Reducing Carbon while Retaining Heritage: retrofitting approaches for vernacular buildings and their residents

Thesis

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Reducing carbon while retaining heritage: retrofitting approaches for vernacular buildings and their residents

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Abstract

Retrofitting the built environment is critical for mitigating devastating climate change. Operational energy from buildings is responsible for 27% of global carbon emissions. However, standard retrofitting approaches are often not appropriate for the 20-30% of UK homes with heritage value. This research examines the potential for realistic carbon reduction from these buildings while retaining their heritage values.

The county of Cumbria was the overarching case for this research which involved a resident survey, 16 individual building-resident case studies with both quantitative and qualitative data, and lifecycle modelling of retrofit options.

The study found that most residents of vernacular buildings, whether with official heritage designation or not, invest heritage values in their buildings and that these values affect the retrofits they consider acceptable and will therefore enact. Meanwhile, most residents already engage in energy conscious behaviour. In contrast to common assumptions, most residents find their buildings comfortable, emphasising excellent summer performance, although previous maladaptions can present challenges. The study further showed that standard modelling tools poorly reflect both vernacular buildings' energy performance and residents' behaviours and preferences, thus frequently recommending inappropriate alterations.

When the embodied carbon of the retrofits was calculated alongside the operational savings it frequently influenced which measures had the lowest lifecycle carbon. There were also positive synergies between measures with low embodied carbon and those acceptable to residents' heritage values; these measures tend to be non-invasive and less technical but are harder to model and quantify and therefore often overlooked.

This research shows that we should acknowledge residents' values and behaviours, consider residents and their buildings as interrelated and

interdependent, and include the embodied impacts of retrofit, if we are to realistically make desperately needed carbon reductions from our buildings. This study has implications for retrofitting approaches and policies for vernacular buildings with applicability far beyond Cumbria.

Dedication

To my Grandparents J and M, for encouraging me to love learning and books, and who didn't get to see this.

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Contents

Figures

Tables

List of publications

Wise, F., Moncaster, A., Jones, D. and Dewberry, E. (2019) 'Considering embodied energy and carbon in heritage buildings – a review', *IOP Conference Series: Earth and Environmental Science*, vol. 329, no. 1, p. 012002 [Online]. DOI: 10.1088/1755-1315/329/1/012002.

Wise, F., Jones, D. and Moncaster, A. (2021) 'Reducing carbon from heritage buildings: the importance of residents' views, values and behaviours', *Journal of Architectural Conservation*, vol. 27, no. 1–2, pp. 117–146 [Online]. DOI: 10.1080/13556207.2021.1933342.

Wise, F., Moncaster, A. and Jones, D. (2021) 'Rethinking retrofit of residential heritage buildings', *Buildings and Cities*, vol. 2, no. 1, p. 495 [Online]. DOI: 10.5334/bc.94.

Wise, F., Moncaster, A. and Jones, D. (2022) 'Residents' comfort perceptions in domestic heritage buildings', *IOP Conference Series: Earth and Environmental Science*, vol. 1085, no. 1, p. 012024 [Online]. DOI: 10.1088/1755-1315/1085/1/012024.

Wise, F., Moncaster, A., Jones, D. and Dewberry, E. (2022) 'Low carbon heritage: residents' views from Cumbria and the English Lake District World Heritage Site', *EEHB2022 proceedings*, Benediktbeuern Monastery, Germany, 4-5th of May 2022 (Forthcoming).

Wise, F., Moncaster, A. and Jones, D. (2022) 'Is it all about the windows? Residents' values in residential heritage buildings' *Central Europe towards Sustainable Building 2022,* 4-6 July 2022, Prague. Forthcoming

Abbreviations

AECB – Association of Environmentally Conscious Builders

ASHP – Air source heat pump

BEIS – Department for Business Energy and Industrial Strategy

BRE – Building research establishment

CAfS – Cumbria Action for Sustainability

CES – Cultural Ecosystem Services

CFL – Compact fluorescent lightbulb

DB – Design Builder

DHW – Domestic hot water

EPC – Energy Performance Certificate

EPD – Environmental Product Declaration

EWI – External wall insulation

FOLD – Friends of the Lake District

GSHP – Ground Source Heat Pump

IEA – International Energy Agency

IWI – Internal wall insulation

kW – Kilowatt

kWh – Kilowatt hours

$kgCO_2e$ -- Kilograms of carbon dioxide equivalent

LCA – Lifecycle assessment

LDNPA – Lake District National Park Authority

LED – Light emitting diode

MEES – Minimum Energy Efficiency Standards

PV –Photovoltaic

RdSAP – Reduced Standard Assessment Procedure

RQ – Research question

RsQ – Research sub-question

SBEM – Simplified Building Energy Model

SPAB – Society for the Protection of Ancient Buildings

WHS – World Heritage Site

WSHP – Water Source Heat Pump

Chapter 1. Introduction

1.1 Carbon reduction and the built environment

The latest report by the Intergovernmental Panel on Climate Change emphasises that anthropogenic climate change is an overwhelming threat to human societies and the natural world (IPCC 2022a). It highlights the need for urgent action to reduce carbon emissions by 43% in this decade, to have any chance of limiting global temperature rise to less than 1.5°C and avoiding devastating and irreversible impacts (IPCC, 2022b). Energy used in buildings is currently responsible for 27% of global carbon emissions each year (Global Alliance for Buildings and Construction et al., 2021). In the EU and the UK the rate of building stock replacement is only around 1% per year, meaning that 85-95% of current buildings will still be extant in 2050 (European Commission, 2020; Almeida et al., 2018). Ensuring that all new buildings have net zero operational carbon through policies such as more stringent building regulations is necessary; however it is not sufficient (Economidou et al., 2020). In order to mitigate emissions from the built environment, it is also critical to reduce carbon from existing buildings through retrofitting on a massive scale (Committee on Climate Change (CCC), 2020; European Commission, 2020).

'Retrofitting' can be defined as alterations carried out in order to improve building performance, either in energy terms or in other respects (ASHRAE 2019). This suggests a broad scope for a range of measures; however retrofit projects generally focus on changes to building fabric or technologies (Gram-Hanssen, Georg, et al., 2018; Mazzarella, 2015). These include improving the insulative qualities of the building fabric through adding insulation and altering or replacing windows, or decarbonising building energy sources through renewable technologies such as heat pumps or solar panels, and improving the efficiency of current systems (Carratt et al., 2020; Fisk et al., 2020). Currently however rates of retrofitting to reduce energy demand are low, while rates of deep retrofit, where energy demand is reduced by 60% or more, only cover 0.2% of the European building stock each year (European Commission, 2020). It has been calculated that rates of retrofit need to more than double across Europe, equating to over 90,000 homes retrofitted every week up to 2030 (European Academies Science Advisory Council (EASAC), 2021). Retrofit policy has been described as piecemeal, often involving short term schemes for individual measures and relying on individual activities and market mechanisms which have failed to deliver the required scale of change (Palmer et al., 2021; Wade and Visscher, 2021).

The energy used in residential buildings is responsible for 15-18% of total operational carbon emissions in the UK and Europe (EASAC, 2021; CCC 2020; European Commission, 2020). Retrofit projects have often focussed on social housing because this can help some of the most vulnerable residents and because economies of scale are more feasible than in privately owned housing (Wade and Visscher, 2021). Owner-occupied homes however make up over 60% of UK housing and there are calls for reducing carbon from these buildings to be an area of policy focus (Wade and Visscher, 2021; Piddington et al., 2020).

Retrofit approaches can often neglect to take detailed account of the values, motivations and behaviours of the building residents (Gram-Hanssen, Georg, et al., 2018; Fouseki and Cassar, 2014). These values and behaviours however, can have a significant impact, both on the types of measures that may be enacted, and on the levels of energy reduction that are possible (Fouseki et al., 2020; Sunikka-Blank and Galvin, 2016; Gram-Hanssen, 2013). Greater recognition of a building and its residents as an interconnected system has therefore been identified as important (Wade and Visscher, 2021; Gram-Hanssen, Georg, et al., 2018).

1.2 Buildings with heritage value and retrofit challenges

The existing building stock across Europe includes between 20-40% which could be classed as heritage. Heritage values may relate to a range of tangible and intangible building aspects (CEN, 2017). The preservation of these heritage buildings and their values is generally acknowledged as critical to retaining the character of the built environment (Historic England, 2020; Mazzarella, 2015).

Heritage buildings are often identified as having poor energy performance because they were constructed before the development of energy standards for buildings (Mazzarella, 2015; Broström et al., 2014). There is some evidence to suggest that actual building performance may be better than generally assumed (Pracchi, 2014; Sunikka-Blank and Galvin, 2012) but there is still a critical need to reduce carbon from all buildings, including those with heritage values (Historic England, 2020).

There is a lack of internationally agreed definitions for buildings with heritage values and a variety of terms are used (Webb, 2017), including heritage buildings, historic buildings, built heritage, immovable heritage and cultural heritage (Webb, 2017; Ascione, Cheche, et al., 2015; Iyer-Raniga and Wong, 2012; Tweed and Sutherland, 2007). There is no single definition of the characteristics which determine a ‘heritage building’, except as one with ‘heritage value’ (Webb, 2017; Broström et al., 2014; Fabbri, 2013). Common characteristics however include, age, construction methods and materials, and designation in planning policies (Webb, 2017; Khodeir et al., 2016; Mazzarella, 2015; Fabbri, 2013). In this research the term ‘heritage building’ will be used to refer to buildings with heritage value as this term appears more prevalent in a UK context (Deliotte, 2017).

Taking the most simple definition of heritage buildings, ‘age’, a review of over 200 articles identified two dates which are often considered important thresholds for heritage buildings in Europe, 1919 and 1945, reflecting changing construction practices after the two world wars (Webb, 2017). Around 22% of residential buildings in the European Union were built before 1945 (Nicol et al., 2015), while the UK has some of the oldest buildings stock in Europe with 20% built before 1919 and a further 15% between 1919 and 1945 (Piddington et al., 2020). Older buildings therefore make up a significant percentage of the European and UK building stock (Herrera-Avellanosa et al., 2019).

One reason why heritage buildings may be more challenging to retrofit is that many of them have traditional construction (Curtis, 2010). This includes solid wall and moisture permeable construction of stone, brick, and timber frame which is often referred to in relation to heritage buildings in the literature (Herrera-Avellanosa et al., 2019; May and Griffiths, 2015), and in technical documentation (HM Government, 2021, p. 977). Not all heritage buildings have traditional construction and not all buildings with traditional construction are heritage buildings but there is a common relationship (Curtis, 2010). Around 20% of buildings in the UK are considered to have traditional construction (May and Griffiths, 2015) and this construction means that these buildings can be at risk of maladaption if retrofit is approached in the same manner as modern buildings (Sesana et al., 2019; Glew et al., 2017; May and Griffiths, 2015).

Another term used in this research is ‘vernacular’ buildings. Again, the definition of this term is not exact, but it is generally considered to relate to buildings of traditional construction that use local materials, may have a distinct local or regional style and are unlikely to have been designed by a professional architect (Ghisleni, 2020; Oliver, 2006). Oliver (2006) describes vernacular architecture as ‘indigenous’ and uses the analogy of architecture as a language to suggest that:

> *Vernacular architecture can be said to be ‘the language of the people’ with its ethnic, regional, and local ‘dialects’. (p.16)*

Vernacular architecture is also often associated with more modest residential buildings. The International Vernacular Architecture Group’s website (Vernacular Architecture Group, 2022) states that it is: ‘An international organisation for all those interested in *lesser* traditional buildings’ [emphasis added] (Vernacular Architecture Group, 2022). In the 19th and early 20th centuries the term vernacular had somewhat primitive and colonial connotations (Oliver, 2006). More recently however both the heritage values of, and the potential to learn from, local construction techniques and traditions is increasingly recognised in a positive light (Cardinale et al., 2013; Oliver, 2006).

‘Vernacular’ is often used synonymously with ‘traditional’ when describing buildings, for example by Brunskill who uses the terms fairly interchangeably in his book on ‘The Traditional Buildings of Cumbria’ (2010). The definition of vernacular buildings used in the current research is buildings of a traditional construction, using local materials or styles. This research focusses on vernacular buildings built before 1940 because these are more likely to have heritage value, 1940 is used instead of 1945 as there was limited construction in the UK during WWII. These buildings, as with traditional construction more generally, may, or may not, have heritage value and therefore also be described as heritage buildings.

