and construction of English homes*. IHS BRE Press.

Ofgem. (2023). *Energy Company Obligation (ECO) | Ofgem*. Ofgem. https://www.ofgem.gov.uk/environmental-and-social-schemes/energy-company-obligation-eco

Palmer, J., Livingstone, M., Adams, A., & Cambridge Architectural Research. (2017). *What Does It Cost to Retrofit Homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/656866/BEIS_Update_of_Domestic_Cost_Assumptions_031017.pdf

Pardalis, G., Mahapatra, K., & Mainali, B. (2022). Comparing public- and private-driven one-stop-shops for energy renovations of residential buildings in Europe. *Journal of Cleaner Production*, *365*, 132683. https://doi.org/10.1016/j.jclepro.2022.132683

Peachey, K. (2023). *Renters compete with 20 others in battle to find a home - BBC News*. BBC News. https://www.bbc.co.uk/news/business-66246223

Power, A. (2008). Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? *Energy Policy*, *36*(12), 4487–4501. https://doi.org/10.1016/j.enpol.2008.09.022

Raslan, R., & Ambrose, A. (2022). Solving the difficult problem of hard to decarbonize homes. *Nature Energy*, *7*(8), 675–677. https://doi.org/10.1038/s41560-022-01075-w

Ravetz, J. (2008). State of the stock—What do we know about existing buildings and their future prospects? *Energy Policy*, *36*(12), 4462–4470. https://doi.org/10.1016/j.enpol.2008.09.026

Residential Logbook Association. (2024). *Digital building Logbooks in the UK: A Primer - February* 2024. https://irp.cdn-website.com/6dcf3abc/files/uploaded/Logbooks_in_the_UK_-_A_Primer-Feb2024-UK.docx_(1).pdf.

Saffari, M., & Beagon, P. (2022). Home energy retrofit: Reviewing its depth, scale of delivery, and sustainability. *Energy and Buildings*, *269*, 112253. https://doi.org/10.1016/j.enbuild.2022.112253

Seifhashemi, M., & Elkadi, H. (2022). Aesthetic appealing wall insulation: A novel approach for uptake of solid wall insulation in the UK. *Building and Environment*, *224*, 109550. https://doi.org/10.1016/j.buildenv.2022.109550

Stafford, A., Gorse, C., & Shao, L. (2011). *The retrofit challenge: Delivering low carbon buildings*.

Sunikka-Blank, M., & Galvin, R. (2016). Irrational homeowners? How aesthetics and heritage values influence thermal retrofit decisions in the United Kingdom. *Energy Research & Social Science*, *11*, 97–108. https://doi.org/10.1016/j.erss.2015.09.004

Wade, F., & Visscher, H. (2021). Retrofit at scale: Accelerating capabilities for domestic building stocks. *Buildings and Cities*, *2*(1), 800–811. https://doi.org/10.5334/bc.158

Webb, J., Emden, J., & Murphy, L. (2020). *All hands to the pump: A home improvement plan for England*. https://www.ippr.org/files/2020-07/all-hands-to-the-pump-july20.pdf

Appendices

Appendix A. Information sheet & consent form

Participant Information Sheet

Research title. Understanding the timeline of retrofit projects on traditionally constructed, owner-occupied homes in the UK

Purpose of the study. The purpose of the study is to gain a better understanding of the anatomy of retrofit projects which have been completed / are currently in progress on traditionally constructed (brick and/or brick and block walls), owner-occupied homes in the UK. This will allow us to begin to map out where there is opportunity for time saving through optimized data collection and advanced manufacturing.

What do I have to do?. The study consists of an online interview which will ask questions about the construction and age of your property, the retrofit work you have / are planning to complete and the timeline in which it was / is planned to be completed in. The interview should take no longer than 60 minutes of your time.

Will my taking part in this project be kept confidential?. There are no personal questions within the interview and all data will remain anonymous within the study. Data will only be identifiable by the property type (detached, semi-detached etc.) and the building age (if known). Where interviews are conducted online, the interview will be recorded for the purpose of transcription and deleted immediately afterwards.

What will happen to the results of the research project?. The research is primarily intended to support the completion of a PhD Thesis and the results may be written up in a journal at a later date or presented at a conference. If any individual data is presented, for example a direct quote from an interview, it will be anonymous and without any means of identifying individuals involved.

Who is funding the research?. The research is supported by funding from the EPSRC (Engineering and Physical Sciences Research Council) and MTC (Manufacturing Technology Centre).

Ethical review of the study. The research project has been reviewed by the University of Cambridge Department of Engineering Ethics Committee.

Contact for further information or qestions. Please feel free to contact Tom Ardron (tga22@cam.ac.uk) with any additional questions or requests for further information.

Appendix B. Interview questions

Interview Questions

Exploring time and cost optimization in energy retrofit programmes of traditionally constructed, owner-occupied UK dwellings

Property information.

- Where is your property located? (City/Town/London Borough name is sufficient)
- What is your property type? *(Detached, Semi-Detached, Terrace etc.)*
- If known, what is the age of your property?
- If known, what is the wall construction of your property? *(Solid wall, cavity wall etc)*
- Are there any specific constraints to the property? (e.g. listed or in a conservation area)
- What was / is the main driver for completing an energy retrofit on your property?

Retrofit overview.

– At what stage is your homes retrofit project at? (Data/Survey; Design; Construction; Completed)
– Was your retrofit completed in one go or is it a long-term project to be completed over time? (If not yet started, please indicate your intentions)
– What is your reason for completing the project in one go / over a longer period?
– What retrofit measures did you / are you planning to complete on your property? *(EWI, IWI, Floor Insulation, MVHR, Windows, Air Source Heat Pump etc)*
– If the project is staged, what order did you / are you intending to complete the works?

– Did / does your project include measures other than those intended to reduce the energy demand of the property? (e.g. extensions / loft conversions)
– How long did your project take in total? *(Years, Months)*
– Who was involved in your retrofit project and when? (e.g. Architect/Designer, Retrofit Coordinator, Engineer, Contractor)

Retrofit stages

Survey/design.

– Did you collect data on the energy demand of the property prior to commencing with the retrofit work? If not, why?
– If known, how long was the phase of work from initiating the project to completing the design phase?
– Were there any parts of the Survey or Design stage that you were surprised by in terms of the amount of time spent?

Construction.

– If known, how long was the construction phase of the retrofit project? (If a staged project, please describe how long each phase of work was and what was involved)
– Were there any parts of the construction stage of the project that you were surprised by in terms of the amount of time spent?

Retrofit reflections.

- Did you collect data on the change in energy demand following the retrofit?
- Were there any parts of the retrofit process that you found to be particularly intrusive?
- If you could complete the project again, is there anything you would do differently?