Planning policies for buildings officially designate some buildings at various levels and these polices can limit the types of retrofit which are allowable (Pickles and McCaig, 2017). In the UK, buildings with specific heritage designation are likely to make up approximately 5-6% of the residential building stock (Li and Densley Tingley, 2021; Historic England, 2015, 2019a), a much smaller proportion than those built before 1945 or with traditional construction. A number of authors have suggested that heritage buildings are only those with official designation (for example, Cabeza et al., 2018; Mazzarella, 2015; Ben and Steemers, 2014). This also seems to be a perception held by some policy makers for example the former UK Housing and Communities Secretary, Robert Jenrick, when speaking to BBC Radio Four’s The World at One in July 2021 suggested that while heritage sensitive retrofit measures were required for the buildings with the highest designation (individual listing) standard retrofit measures and approaches were likely to be suitable for most older buildings (Anon, 2021).

Many authors however have identified that official designation is not required for buildings to have important heritage values, both individually and as part of a wider cultural landscape, which need to be retained in retrofit (Loli and

Bertolin, 2018; Eriksson et al., 2014). Indeed, the need to acknowledge heritage values in undesignated buildings, and the implications that this may have for carbon reduction from these buildings, has been emphasised by some authors, and in European Standard 16883 on the Conservation of Cultural Heritage (Herrera-Avellanosa et al., 2019; CEN, 2017).

The EU's Energy Performance of Buildings Directive (EPBD) (EU Directive, 2010), requires specific energy performance improvements, and the recast in 2018 placed particular emphasis on the retrofit of existing buildings (EU Directive, 2018). However, it allows member states to choose how they apply these energy requirements to officially designated heritage buildings if compliance would harm their historic character. The UK transferred these regulations into UK law following Brexit and Part L1b of the English Building Regulations currently allow officially designated buildings or those with traditional construction to make 'reasonably practical' energy savings which:

> *Should not prejudice the character of the host building or increase the risk of long term deterioration of the building fabric or fittings (HM Government, 2021, p. 977 para. 3.9)*

These regulations however provide no guidance on how the character of the building is to be identified or how to assess these risks, nor on the actions that should be taken for buildings that do meet these criteria.

Meanwhile the EU's Renovation Wave Strategy aspires to double the annual rate of energy retrofit by 2030 and increase the percentage of deep retrofit (European Commission, 2020). The Renovation Wave Strategy identifies 'respect for aesthetics and architectural quality' as a key principle (European Commission, 2020, p. 3), and identifies the need for specific skills to safeguard historical buildings and their heritage values.

As part of the Renovation Wave Strategy revisions to the EPBD are currently being considered. This includes mandating that countries should develop long term renovation strategies to reach net zero by 2050, including interim targets, and the widespread use of minimum energy efficiency standards

(MEES) for buildings (European Commission, 2022). It is unclear if exemptions for designated heritage buildings will still apply or not. There are currently no consistent policies across Europe on how to enact retrofit sensitively for these buildings (Mazzarella, 2015), only recognition that more holistic approaches are required (Herrera-Avellanosa et al., 2019).

The significant percentage of European and UK buildings likely to have heritage value, both designated and undesignated, means that carbon reduction from this segment of the building stock is important (Herrera-Avellanosa et al., 2019). However, their heritage values, and vernacular construction may mean that standard retrofit approaches are not appropriate and these buildings are therefore often considered 'hard to treat' (European Commission, 2020; Mazzarella, 2015). Meaningful carbon reduction requires retrofitting that is compatible with these buildings' values and construction on a much larger scale than is currently realised (Eriksson et al., 2019; Herrera-Avellanosa et al., 2019).

Reducing carbon emissions from the existing built environment is therefore critical in efforts to mitigate climate change. Heritage buildings, like all buildings, require retrofitting at a dramatically increased pace to reduce their energy use and associated emissions. However, achieving this carbon reduction while retaining these buildings' heritage values may present a variety of specific challenges that have not yet been fully addressed. The potential to reduce carbon while retaining heritage is therefore the topic of this research.

1.3 Thesis structure

This thesis will be structured as follows. Chapter Two examines the literature on heritage retrofitting, considering the views, values and behaviours of residents, the technical performance of heritage buildings and its reflection in energy modelling, as well as lifecycle impacts relating to carbon reduction from heritage buildings. Key gaps are identified, framing the priorities for the current research, and developing the research aim and questions. Chapter

Three then sets out the overarching research design and describes the individual methods used to address the research questions, providing details about their role in the research and how the methods complement each other.

Chapters Four, Five and Six outline the results of the research, exploring the experiences of residents within their buildings by examining the heritage values, views - including motivations for retrofit, attitudes to carbon reduction and perceptions of their homes - and behaviours of residents. Chapter Four explores the heritage values that residents of vernacular buildings may invest in their homes and compares these to the values recognised by policy designations. Chapter Five considers the acceptability of different retrofits to residents and identifies the barriers they perceive as important when negotiating retrofit decisions. Chapter Six goes on to investigate the energy behaviours that residents engage with and the perceptions of indoor comfort that influence these behaviours.

The first three of the six analysis chapters therefore develop an understanding of the experiences and roles of building residents. Chapters Seven and Eight, in contrast examine the technical side of the building-resident relationship. Chapter Seven compares the actual measured energy performance of a number of individual vernacular dwellings, comparing these with national averages, and with standard modelling results for these buildings. Chapter Eight moves on to consider the possibilities of retrofit, calculating the operational, embodied and lifecycle carbon saving potential of a range of individual retrofit options for a number of real buildings, using detailed energy simulations and lifecycle assessment.

The final analysis chapter, Chapter Nine, considers both residents and technical building performance together as part of a holistic relationship. It assesses the lifecycle impact of the retrofit measures explored in Chapter Eight when combined into different packages and considers how realistic these packages may be, taking the heritage values, views and behaviours of residents, and the policy landscape, into account.

In the final two chapters the individual results from each of the proceeding chapters are brought together to demonstrate the important of a holistic understanding of the resident-building relationship. Chapter Ten discusses the findings and considers the implications for future retrofitting approaches for vernacular buildings, as well as making recommendations for policy and practice. Finally, in the concluding chapter, the research questions are addressed and reflected on, and limitations to this study and future research needs are considered. Ethical information, methodological details, and links to underlying data are included in the appendices.

Chapter 2. Literature and context

2.1 Introduction

This chapter examines the literature surrounding the reduction of energy and carbon from buildings with heritage values and identifies a range of challenges, opportunities, and research gaps. It begins by considering the types of values that are identified in these buildings and the implications of these values for retrofitting. A number of barriers that residents can experience in retrofitting heritage and vernacular buildings are identified. The role of residents' energy behaviours within buildings, and heritage and vernacular buildings in particular, are then examined and the importance of residents' perceptions of comfort in their buildings are interrogated. Research on the actual performance of heritage buildings is investigated and some of the challenges with energy simulations of these buildings are identified. Finally, lifecycle carbon and its calculation is introduced and its effects on retrofitting considered. Identified research gaps are then summarised and a research aim, and specific research questions, are developed to address these gaps.

2.2 Heritage values and retrofitting

The characteristics of heritage buildings are defined in various ways by different authors (Webb, 2017; May and Griffiths, 2015; Mazzarella, 2015). Irrespective of age, construction type or statutory protection however, heritage buildings are generally agreed to be those that have 'heritage value' and a variety of values are recognised by the international community (Herrera-Avellanosa et al., 2019; Lidelöw et al., 2019; Webb, 2017).

The Burra Charter states that heritage value or cultural significance means:

> *Aesthetic, historic, scientific, social, or spiritual value for past, present or future generations… places may have a range of values for different individuals or groups. (Australia ICOMOS, 2013, p2).*

The Burra Charter is an important international standard for the management of cultural heritage, developed by the Australian International Council on Monuments and Sites (ICOMOS) (Webb, 2017; Fouseki and Cassar, 2014; Australia ICOMOS, 2013; Fabbri, 2013; Mason, 2006). This charter expands and builds on the Venice Charter of 1964, which was a major undertaking to create an international framework for the conservation and restoration of historic monuments and sites (ICOMOS, 1964).

The European standard EN 16883 identifies a similar range of heritage values to the Burra Charter, stating that these values can encompass different aspects which include: 'architectural, artistic, economic, social, symbolic, technological and material' (CEN, 2017, p. 5). The Welsh historic environment service, Cadw, also identify that values can relate to: material elements such as architecture or construction; the ability to provide historical knowledge both specific to the individual building and more broadly; and to the social, cultural and economic values that are provided for communities (Cadw, 2011). The values of any building will be specific to that building and may include one or many of this wide range of tangible and intangible values (Herrera-Avellanosa et al., 2019; Khodeir et al., 2016; Mazzarella, 2015).

Tangible values could include specific features such as windows which are often identified as being valued by residents for more than just their functionality (Gerhardsson and Laike, 2021). Windows are widely considered to have significant heritage values both as a substantially visible feature of a building's façade and because of their historic manufacturing techniques (Litti et al., 2018; Bakonyi and Dobszay, 2016; Sedovic and Gotthelf, 2005). The visual appearance of original single glazing can be very different to that of modern glass, creating different reflections as a result of its traditional manufacture (Smith, 2014). The replacement of original windows is therefore often prohibited by planning regulations in designated buildings (Curtis, 2010). Residents of older buildings, as well as conservation experts (Ginks and Painter, 2017), have been shown to value original windows both for their character and their craftsmanship (Mallaband et al., 2013).

Intangible values meanwhile include aspects such as the ‘sense of place’ of the building in its wider cultural and natural landscape. Place based values are part of what are termed cultural ecosystem services (CES), although these have been under researched compared to physical ecosystem services (Schaich et al., 2010). CES and placed based values have been identified as multidimensional and relating to a range of varied qualities on different scales, from individual features to broader landscapes (Soini et al., 2012; Schaich et al., 2010). There is limited empirical research into the values that residents themselves invest in their buildings, or on the role of the built environment in the literature on place based values. A connection to local landscapes and traditions has however been identified as important to residents, particularly in protected areas such as national parks or similar (Vlami et al., 2020; Bieling, 2014). These connections in some cases are an important part of residents’ identity (Olwig, 2018; Bieling, 2014) and are also often associated with an increased sense of responsibility and stewardship (Fouseki et al., 2020; Schaich et al., 2010; Davenport and Anderson, 2005). Another example of intangible values includes a sense of connection to previous residents, which can either be linked to specific features or be related to a more general ‘sense of history’ (Lipman and Nash, 2019). Intangible values can also relate to customs, practices and skills, which are likely to have an impact on energy use as well as heritage value (Pili, 2017).

For designated heritage buildings with officially recognised values, planning policies may limit the types of alterations that are allowable for different designation levels. Designations include individual and area designations. In England, Listed Buildings are those included in the National Heritage List (Pickles and McCaig, 2017). Buildings can be Listed as Grade I, Grade II* or Grade II, with Grade I, the highest category of recognised value, only including 2% of all listed buildings (Historic England, 2019a). Historic England, Historic Environment Scotland and Cadw (Wales) have a statutory consultative role in their respective countries for projects where changes to Listed Buildings are considered, and are also involved in compiling listings (Historic England, 2019b). Conservation areas are Local Authority designations that cover a number of buildings or a particular area (Pickles and McCaig, 2017). It is estimated that 1-2% of UK buildings are listed (Historic England, 2019a; Historic Environment Scotland, 2019; Cadw, 2018), while there are around 10,000 conservation areas in England covering multiple buildings and potentially up to 4% of UK homes (Li and Densley Tingley, 2021; Historic England, 2015). In addition to the above designations, buildings within National Parks and buildings with traditional construction also have a level of planning protection. In the first instance this primarily relates to their contribution to the overall character of the area and in the second to their construction techniques (Pickles and McCaig, 2017).

Listed buildings require specific consent for all exterior and many interior alterations, while in some conservation areas, ‘area design guides’ are provided and certain external changes may be excluded from normal ‘permitted development’ rights and require permission (Pickles and McCaig, 2017). It is still possible to make alterations to designated buildings but additional justifications, efforts, and compromises may be required and decisions can be contentious (Friedman, 2015). The replacement of original sash windows with triple glazed replicas and the addition of solar panels to a Grade I listed building belonging to Trinity College, Cambridge, for example, required intervention by the Secretary of State because of fierce opposition from Historic England (Smith, 2014). Part of the argument successfully made by the college was that through their retrofit they were enabling preservation of the authenticity of the building’s continued use as accommodation, which they felt balanced the alterations to the external appearance (Smith, 2014). In this instance the intangible values of the college overruled the tangible values identified by Historic England.

This also highlights another important point, identified in the Burra Charter, that different individuals or groups may have a range of different values for the same places or buildings. Tweed and Sutherland (2007) for example, identified that the values that communities invested in their built heritage differed from those recognised in policy in their examination of sustainable urban development in five European cities. They also suggest that heritage designations are often imposed in a top down manner, meaning that buildings, features, and areas that are of value to communities may not be recognised (Tweed and Sutherland, 2007). This is also identified by Smith (2006) who further argues that definitions of heritage are often expert led and can face accusations of elitism.

A study of the UNESCO World Heritage City of Visby (Sweden), found that residents' values broadly did agreed with the city's official heritage characterisation document, which identifies the importance of retaining original windows, doors and roofs (Eriksson, 2018). When asked about their own homes as opposed to photos of archetype buildings however, residents were more likely to identify intangible values around the building in its context, instead of specific features. This emphasis on intangible values was also seen in a study of the users of a heritage building at Durham University which found that users valued its sense of history, despite very limited knowledge of the building's past (Adams et al., 2014).

There is only limited evidence for the values that residents invest in their buildings and some of these values appear to vary from the values identified in policy (Fouseki et al., 2020; Fouseki and Cassar, 2014). Understanding these values is important, not only to understand residents' values for their buildings, but also because these values may affect the retrofits that they will undertake, with implications for carbon reduction. Interviews with residents in undesignated heritage buildings in Cambridge who had undertaken retrofit illustrates this point (Sunikka-Blank and Galvin, 2016). This study showed that residents' heritage values had a strong effect on their retrofit decisions. Values mostly related to a desire to retain aesthetic character but also included authenticity of construction details, with one resident refusing to utilise a building style common in the local countryside but not seen in urban Cambridge. The authors emphasised the small scale and specific context of their study and highlighted the need for further research exploring the effect of residents' heritage values on retrofit decisions (Sunikka-Blank and Galvin, 2016). A study conducting research in three countries made similar findings and also called for more in depth research on this topic (Fouseki et al., 2020).

Numerous studies of energy reduction in all residential buildings have highlighted the fact residents do not make decisions based on cost benefit analyses, and instead negotiate decisions based on their values, motivations and ability to navigate a range of constraints and barriers (Hrovatin and Zorić, 2018; Shove, 2018; Wilson et al., 2015; Haines and Mitchell, 2014). For residents of heritage buildings in particular, the values that they invest in their homes are another factor that they must negotiate when trying to identify appropriate retrofits.

Retrofits in owner-occupied buildings are generally instigated, managed, and often largely funded, by residents, and if a measure is not acceptable to them they will not enact it (Fouseki et al., 2020; Nicol et al., 2015; Haines and Mitchell, 2014; Mallaband et al., 2013). Residents' heritage values are therefore particularly important in a UK context where 63% of dwellings are owner-occupied (Piddington et al., 2020). A greater understanding of these values is therefore critical to identifying acceptable retrofit measures and increasing the incidence of retrofit for carbon reduction.

Residents' heritage values however often appear to be neglected in policy and research, something which has been identified as due to limited consultation and a preference for expert-led solutions (Fouseki et al., 2020; Mısırlısoy and Günçe, 2016; Fouseki and Cassar, 2014; Smith, 2006). In their review of the heritage retrofit literature, Lidelöw et al (2019) identified a lack of consideration of the heritage values of specific buildings, with studies often relying on generalisations. Residents' values meanwhile are acknowledged to be unique and context specific (Herrera-Avellanosa et al., 2019) and recommending standard retrofit measures is therefore likely to be unacceptable to some residents. There is a tendency in the literature to give only limited space for considerations of heritage (for example Ascione, Cheche, et al., 2015), to take planning restrictions as the sole arbiter of value (as in Harrestrup and Svendsen, 2015), or to assume that the building façade is the only element of importance (Zagorskas et al., 2014).

The heritage retrofit literature includes a significant number of technical feasibility studies, where seeking the views of residents is beyond their scope López and Frontini, 2014). However even in empirical heritage retrofit studies there is only limited engagement with the views and values of residents (Ben and Steemers, 2014). There can be a tendency for these types of studies to present heritage values as barriers to standard retrofit approaches (Tokede et al., 2017; Magrini and Franco, 2016) and many authors highlight the challenge of balancing heritage values, and their attendant constraints on acceptable changes, with effective retrofitting (Broström et al., 2014; Cassar, 2009).

Meanwhile a number of studies have attempted to quantify heritage values in order to help weigh them against quantitative environmental and economic considerations. A Swedish project developed a model to aid decision making which characterised building stocks and set environmental, economic and heritage conservation targets (Broström et al., 2014). Economic and technical optimisation was used to narrow the list of measures, which were then weighted against their heritage impact. This was quantified using the same five-level scale as the economic and environmental criteria. The authors felt that this model had the potential to improve the transparency of decision making but identified challenges with quantifying subjective heritage values, especially in undesignated buildings. The heritage values used in the study were also determined by experts without reference to the values of residents.

A similar quantification tool, designed to aid decision making, was created as part of the EU's EFFESUS (Energy Efficiency for EU Historic Districts Sustainability) project (Eriksson et al., 2014). The authors identified challenges such as time intensive data entry, but conversely, a lack of sufficient detail for individual buildings because of the design for district level decisions, and the model has not be made publicly available (Rodriguez-Maribona and Grün, 2016). Meanwhile attempts to quantify heritage, and other subjective values, for use in an Italian adaptive re-use case study, were stymied by a lack of consensus amongst the multidisciplinary expert panel, who each privileged the importance of their own specialism (Ferretti et al., 2014).

It therefore appears that attempts to quantify subjective and specific heritage values to enable their comparison with other parameters present challenges in practice. The quantification of heritage values may also encourage a sense that they are interchangeable with other values, which may be particularly problematic when economic issues are considered (Mason, 2008). Heritage buildings can have significant economic benefits (Deliotte, 2017), especially through heritage tourism, and some authors have argued that putting a monetary figure on heritage values can encourage their preservation (Ferretti et al., 2014; Bullen and Love, 2011). An overemphasis on economic value however could lead to negative effects on heritage values, as seen in a study on the adaptive-reuse of heritage buildings in Hong Kong, which advocated the relaxation of heritage planning protections to make these buildings more attractive to investors and developers (Yung and Chan, 2012).

The Burra Charter deliberately excluded economic benefits in order to avoid a dilution of the importance of heritage preservation as a good in, and of, itself (Mason, 2006). Heritage values can be described as a non-renewable resource which should be maintained for future generations (Vakhitova, 2015; Fabbri, 2013). Therefore, although economic considerations may be beneficial, and perhaps necessary for heritage retrofit projects, they must also be approached with caution (Mason, 2008).

In summary the possession of heritage value is the primary defining feature for heritage buildings. These values may encompass a range of both tangible and intangible aspects of both the building and its surroundings. Moreover, these values will be individual and context specific for particular buildings and areas. The heritage values that residents invest in their buildings appear to differ somewhat from those identified in policy. Residents' values however are often neglected in heritage retrofit studies which tend to use generalisations, planning designations or expert determined quantifications of value to identify appropriate measures. There are additional challenges with the quantification and potential trade-offs of heritage value against other benefits, in particular economic considerations. Some authors suggest that heritage values should be viewed as a non-renewable resource, and therefore by implication one which cannot be traded for any other consideration. Residents' values are also likely to affect the retrofit measures that they would find acceptable and therefore enact. A greater understanding of the heritage values of residents, and the influence of these values in determining the acceptability of retrofit measures, is therefore required.

2.3 Barriers to retrofit

There are a number of acknowledged barriers to retrofit for residential buildings more generally. Residents must negotiate a range of complex, and sometimes competing, factors when making retrofit decisions. These generic barriers include financial, and particularly capital, costs (Albrecht and Hamels, 2021), a lack of skills within the construction industry (EASAC, 2021; Simpson et al., 2021), access to information on retrofit (Gram-Hanssen, Jensen, et al., 2018), and time commitment and level of disruption (Fawcett and Topouzi, 2020). These and other barriers also apply to heritage buildings and are often exacerbated by their traditional construction and the need to retain their values.

Access to appropriate information is commonly identified as a key barrier for all homes, with an emphasis on the need for knowledge to come from trusted sources and be relevant to residents' individual contexts (Gram-Hanssen, Jensen, et al., 2018; Maby and Owen, 2015). However there is a particular need in heritage buildings for accurate, detailed, and individually context specific information which comes from trusted sources (Herrera-Avellanosa et al., 2019). Residents' values are likely to influence their retrofit decisions, meaning that they may not find standard retrofit measures acceptable. Indeed, residents have been found to actively engage in modifying measures to their specific contexts and values, rather than being passive recipients of standard solutions (Galvin and Sunikka-Blank, 2014). Independent and context specific advice on more heritage sensitive options is therefore seen as a key requirement for effective heritage retrofitting, with informational barriers identified as more problematic than a lack of technical solutions (Herrera-Avellanosa et al., 2019).

More generally several studies have found that residents may often participate in ‘knowledge networks’, where they seek advice on retrofitting from friends, family, and colleagues, also identifying that these unofficial information sources can significantly affect decision making (Bartiaux et al., 2014). Advice from personal contacts has also been seen to increase retrofit adoption rates (Hrovatin and Zorić, 2018; Galvin and Sunikka-Blank, 2014). This emphasises that residents are part of a social network, rather than isolated actors, and that retrofit decisions are much more complex than simple cost benefit analyses (Bartiaux et al., 2014).

Cost is considered a key issue for all retrofits, and the need for financial incentives and support for retrofit is often identified (Bartiaux et al., 2014). Access to sufficient capital investment for retrofit is seen as a particular challenge (Albrecht and Hamels, 2021; Hrovatin and Zorić, 2018). A range of policy instruments have focussed on reducing the initial financial burden on residents, such as low interest government backed loans, support packages for low income or fuel poor households, and grant support for particular measures, such as the UK government’s recently announced boiler upgrade scheme (BEIS, 2021a; Giraudet et al., 2021). The French government offer reduced rates of taxation such as VAT on retrofit (Giraudet et al., 2021), while the Italian Government are currently running a scheme offering 110% returns on the cost of retrofit measures through tax relief over five years for costs of up to €100,000 (Mates, 2021). A study from Belgium identified that the use of loans may not be suitable for over 50% of households however, as they already have significant financial commitments and limited disposable monthly income so cannot take on more financial commitments, even at low or zero rates of interest (Albrecht and Hamels, 2021).

The use of on-bill measures is also being considered as a method of mobilising capital for retrofit in the EU. This is where retrofits are installed at no up-front cost, residents continue paying the same amount on their energy bills and the resulting overpayment -because less energy is actually used post retrofit- is used to pay back the capital cost of the measures (RenOnBill, 2021). This method is used for example with EnergieSprong, which is a rapid, whole house retrofit program, first developed in the Netherlands but now operating internationally (Energie Sprong UK, 2022). Importantly EnergieSprong guarantees a certain level of actual, rather than only predicted operational savings over a thirty-year lifespan (Fawcett and Topouzi, 2019, 2020). These types of schemes require regulatory changes to enable payment to utility companies for ‘energy services’ rather than specifically ‘energy’, and a range of changes to financial mechanisms (RenOnBill, 2021; Fawcett and Topouzi, 2019).

Cost and mechanisms for providing financial support are therefore important issues for retrofit and an area of policy focus for both the European Union and many individual countries (European Consumer Organisation (BEUC), 2021; European Commission, 2020). The need to leverage private capital is also identified as a key issue (European Commission: Directorate General for Education, Youth, Sport and Culture, 2021). For heritage buildings cost is often even more of a barrier that in more modern properties, because traditional materials and more sensitive retrofit options such as secondary glazing can often be more expensive than more mainstream measures (Herrera-Avellanosa et al., 2019).

Cost as a barrier to retrofit however has received the most attention from policy makers while other social aspects, which have been highlighted as just as important, are often neglected in policy responses (Albrecht and Hamels, 2021; EASAC, 2021; Rosenow and Eyre, 2016; Mallaband et al., 2013). Palmer et al (2021) have identified that in the UK successive governments’ have assumed that if retrofit is financially attractive it will drive take-up despite this consistently being shown to not be the case due to other barriers which are not addressed. This is especially true for buildings with traditional construction, for example retrofit levels for solid wall insulation have been consistently lower than predicted in successive UK carbon budgets despite ambitions being scaled back in each (Gillich et al., 2019). This gap suggests that other barriers are present, such as measures being incompatible with residents' heritage values.

Skill gaps associated with retrofit, and a lack of industry knowledge and qualifications relating to energy retrofit in general, are identified as a challenge across the UK, and indeed European, construction industries (EASAC, 2021; Palmer et al., 2021; Simpson et al., 2021; Clarke et al., 2016). However for heritage buildings the need for knowledgeable, experienced and skilled tradespeople is particularly acute because of the locally contextualised challenges that their often traditional construction presents (Gram-Hanssen, Jensen, et al., 2018; Galvin and Sunikka-Blank, 2014). Interviews with residents in solid walled buildings about previous retrofits identified challenges with finding reliable tradespeople, as well as issues with the quality of work and its compatibility with traditional construction (Mallaband et al., 2013). Residents also expressed frustration that tradespeople often failed to share the knowledge or appreciation of historic building features that residents had in their buildings. Residents identified that these poor experiences would make them less inclined to undertake further retrofit because of the perceived risks.

The development of the UK PAS:2035 standard for domestic retrofitting aims to provide a framework for encouraging quality retrofit processes. This includes requirements for work on buildings with traditional construction to take account of their performance, and to include specialist assessments of moisture management (BSI 2020). There are however concerns about the lack of tradespeople with appropriate expertise to implement this standard with regard to buildings with traditional construction (Edwards, 2020). PAS2035 also emphasises the need for a whole house retrofit approach which considers both the building and its residents, something which many authors have highlighted is needed (Magrini and Franco, 2016; Mısırlısoy and Günçe, 2016; de Santoli, 2015).

The time and disruption caused by retrofit are additional barriers (Fawcett and Topouzi, 2020). Time challenges can include both the time that the retrofit installation takes but also the time capacity that residents feel that they need to invest in identifying appropriate measures and tradespeople and making retrofit decisions. This second capacity issue can be exacerbated for heritage buildings because of the challenges already identified around finding information and tradespeople appropriate to heritage homes (Mallaband et al., 2013).

Finally, the application of planning policy to designated heritage buildings has also been identified as an important and heritage specific barrier (Pendlebury et al., 2014; Stuart, 2014). Several studies have identified inconsistency in planning decisions across the UK, between, and in some cases even within, different planning authorities (Stuart, 2014; Friedman and Cooke, 2012). Attitudes towards the acceptability of slimline double glazing in listed buildings were, for example, found to vary amongst conservation officers in different regions of the UK (Ginks and Painter, 2017). A PhD on planning constraints confirmed a lack of consistency and reliability in planning decisions (Friedman, 2015). This was attributed to a lack of national policy and the dispersed and discretionary nature of decision making, although this may also have benefits in terms of allowing more consideration of local circumstances (Ministry of Housing Communities and Local Government, 2019).

While key generic barriers to retrofit have been identified in the literature as cost, information, disruption, time and quality, these same barriers are often exacerbated for the residents of heritage buildings, although residents' perceptions of these barriers have received surprisingly little research attention (Rosenow and Eyre, 2016; Fouseki and Cassar, 2014; Mallaband et al., 2013). For residents of heritage buildings the role of information is highlighted as even more critical, along with identifying specifically skilled tradespeople, planning inconsistencies and being able to identify measures acceptable to their heritage values (Herrera-Avellanosa et al., 2019). More understanding of the specific barriers that residents in heritage buildings must negotiate during retrofitting is therefore needed.

2.4 Energy behaviours

Residents' 'energy behaviours' are actions, activities and habits that affect energy usage within buildings, such as heating temperatures and patterns, window opening/closing, lighting behaviours, clothing levels and occupancy patterns (Cassar, 2009). Energy behaviours are recognised as critical factors in the energy demand from buildings and in particular from heritage buildings (Berg et al., 2017; Fouseki and Cassar, 2014). In one UK heritage study with the same technical conditions across homes, energy behaviours were found to affect the energy savings of retrofit measures by 62–86% (Ben and Steemers, 2014). Behaviours were also shown to cause significant variation in energy demand in a study of a Danish heritage apartment block (Harrestrup and Svendsen, 2015).

The energy behaviours that residents engage in can sometimes differ in heritage buildings as opposed to more modern buildings (Henry, 2007). Residents of heritage buildings in rural Sardinia for example, had different seasonal use patterns for various areas of the house, depending on temperature changes (Pili, 2017). In rural multi-family heritage buildings in China meanwhile, reduced hot water and television use was identified, compared with modern buildings (Li et al., 2012). This was considered to be partly because of increased communal engagement through the use of courtyard spaces for cooking and socialising. Some of these behaviours are, of course, quite different from common lifestyles in the UK, but highlight potential behavioural variations and intangible heritage values around customs and behaviours.

The behaviours of heritage residents can sometimes utilise inherent low energy aspects of heritage buildings, such as high thermal mass, active and passive ventilation strategies and traditional shading/thermal features for windows (Pender and Lemieux, 2020; Curtis, 2010; Henry, 2007). Non-permanent fittings can improve occupant comfort and reduce heat loss, thereby reducing energy and carbon (Khan, 2018; Humphreys et al., 2011; Curtis, 2010). The use of spot heating can reduce the need to heat the whole building (Pan et al., 2018; Aste et al., 2016), by emphasising the goal of keeping people, rather than buildings, warm (Humphreys et al., 2011).

In residential buildings more widely, studies have shown that residents often negotiate creative and informal comfort practices, specific to their own circumstances and context, although these are frequently given little attention by policymakers (Hansen et al., 2018; Hampton, 2017). This could include utilising different spaces at different times or making use of personal insulation or personal heating systems. These types of behaviour are often particularly found in buildings which are considered to be less energy efficient. This is often attributed to residents being unable to pay for a comfortable level of heating and therefore suffering from fuel poverty (Sunikka-Blank and Galvin, 2012). However these practices have been found, in some cases, to be positive choices, related to a sense of sufficiency and frugality (Galvin and Sunikka-Blank, 2016; Royston, 2014), especially in older buildings (Hansen et al., 2018; Madsen, 2018).

Behavioural alterations can have a greater impact on energy and carbon reduction than physical retrofits, are less likely to negatively affect heritage values and have a much lower financial cost (Berg et al., 2017; Harrestrup and Svendsen, 2015; Gram-Hanssen, 2013, 2014). Understanding residents' behaviour is therefore critical in attempts to reduce carbon from heritage buildings (Berg et al., 2017; Fouseki and Cassar, 2014). Despite their importance, behaviours are often considered to be outside the scope of energy retrofit projects, which tend to focus on material changes (Abdul Hamid et al., 2020; Rospi et al., 2017; Ascione, Cheche, et al., 2015; Akande et al., 2014). A 2018 literature review highlighted the importance of behaviours in all residential buildings and found that many behavioural studies focus on functional aspects of behaviour, such as window opening, heating, and air conditioning, with behavioural patterns around lighting, blinds and curtains, clothing levels and occupant locations in a space seldom examined (Sadat Korsavi et al., 2018)

Instead some authors have framed residents' behaviours as a barrier to carbon reduction, suggesting that residents can engage in 'wrong' habits or behaviours, which fail to match standard behavioural assumptions and are therefore considered to increase energy use (Abdul Hamid et al., 2020; Ascione et al., 2020; Pigliautile et al., 2020). However, evidence suggests that in older buildings residents' actual behaviours are more likely to result in lower energy demand than standard assumptions because of their individual heating practices (Kane et al., 2015; Sunikka-Blank and Galvin, 2012). The need to consider residents' specific requirements is also important, for example older users or those with health conditions might require higher temperatures, and those who work from home might need longer heating hours (Cosar-Jorda et al., 2019).

Behaviours are complex, and predicting their influence on energy demand is acknowledged to be challenging (Webb, 2017). However The International Energy Agency (IEA) recently emphasised that required levels of global carbon reduction will not be possible without individual behavioural change across a broad range of activities (IEA, 2021). Understanding residents' behaviours is therefore critically important. These behaviours, and residents' interactions with their buildings and systems, are however rarely engaged with in energy policies for buildings (Gram-Hanssen, Georg, et al., 2018; Gram-Hanssen, 2014; Kohler and Hassler, 2012).

In summary, residents' energy behaviours generally are acknowledged as critical for determining building energy demand and have greater potential for carbon reduction than many technical measures. Residents in all homes have been found to engage in individual behavioural and comfort practices and there is some evidence to suggest that heritage building residents may be more likely to engage in specific practices and behaviours. Despite their importance however, energy behaviours are often considered outside the scope of retrofit projects and rarely included in retrofit policy. There has been little research investigating specific behaviours in heritage buildings and there is clearly a need for more research in this area to better inform policy and practice.

2.5 Comfort perceptions

Heritage buildings are often considered to be energy inefficient and uncomfortable to live in (Cabeza et al., 2018; Broström et al., 2014). In this context improving comfort is often identified as a key motivator for residents' renovation decisions (Herrera-Avellanosa et al., 2019). Comfort perceptions are also important drivers of energy behaviours, particularly in relation to heating practices, which are the main source of energy and carbon emissions from residential buildings in northern Europe (Berg et al., 2017).

An understanding of residents' comfort perceptions is therefore important as a driver for energy behaviours, and potentially, for retrofit. In the UK however, the perceptions of residents have received little research attention to either support or reject the view that heritage buildings provide poor comfort satisfaction (Balvedi et al., 2018). One survey of UK residents did show that fewer residents of pre-1945 homes were satisfied with their thermal comfort in winter (72%) than those of post-2000 homes (95%) (Bateson, 2018). However, in summer the opposite was true, with 89% of pre-1945 residents satisfied, compared with only 76% in post-2000 homes. This perhaps reflects the growing problem of summer overheating in modern buildings in the UK, which seems likely to lead to increased energy use for cooling systems (Ozarisoy and Elsharkawy, 2019; Adekunle and Nikolopoulou, 2018; Jones et al., 2016).

In other countries, several studies have suggested that residents of heritage or vernacular buildings may in fact perceive them to perform as well as, and in some cases better than, more modern homes (Martínez-Molina et al., 2016). A study in a warm and humid region of China compared the indoor environmental perceptions of residents of 'Tulou' rammed earth heritage buildings with those of modern rural buildings (Li et al., 2013). This found that the heritage building residents had higher perceptions of comfort than the modern building residents across a range of indicators. Similarly, a comparative study of naturally ventilated heritage buildings and modern, air conditioned buildings in Libya, also identified higher satisfaction with thermal comfort in the heritage buildings (Ealiwa et al., 2001), and a study of heritage buildings compared with modern buildings in India also identified better perceptions over three different seasons in the heritage buildings (Dili et al., 2010). These perceptions of comfort are likely to affect both residents' energy behaviours, and the retrofit options that they might consider (Martínez-Molina et al., 2016). All of these studies were carried out in relatively hot climates, so might equate better to UK summers. Winter comfort in residential heritage buildings in cooler climates has received little in-depth research attention which examines residents' individual comfort perceptions.

Literature reviews on thermal comfort in heritage buildings (Martínez-Molina et al., 2016), and in buildings more generally (Rupp et al., 2015) have also identified that naturally ventilated buildings are perceived to perform better than mechanically ventilated buildings. Recent studies have highlighted the importance of occupants being able to control their environment, and suggest that if they have greater control they are likely to accept greater thermal variations (Altomonte et al., 2020; Ortiz et al., 2020). Other reviews have evidenced the need for the improved design of building systems and management (Bordass, 2020; Brager et al., 2015). Meanwhile identifying that much of the research on comfort has focussed on commercial buildings (Day et al., 2020; Brager et al., 2015). Day et al highlight that building standards may not be conducive to individual comfort:

> *Ultimately buildings are designed and built for people. However, building systems are engineered to meet codes, standards and guidelines, which does not necessarily correlate to occupant satisfaction or comfort (Day et al., 2020, p. 11).*

In particular, standards tend to be designed for 'average users' however as Altomonte et al identify, very few users are in fact 'average' (2020).

The importance of evaluating comfort perceptions pre- and post-retrofit have also been identified (Bordass, 2020). Most comfort evaluations relating to retrofit have been carried out for low-income households in the context of externally funded schemes (Fisk et al., 2020). This focus on low-income households, who are more likely to be suffering from fuel poverty and/or occupying poor quality housing (Broderick et al., 2017; Teli et al., 2016; Hong et al., 2009), may be one of the reasons that comfort is often identified as a key driver for retrofit. There has been less research into the comfort perceptions of higher income households.

Understanding residents' perceptions of comfort before retrofit is particularly important because of the rebound effect, where predicted energy savings from retrofit do not materialise because of user behaviour (Sorrell et al., 2018; Webb, 2017; Galvin, 2015). Improving comfort by increasing heating temperature set points is a common direct rebound effect associated with energy retrofits in all buildings (Sorrell et al., 2018). Studies of direct rebound effects for retrofitting in the UK have found rebounds of up to 36% (Chitnis *et al.* 2014; Galvin 2014; Sorrell *et al.* 2009). These figures tend to be higher amongst those unsatisfied with their original comfort levels, which may be related to fuel poverty (Sorrell *et al.* 2009). Where residents are satisfied with comfort levels before retrofit, rebound effects may be significantly lower (Aydin *et al.* 2017; Giraudet *et al.* 2021).

Perceptions of indoor environmental quality (IEQ) are generally examined across a range of categories, including temperature, ventilation, air quality, moisture, light and noise levels (Ortiz et al., 2020; Li et al., 2013), although temperature and ventilation are the most commonly studied (Martínez-Molina et al., 2016; Brager et al., 2015). As noted by a Malaysian study, people have different thermal comfort ranges (Omar and Syed-Fadzil, 2011). This can also depend on how much they adapt their behaviour to different temperatures, such as wearing jumper and slippers in colder conditions, indeed, studies have shown that personal insulation is one of the most effective ways to improve thermal comfort (Shove, 2018). Insulation of extremities such as the use of slippers or gloves has been found to have a disproportionately large effect on experiences of thermal comfort (Yang et al., 2018; Humphreys et al., 2011). Tentative findings suggest that the use of more clothing layers in winter may be linked to the age of buildings and be more likely in households with higher education levels (Hansen et al., 2018).

The identification of thermal comfort conditions varying between people, is a key part of the concept of adaptive thermal comfort, first developed by Nicol and Humphreys (Nicol et al., 2020; Nicol and Humphreys, 1973), where people use adaptive opportunities such as window opening, changing location or altering levels of personal insulation to maintain comfort. People also acclimatise to different conditions after a certain period and indoor comfort perceptions are also linked to external conditions (Nicol et al., 2020). Adaptive comfort strategies also highlight the positive psychological effect of user control on comfort perceptions and emphasise that people can be comfortable at a wide range of temperatures.

This concept has been contrasted with many of the steady state and narrow temperature band models that have been used to inform building designs and standards (Altomonte et al., 2020; Hellwig et al., 2019). Adaptive comfort principles have however been used in European Standard EN16798, when considering buildings that are in free running mode (not mechanically heated or cooled) (BSI, 2019; Hellwig et al., 2019). Other authors have highlighted evidence suggesting that adaptive comfort models should be extended at least to mixed mode buildings, and potentially to mechanically conditioned buildings as well (Parkinson et al., 2020; Carlucci et al., 2018). Altomonte et al (2020) have also found that standards tend to aim for thermal neutrality and steady states, whereas levels of increase thermal variation have been shown to improve comfort perceptions and potentially also have health and wellbeing benefits (Hellwig et al., 2019; Brager et al., 2015).

Adaptive comfort strategies are likely to have clear applicability to heritage buildings. Indeed Humphreys et al produced guidance for Historic Scotland examining some of the opportunities of utilising traditional features of heritage buildings and focussing on spot heating and personal heating systems rather than heating whole spaces to high levels (2011). There is increasing interest in the use of personal conditioning systems (PCS), including individual heating, chair heating, wearable solutions and smart textiles (André et al., 2020; Pan et al., 2018). Many of these utilise new or emerging technologies, such as thermoelectric fans for stoves to help distribute warm air around spaces.

There are also benefits from traditional and passive means of maintaining thermal comfort (Pender and Lemieux, 2020; Khan, 2018). These include making use of, or reinstating, traditional features such as interior shutters or blinds for both winter and summer comfort (Curtis, 2010; Henry, 2007), with studies suggesting that some window additions can reduce heat loss from original windows to a level comparable with replacement with double glazing (Litti et al., 2018; Curtis, 2010; Wood et al., 2009). Other features such as timber panelling or cloth wall hangings meanwhile may have the potential to reduce heat loss from occupants to cold wall surfaces and therefore increase comfort (Khan, 2018; Baker, 2011). Meanwhile individual or localised heating sources and the use of different spaces at different times and seasons can be effective ways of increasing residents' comfort perceptions in their buildings and have many historic antecedents (Hawkes and Lawrence, 2021; Pender and Lemieux, 2020). A study of heritage sensitive carbon reduction for Hexham Abbey recommended offering visitors warm robes to wear to reduce the need for heating (Pendlebury et al., 2014). These were inspired by monks' robes and were part of a suite of measures for carbon reduction, alongside sensitively sited solar panels. This particular traditional solution may not be suitable or acceptable for everyone but there may be opportunities for some traditional measures to play a useful role in carbon reduction and comfort improvement.

The potential of these types of measures to improve comfort, and therefore potentially reduce carbon through reduced heating demand, may be significant (Pender and Lemieux, 2020; Khan, 2018; Henry, 2007), and could link in well with the informal heating and comfort practices that some studies have shown residents already engage in. However there is little research on these types of measures and they are rarely considered in retrofit projects (Pender and Lemieux, 2020), partly because they may be challenging to model using standard tools (Pender, 2021).

Residents' comfort perceptions are therefore a key driver of energy behaviours and considered an important motivator for retrofit. Heritage buildings are often considered to provide poor comfort; however studies from a range of countries suggest that they may actually be perceived to perform as well as, and in some cases, better than, more modern buildings by their residents, especially in warm climates. It is probable that residents of heritage buildings have perceptions and behaviours consistent with adaptive thermal comfort strategies. There is limited evidence suggesting traditional building features can have comfort benefits as part of both personal and building level comfort systems. What is still missing is an understanding of the perceptions of comfort of heritage residents in the UK and an understanding of how these perceptions might be affected by their heritage values.

2.6 Actual building performance

Heritage buildings are generally considered to be energy inefficient, as previously mentioned (Pracchi, 2014). This is principally due to the perception of very poor thermal envelopes compared with modern buildings, and this can often be used as a justification for retrofit (Cabeza et al., 2018; Rospi et al., 2017; Rasmussen et al., 2015; Broström et al., 2014).

However there is a growing body of evidence to suggest that some heritage buildings have better performance than is often assumed (Pender and Lemieux, 2020; Pracchi, 2014). A range of authors have identified that the high thermal mass of heritage buildings, their natural ventilation, and their design and layout for local microclimates are all reasons why they can perform better than predicted (Hawkes and Lawrence, 2021; Gigliarelli et al., 2016; Rye, 2015; Gagliano et al., 2014). Heritage buildings may have inherently low energy features, partly because many of them were designed when energy was much more expensive and harder to access than in more recent times (Cantin et al., 2010; Curtis, 2010). The use of traditional shading, strategic window opening, and the use or reinstatement of other traditional features such as light wells and ventilation shafts can reduce energy use in warmer climates (Azmi and Ibrahim, 2020; Omar and Syed-Fadzil, 2011; Thornton, 2011; Henry, 2007). These features can often reduce or negate the need for air conditioning in hot countries which is a significant energy consumer (Psomas et al., 2016; Cardinale et al., 2013; Henry, 2007). Meanwhile traditional features such as external or internal shutters and storm doors, as well as layouts benefitting from solar gain and locating buildings in sheltered areas taking account of prevailing winds can reduce energy demand in cooler climates (Hawkes and Lawrence, 2021; Berg and Fuglseth, 2018; Curtis, 2010).

In some cases, heritage buildings may even perform better than contemporary buildings when measured data is compared. Two companion studies of measured indoor environmental quality and energy performance compared Tulou buildings (circular, rammed earth, multi-family heritage buildings) with modern rural buildings in south-eastern China (Li et al., 2012, 2013). Environmental monitoring showed that, as well as perceived better performance, the heritage buildings also had better measured indoor environmental quality over a range of indicators, despite using 28% less energy on average than the modern buildings. This was mainly attributed to the Tulou buildings' high thermal mass and good natural ventilation, which reduced heating and cooling demands. A similar result was found by a European field study which measured the thermal performance and energy use of ten different French heritage buildings, compared with a reference building constructed to modern French buildings standards (Cantin et al., 2010). Four of the ten heritage buildings had an energy demand below or similar to that of the reference building. The others had slightly higher demand than the reference building but compared with the average French residential building stock, the heritage buildings used between 38-71% less energy per square meter per year. It would therefore appear that some heritage buildings have better actual measured performance than is generally thought.

2.7 Energy modelling of buildings

Assessments of building energy performance, retrofit decisions, and potential energy and carbon savings are often informed by building energy simulation models (Kane *et al.* 2015). A number of studies have found however that standard energy models poorly reflect the actual fabric performance of vernacular and heritage buildings (Cardinale et al., 2013; Ingram et al., 2011).

Research by Pracchi (2014) compared standard and calculated u-values – a measure of thermal transmittance through building elements – with actual measured values, finding that for both brick and stone walls for 22 case studies the actual walls had significantly lower u-values and therefore better energy performance. Pracchi also used three different simulation models to predict energy demand for three heritage churches in Italy, identifying overestimates of 52-63% compared to the actual energy demand. When in-situ, measured u-values were used, the models still predicted 22-38% higher energy demand. The author suggests that these discrepancies may relate to a poor assessment of the buildings' thermal mass and a lack of ability to model the heating options and schedules used in the churches. The importance of thermal mass (Cardinale et al., 2013; Goodhew and Griffiths, 2005) and the overestimation of u-values in traditional construction have also been identified by other studies (Chambers et al., 2020; Litti et al., 2018; Li et al., 2015; Hulme and Doran, 2014; Baker, 2011). One of the reasons for this discrepancy is that masonry walls, modelled as homogenous stone, may actually have very diverse make ups, including high proportions of mortar and air, and may be affected by varying densities and moisture levels (Pohoryles et al., 2020; Li et al., 2015).

In addition to the better than predicted technical performance of heritage building envelopes, the need to consider the varied behaviours of residents in order to make accurate predictions of energy demand has been highlighted (Berg et al., 2017). For effective energy and carbon reduction from retrofitting, clearly pre-retrofit energy use must be understood and, as identified above, this is largely dependent on residents' energy behaviours (Kohler and Hassler, 2012). As eloquently stated by Gram-Hanssen:

> *Homes do not consume energy; people in homes with different types of practices and different technologies consume energy (2014, p. 396).*

A UK study identified that the Cambridge Housing Model (a UK energy model used in government policy) was a good predictor of monthly gas use for houses built after 1919 but significantly overestimated the energy demand of those constructed before 1919 (Summerfield et al., 2015). The authors highlighted the need for more accurate u-values and an increased understanding of residents' heating behaviours to reduce the discrepancy. Actual behaviours should therefore be taken into account (Carratt et al., 2020); however many energy simulation models use standard behavioural assumptions in their assessments (Jain et al., 2020).

A key tool designed to assess the energy performance of buildings are the models used across Europe and the UK to produce Energy Performance Certificates (EPCs) (EU Directive, 2018). EPCs provide an energy efficiency rating for buildings and are required whenever buildings are sold or let (Department for Communities and Local Government (DCLG), 2017). EPCs are designed to encourage energy efficiency improvements to the building stock, and to identify potential energy and financial savings from recommended retrofit measures (BEIS 2020a); however, their effectiveness in developing retrofit practices has been questioned in many countries (Bartiaux *et al.* 2014).

EPCs are also increasingly being used as a policy tool to mandate the retrofitting of existing buildings through the use of minimum energy efficiency standards (MEES). These standards require buildings to achieve a certain energy rating before they can be sold or let and are part of the EU's recent building renovation strategy (European Commission, 2020). MEES based on

EPCs have been applied in the UK for rented buildings and may be extended to privately owned dwellings in the future (CCC, 2020; BEIS 2020a). The UK modelling tool for producing EPCs for existing buildings is the Reduced Standard Assessment Procedure (RdSAP) (DCLG 2017). EPCs derived from RdSAP are often used to inform government funded retrofit programmes, such as the Green Deal, the Energy Company Obligation and the recent Green Homes Grant (BEIS 2020b; Glew et al., 2017; Shrubsole et al., 2014).

If models are inaccurate, however, then both environmental and financial targets may not be realised, because if models start with a higher figure for current energy use than in reality, the savings from subsequent retrofit will be lower than modelled. Sunikka-Blank and Galvin (2012) described this as the 'pre-bound effect' as identified in their study of the German building stock. This found an inverse correlation between actual and modelled energy; older, and supposedly less efficient buildings consumed up to 40% less energy than predicted by their EPC rating while newer and supposedly highly efficient buildings consumed more energy than predicted. A large proportion of this difference was attributed to residents' behaviours not being reflected in standard assumptions. These findings have been confirmed by other large studies of the Dutch, Swiss and Danish housing stocks (Cozza et al., 2020; Gram-Hanssen, Georg, et al., 2018; Majcen et al., 2013), calling into question the ability of EPC simulation tools to accurately assess energy demand from older buildings, and suggesting that reaching target ratings for these buildings may not lead to the expected savings (Summerfield et al., 2019). This is acknowledged by European Standard EN 16883 on improving the energy performance of historic buildings, which identifies that standard calculations are often inappropriate for heritage buildings and recommends a tailored approach to energy modelling (CEN, 2017).

The types of retrofits recommended by EPCs and other standard models may also not be appropriate for the traditional construction of most heritage buildings and do not take the current condition of the building into account (Alembic Research et al., 2019; Glew et al., 2017). Recommendations may also fail to address the need to manage or remove previous maladaptions, or the need to take appropriate moisture management into account. Maladaptions can include the use of impermeable materials, such as modern cement on breathable buildings, and can lead to significant moisture issues and damage to the building fabric (Glew et al., 2017; May and Griffiths, 2015). Many older buildings have already suffered various maladaptions (Whitman et al., 2019; May and Rye, 2012).

Many projects have been identified as approaching heritage retrofits in the same manner and using the same techniques as they would for standard retrofit projects (Sesana et al., 2019; Glew et al., 2017; Webb, 2017). This approach tends to privilege technical energy efficiency improvements, neglects residents' values and behaviours, and views heritage values as a barrier to the use of standard solutions (Lidelöw et al., 2019; Magrini and Franco, 2016). Heritage buildings however have unique features and are non-standard and context specific (Lidelöw et al., 2019; Cellura et al., 2017; Webb, 2017; López and Frontini, 2014). The need to acknowledge current building conditions also links to the positive performance aspects that traditional features of heritage buildings may have and to opportunities to utilise these features to reduce carbon in a heritage sensitive, or even heritage enhancing, manner (Pender and Lemieux, 2020; Griffiths and Goodhew, 2015; Curtis, 2010).

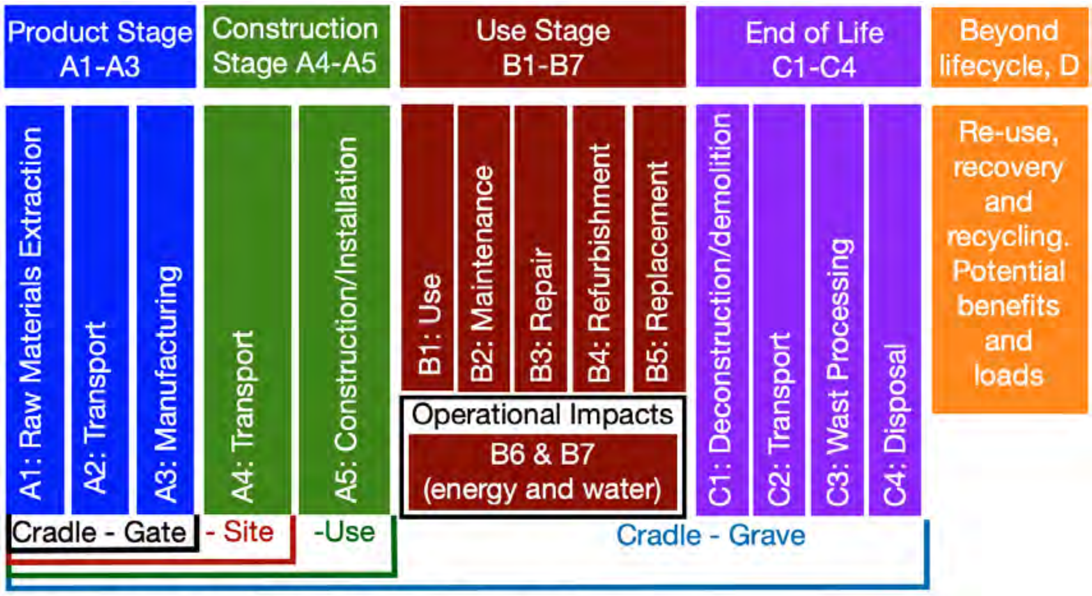
Evidence that heritage buildings may perform better than predicted does not mean that energy and carbon from these buildings does not need to be reduced. The need to mitigate climate change is such that carbon emissions from all buildings must be urgently reduced, including those from heritage buildings (IPCC, 2022b; Global Alliance for Buildings and Construction et al., 2021; Cassar, 2009).

There is therefore only limited research in the UK relating to the energy performance of heritage buildings compared with standard models such as UK's RdSAP. Further research on the differences between actual and modelled building performance would therefore be of value, especially to identify the likely impact of the increasing use of MEES in UK and European policy. If models overestimate the actual energy demand from heritage buildings, then savings from retrofit will also be overestimated, potentially jeopardising both national carbon targets and personal financial viability.

2.8 Lifecycle carbon implications

All retrofit projects, as well as making operational energy and carbon savings from reduced energy use for heating, cooling, and other uses, have an embodied impact. This is the energy and associated carbon emissions required to extract raw materials, transport them, manufacture them into products, transport these products to site and install them, as well as any maintenance or replacements required during the building's lifetime and finally the end-of-life removal and disposal (Figure 2.1). The lifecycle impacts of a building are the sum of the embodied impact and the operational impacts (Birgisdottir et al., 2017). A range of environmental impacts can be considered in lifecycle assessment (LCA), including carbon emissions, energy, land use, ozone depletion and water use. For buildings however energy and global warming potential, commonly termed carbon and reported in kilograms of carbon dioxide equivalent ($kgCO_2e$), tend to be the main indicators reported (Pomponi and Moncaster, 2017; Moncaster and Symons, 2013). For a retrofit project, a similar calculation can be made but in this case the retrofits will be assumed to be reducing the operational impacts compared with pre-retrofit. The lifecycle impact of a retrofit project is therefore the net impact of the embodied 'costs' and the operational 'savings' of the retrofit measures. If operational energy savings are not as high as predicted by models, the embodied costs could outweigh them and have been shown to increase lifecycle emissions in some cases (Asdrubali et al., 2019; Pracchi, 2014; Iyer-Raniga and Wong, 2012).

Figure 2.1: Lifecycle stages for construction and retrofit



Adapted from BS EN 15978:2011 (BSI, 2021, p.23)

While the use of LCA for buildings is becoming more mainstream it is still not commonplace. The calculation of lifecycle carbon is currently not recognised in UK national policy, for example not being included in the UK Government's recent Heat and Buildings' strategy (BEIS 2021a), despite many authors highlighting its importance (Pomponi et al., 2020; Moncaster et al., 2019; Berg and Fuglseth, 2018). A number of European nations such as Finland, Sweden and Denmark however have recently introduced embodied carbon calculation requirements as part of building policies (Attia et al., 2021; Kuittinen and Häkkinen, 2020).

What little research there is on embodied carbon and heritage buildings has mainly focussed on whether retrofitting existing buildings, or demolishing them and replacing them with new buildings, would make greater lifecycle savings (Baker et al., 2017). Retrofit has much lower upfront embodied carbon than demolition and rebuild (Moncaster et al., 2019; Berg and Fuglseth, 2018) and a number of authors have demonstrated that it also has lower lifecycle carbon (Baker et al., 2021; Redden and Crawford, 2021; Historic England, 2020). Comparative studies of heritage buildings in various European countries have shown that retrofit can lead to between 4 - 57% greater lifetime carbon savings than demolish and rebuild (Marique and

Rossi, 2018; Weiler et al., 2017; Ferreira et al., 2013). The saving is dependent on the specific context; a Portuguese study of a heritage palace found lifecycle carbon savings of 13% for retrofit, despite the need for extensive concrete and steel reinforcement of the heritage building due to its location in a seismically active area (Ferreira et al., 2015).

More generally, an international investigation of 80 case studies on retrofitting existing buildings also identified that retrofit had around half the embodied energy and carbon per metre squared of new build (Moncaster et al., 2019). A small number of authors have suggested that the embodied carbon already extant in heritage buildings should be included in calculations as wastage if these buildings are demolished (Akande et al., 2014; Merlino, 2014). Most studies however consider this to be a historical 'sunk cost' and only include the embodied carbon required for demolition and new construction (Baker et al., 2017).

An additional consideration is the temporal aspect of emissions (Pomponi et al., 2020). The greatest proportion of the embodied carbon cost is emitted during the construction phase while the operational carbon savings are spread across the lifespan of the building (Pomponi and Moncaster, 2017). The time constraints on dramatically reducing carbon emissions, and the danger of irreversible tipping points, mean that reducing embodied emissions now, may be proportionally more critical than higher operational savings over 50 or 60 years (Berg and Fuglseth, 2018; Zhang and Wang, 2017). The steady decarbonisation of electricity, and the planned decarbonisation of heat, such as through the use of heat pumps, also mean that future operational emissions will be lower (BEIS 2021a). The need for policies to support retrofit have therefore been highlighted, for example by reducing VAT on retrofit so that it is comparable or lower than new construction (House of Commons Environmental Audit Committee, 2021; Smith et al., 2021; Dubois and Allacker, 2015).

Despite the evidence that retrofit leads to lower carbon than the alternative of demolish and rebuild, there is still a need to compare different solutions to assess the lowest lifecycle impact (Sesana et al., 2019; Rodrigues and Freire, 2017). There is some evidence that embodied impacts affect the most appropriate retrofit options and that in some cases smaller interventions may actually be better, in lifecycle terms, than more extensive measures (Asdrubali et al., 2019; Berg and Fuglseth, 2018; Kyriakidis et al., 2018). An Australian study of eight heritage buildings found that double glazing with UV film actually increased the buildings' lifecycle energy by an average of 2% (Iyer-Raniga and Wong, 2012). In contrast, secondary glazing reduced lifecycle energy by 2% and thermal curtains, which would have a much lower impact on heritage values and lower financial costs, reduced lifecycle energy by 3%. Meanwhile a study examining retrofits packages for an 80-year old Italian school identified that the cost optimal package, which involved more limited interventions, was significantly better in lifecycle carbon terms than retrofitting to government standards or as a nearly zero operational energy building (Asdrubali et al., 2019). Other studies have compared specific heating systems (Lin et al., 2021) or insulation materials (Llantoy et al., 2020), identifying that higher levels of insulation do not necessarily lead to greater lifecycle savings depending on building and use characteristics (Rodrigues and Freire, 2017)

There is also some limited evidence suggesting that traditional, natural and local materials, such as wood, stone, and lime renders, have lower embodied energy and carbon than more modern, highly manufactured materials (D'Alessandro et al., 2017; Brandão et al., 2016; Bin Marsono and Balasbaneh, 2015; Gong et al., 2012; Ip and Miller, 2012). Thermal lime plasters for example were shown to have low embodied carbon and significant thermal benefits for traditional adobe walls in southern Europe (Kyriakidis et al., 2018). Many of these studies tend to focus on individual material comparisons and often only cover cradle to gate impacts (Figure 2.1). A study commissioned by Historic Scotland identified the importance of considering transport emissions and the benefits of using local materials, especially for heavy materials such as stone (Crishna et al., 2010). These traditional and local materials are also more likely to be sensitive to the heritage values of the building and may be more compatible with their traditional construction (Berg and Fuglseth, 2018; Curtis, 2010).

A number of studies have also identified the importance of considering the lifespan and durability of retrofits and their maintenance requirements as part of LCA studies (Litti et al., 2018; Kayan et al., 2017; Chiang et al., 2015). This includes studies on mortars (Pineda et al., 2017), paints (Kayan, 2017) and cleaning products (Franzoni et al., 2018) for heritage buildings. A lack of studies which assess the lifecycle maintenance of wooden components and elements such as windows was identified. Litti et al highlight the need for further studies on this topic although their own paper only considers operational energy for a range of window alterations (Litti et al., 2018).

Meanwhile interviews with Australian building developers identified that they felt little incentive to invest the time and effort in calculating embodied carbon (Wilkinson and Remoy, 2017). The majority stated that this was not something that they would engage in unless it was mandatory because it was not something that their clients were demanding. Many authors have identified the difficult and time-consuming nature of LCA studies but emphasise their importance for gaining a full understanding of the whole life carbon impacts of heritage building retrofits. (Berg and Fuglseth, 2018; Loli and Bertolin, 2018; Grytli et al., 2012).

Several reviews have identified the need for embodied calculations for retrofit to be included in energy policies (Lidelöw et al., 2019; Zeng and Chini, 2017). The lack of inclusion of embodied and lifecycle carbon in tools, policies and frameworks has also been identified by many authors (Lidelöw et al., 2019; Conejos et al., 2016; Ferreira et al., 2013; Iyer-Raniga and Wong, 2012). Sustainable certification schemes such as LEED and BREEAM which do encourage the use of low carbon materials are generally considered poorly suited to heritage buildings (Bertolin and Loli, 2018; Balderstone, 2012). In recent years an increasing number of industry organisations have however started to develop guidance, tools and optional standards for measuring embodied carbon (Chartered Institution of Building

Services Engineers (CIBSE), 2022; London Energy Transformation Initiative (LETI), 2020; Royal Institution of Chartered Surveyors (RICS), 2017). The EU is also encouraging a consideration of lifecycle impacts as part of its recently released ‘Levels’ framework (European Commission, 2021) and some UK nations and regions have included embodied carbon measurements in their local plans or policies (for example, Greater London Authority, 2021; Welsh Government, 2021). These developments are positive but there is still a need for greater policy recognition and assessment of lifecycle carbon at a national and international level (Moncaster et al., 2019).

A lifecycle perspective which considers embodied, as well as operational, carbon, is therefore required to fully understand the environmental impact of retrofitting or new build. Retrofit has been found to have lower embodied and generally lower lifecycle carbon than demolish and rebuild. There would therefore appear to be a strong case for retrofit over demolition and rebuild in lifecycle carbon terms as well as for heritage retention. There is evidence to suggest that including embodied carbon in assessments affects the identification of the most appropriate retrofit measures, with some measures having the potential to actually increase lifecycle impacts. It is likely that some traditional and local products will have lower embodied impacts than more technical measures and these types of changes may also be more compatible with the values and construction of heritage buildings. There is a general lack of policies mandating the measurement of embodied carbon at a national or international level across the UK and Europe, although some countries have recently taken steps towards regulating embodied carbon. Currently heritage retrofit studies mostly focus on operational effects, with few calculating lifecycle impacts (Loli and Bertolin, 2018; Webb, 2017; Munarim and Ghisi, 2016). This is a significant research gap (Berg and Fuglseth, 2018; Pracchi, 2014).

2.9 Summary of research gaps

The tangible and intangible values that residents invest in their building often differ from those recognised in planning policy. These policies, and the heritage retrofit literature, similarly neglect to consider the specific values of residents. These values affect residents' retrofit decisions and are important for carbon reduction since the majority of residential retrofit in the UK is resident led. A greater understanding of the heritage values that residents invest in their buildings is therefore important to inform and support residents' decision making.

However, a range of barriers to residential retrofitting have been identified, including access to trustworthy and context specific information, the upfront cost of measures, finding appropriate tradespeople, disruption and the time or capacity to plan or manage retrofit processes. These barriers have been identified as important but so far have not been researched in any depth for heritage building residents.

While fabric retrofit is important for all buildings to reach global climate targets, energy behaviours will also have a key role to play. These behaviours are of critical importance to energy demand in buildings, with evidence that they can have a greater effect on energy than some technical measures. Such behaviours are generally overlooked in policy and in much of the retrofit literature, with standard assumptions used that sometimes bear little resemblance to residents' actual behaviours. There are suggestions that residents' behaviours in heritage buildings may differ to those in more modern buildings, but this has not been investigated in northern Europe where the behaviours of heritage residents are poorly understood.

Interlinked with residents' energy behaviours are residents' perceptions of comfort within their buildings, which may also be a motivation for retrofitting. Heritage buildings are commonly considered to be uncomfortable to live in but, in contrast to this general belief, evidence from a number of studies suggests that, in some circumstances, they are perceived to perform better than more modern buildings by their residents, whose behaviours and perceptions may be more compatible with adaptive comfort strategies. However much of the research in this field has focussed on commercial buildings and there is very little research into residents' comfort perceptions in heritage buildings in the UK.

There is also evidence that, as well as being perceived to perform better than generally acknowledged, some heritage buildings have better than expected actual performance, and many of the original features of heritage buildings can have inherent, low energy aspects, which could potentially be utilised to reduce energy demand. The technical performance of these buildings and their residents' behaviours however, appear to be poorly represented in some energy simulation models, commonly leading to overestimations of energy demand. Energy Performance Certificates, which are increasingly being used by the EU and UK as policy tools to encourage energy retrofitting, appear to poorly represent older buildings across several countries, although there have been limited studies focussing specifically on heritage buildings.

Finally, the effect of embodied impacts on the lifecycle carbon of retrofitting heritage buildings has been found to be of critical importance, although generally overlooked. When a lifecycle perspective is taken, retrofitting makes significantly greater savings in carbon terms than demolish and new build. Taking embodied carbon into consideration can also affect the choice of retrofit option. Measuring embodied carbon is generally now acknowledged as important and is starting to appear in some countries' building regulations but is still uncommon in the heritage retrofit literature, with little research into the embodied impact of different retrofit measures and a focus on operational impacts.

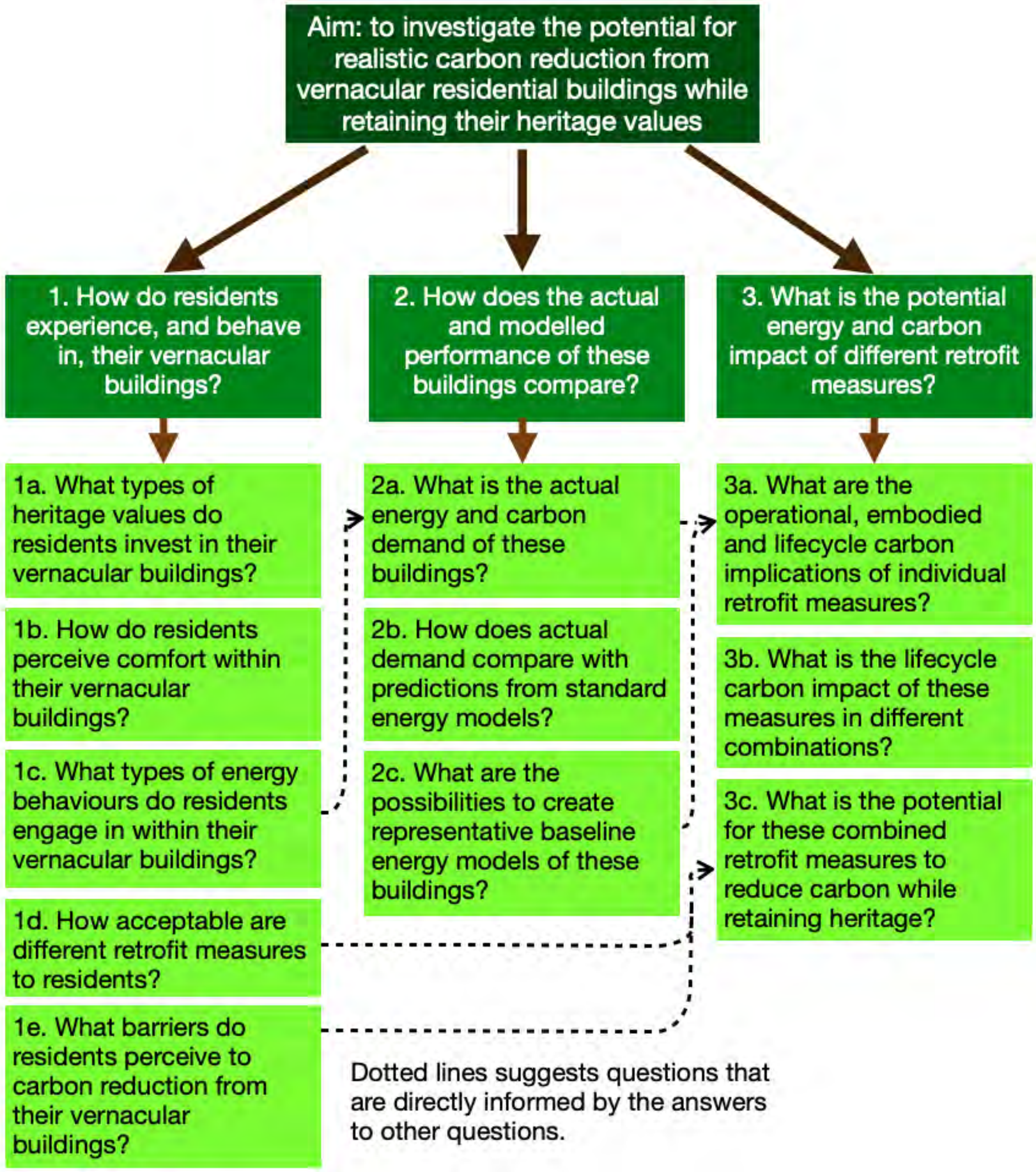
In order to achieve real carbon reduction from heritage buildings, a number of interlinked areas for further research are therefore crucial. These areas relate to both residents' heritage values, retrofit barriers, energy behaviours and comfort perceptions, and to how the actual performance of heritage buildings are reflected in standard models and the importance of assessing the lifecycle, not just operational impacts. There are also a number of interdependencies. One example is residents' energy behaviours in heritage buildings, which are influenced by residents' comfort perceptions and in turn influence the energy demand of the building. These behavioural aspects are neglected in standard models, as is the thermal performance of heritage materials.

These areas and the links between them suggest that there is a significant need for investigation of the relationship between residents and their buildings in the context of retrofit for carbon reduction and particularly for vernacular and heritage buildings.

2.10 Research aim and questions

This research therefore aims to investigate the potential for realistic carbon reduction from vernacular residential buildings while retaining their heritage values, by examining the views, values and behaviours of their residents, the reflection of actual energy performance in energy models and the lifecycle potential of retrofit measures. Three specific research questions and eleven sub-questions have been developed to frame this research (Figure 2.2).

Figure 2.2: Research aims and question tree



Vernacular buildings will be examined in this research and will be considered to be heritage buildings if their residents invest values in them. A focus on heritage buildings would lead to confusion about whose values were being recognised. As this research focusses on residents' heritage values rather than those recognised by policy, vernacular buildings will be considered.

Question one, 'How do residents experience, and behave in, their vernacular buildings' addresses the role of residents. This includes five sub-questions on the types of values that they invest in their buildings (1a), how they perceive comfort in their buildings (1b) and the types of behaviours that they engage in (1c), as well as the acceptability of retrofit measures (1d) and perceived barriers to carbon reduction (1e).

Question two, ‘how does the actual and modelled performance of these buildings compare,’ investigates their buildings. Identifying the actual energy demand of these buildings (2a) and how this compares with predictions from standard energy models (2b), while also considering the abilities of models to create representative baselines for these buildings (2c). Question two, and sub-question 2a in particular, will be informed by sub-question 1a because energy demand is strongly influenced by residents’ behaviours. The answers to these two questions will develop an understanding of the current status of these buildings in terms of energy use, comfort, performance and residents’ views and values.

Question three, ‘what is the potential energy and carbon impact of different retrofit measures,’ then examines the options for future carbon reduction by assessing the implications of a range of retrofit measures for carbon reduction and heritage retention, using the understanding of actual building performance developed in question two. The sub-questions consider the operational, embodied and lifecycle carbon of individual measures (3a) and the lifecycle impact of these measures in a variety of combined packages (3b). These packages are then related back to the experience of residents identified in question one by considering how likely it is that they might be enacted by residents in reality (3c).

In combination, these specific research questions address the overarching aim and support reducing carbon from vernacular buildings while retaining their values. These research questions address a range of both social and technical aspects of heritage buildings and their residents, meaning that a research design utilising a range of different methods is required.

Some material in this chapter has been previously published in (Wise et al., 2019)

Chapter 3. Research Design and Methods

3.1 Research design

The 'worldview' adopted for this study was classical pragmatism. A worldview encompasses both the ontology and epistemology of the research and the general attitude to the nature of research by the researcher (Creswell and Creswell, 2018). A classical pragmatic approach is considered to have a good fit with multiple methods which address a variety of questions (O'Sullivan and Howden-Chapman, 2017; Morgan, 2014). Classical pragmatism steps across the epistemological divide between positivism and interpretivism, and their typical associations with quantitative and qualitative data respectively, and argues that the best method is the one most appropriate to answering the questions under consideration (Morgan, 2014; Biesta, 2010). In particular, pragmatism acknowledges that what holds true in one circumstance may not be the case in another and will be, at best, a good working theory (Simpson, 2018).

Pragmatism advocates the use of an abductive research logic which involves a mix of hypothesising, exploratory research and redeveloping the hypothesis through a number of iterations, depending on the practical realities of the results (Simpson, 2018). As part of this approach the need for critical reflection is identified as a vital element in creating meaningful knowledge (Coghlan and Brydon-Miller, 2014). A pragmatic approach was therefore considered appropriate to this study, with its compatibility to abductive logic and multiple methods deemed useful for the varied nature of the issues considered.

This research utilised a case-based design. According to Yin (2014, p. 15), this design is appropriate where the aim is to empirically examine complex and contemporary phenomena in depth, and where there are likely to be contextual elements which are pertinent to the phenomena investigated. Case-based research is useful where the case itself is an entity of interest, in addition to its individual components (Byrne, 2020). This is relevant in the context of the research questions which consider the interaction between a range of different aspects affecting heritage retrofit as well as the aspects themselves.

Case study research can be applied at numerous different scales, including individuals, institutions, areas, ecosystems, economies or countries (Byrne, 2020) although the methodological literature tends to focus on studies of social phenomena (such as Yin, 2014; Byrne and Ragin, 2009). The use of case studies has been identified as one of the most prevalent designs for heritage building research (Lidelöw et al., 2019; Webb, 2017). Much of this previous research however tends to focus on technical case studies of building retrofit and does not consider their occupants. In contrast, and to address the research questions, the research in this thesis investigated both the technical aspects of the building and the values, views, and behaviours of the building's residents.

Case based research is considered particularly valuable for capturing the richness and detail of phenomena in specific, real world contexts and for allowing multiple points of evidence to be used (Yin, 2014). This type of research is also well suited to examining complex topics that require a range of different research methods (Byrne and Ragin, 2009). Research using mixed methods has the potential to add both breadth and depth of understanding to the topics investigated and to provide opportunities for the corroboration of different sources of data (Theirbach et al., 2020; Doyle et al., 2016). Given the diverse aspects that appear to influence the opportunities and challenges for carbon reduction with heritage retention from vernacular buildings, a multi-disciplinary and mixed methods approach is desirable. A range of different methods were therefore used within the case study design to provide multiple evidence points and to best answer the research questions and aim.

Evidence gained from case study research is context specific, although it is recognised that conclusions can often be generalisable to other similar circumstances beyond the specific context (Byrne, 2020; Gomm et al., 2000).

Flyvbjerg (2006) emphasises the importance of context dependant knowledge and the suitability of case studies for developing this experience based learning. Byrne (2020) highlights the need to consider which aspects of case research findings are likely to have wider applicability and in what contexts these are likely to apply. This fits well with a pragmatic worldview which highlights the importance of experiential learning, context specific research and reflection (Morgan, 2014).

Given the contextual nature of vernacular buildings (Herrera-Avellanosa et al., 2019), the County of Cumbria in northwest England was chosen as the overarching case for the research. Cumbria is a mainly rural, upland and coastal region and is also one of the most geologically diverse areas of the UK, with a complex geological history most recently shaped by glaciation (Lake District National Park Authority, 2018; Brunskill, 2010). This means that the historic built environment uses a diverse range of materials across the county and different areas have distinctive local characters (Brunskill, 2010; Denyer, 1991).

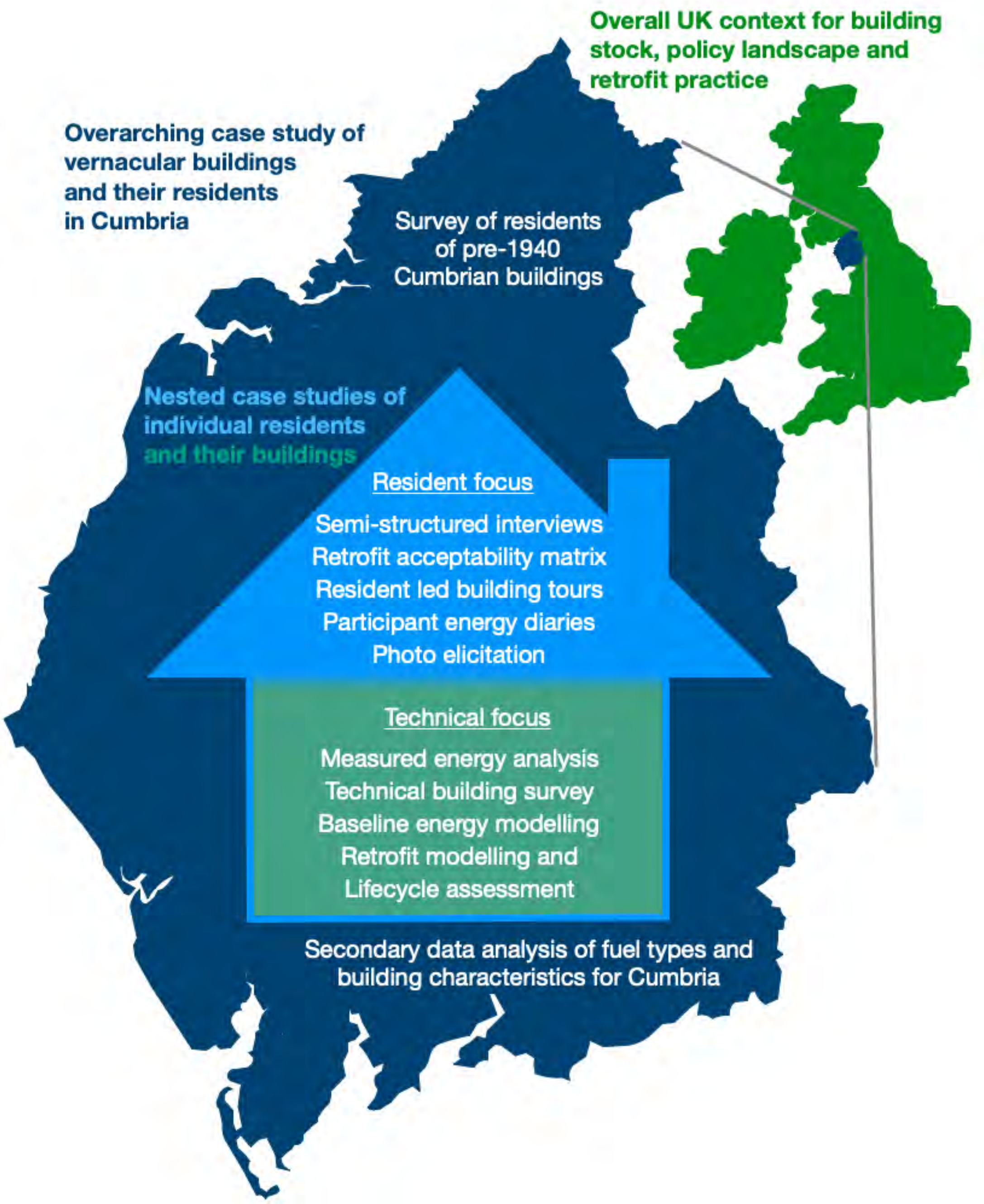
The architecture in eastern and central Cumbria (Figure 3.1) is mainly farmstead and villages, dating from the 17th century, while there is more industrial heritage on the west coast, southern Furness peninsular, and in the city of Carlisle (Brunskill, 2010). The late 18th and early 19th centuries saw a significant construction boom due to the growth of tourism inspired by the birth of the romantic movement (Denyer, 1991), and the visitor economy is still a major factor, with over 24% of houses in the Lake District National Park holiday lets or second homes (LDNPA, 2018). The Lake District National Park was recently inscribed as a Cultural Landscape World Heritage Site (WHS) for its outstanding natural and built environment (LDNPA, 2020).

Figure 3.1: Map of Cumbria

This area was chosen as it has a high proportion of vernacular buildings, with a range of different characters and styles providing a good level of variation within a geographically bounded area. This diversity could be disadvantageous because it may be more challenging to identify themes across different building types. However, it is also advantageous, because if findings do apply across this varied context, it is likely that they will have broader general applicability. The presence of the cultural landscape WHS also identifies a range of potential heritage values (LDNPA, 2020). Furthermore, there is an emphasis on urban heritage buildings in much of the literature (for example, Eriksson, 2018; Sunikka-Blank and Galvin, 2016) and the generally rural nature of Cumbria provided a useful investigative context of a more dispersed historic environment. In addition, personal knowledge of the area and local contacts were beneficial for the research.

Within the overarching case study a number of data sources were developed and, as part of the abductive approach, a sequential (Theirbach et al., 2020) and multiphase research design was used (O'Sullivan and Howden-Chapman, 2017). First, a broad overview of vernacular buildings and their residents in Cumbria was developed through a survey of residents, and through examining secondary data on the Cumbrian built environment. Within this broader context a number of what Yin (2014) terms 'embedded' and Olsen (2009) calls 'nested' case studies, were then examined. These nested studies investigated individual households and their buildings in greater depth than could be achieved with the larger scale survey. A variety of methods were used to develop an understanding of the current actual performance of each building, and how residents experience and behave within it, before the potential of a range of retrofit measures were assessed for their ability to reduce carbon while retaining heritage. The use of multiple nested cases within the larger study provided the opportunity for a multiple case design which is considered beneficial for examining the wider applicability of findings and increasing the rigour of the research process (Yin, 2009, 2014). The Cumbrian specific data was also compared with national information on energy use in residential buildings and other relevant secondary data, such as average floor areas and fuel types, and was informed by the UK policy landscape. The research design is summarised diagrammatically in Figure 3.2, while specific details on individual methods are discussed in the following sections.

Figure 3.2: Overview of research design and individual methods



In summary, a case study research design was considered to be a good fit with the contextual and specific nature of vernacular buildings. This research examined a specific context but has findings that are applicable beyond this context. The use of mixed methods in a multiphase research design provides opportunities for multiple data points and the corroboration of results. This is compatible with the abductive research methods advocated by a pragmatic world view. The use of a range of methods can help to develop a fuller understanding of complex issues. This research design therefore helped to address the research questions and aim.

3.2 Survey research

The first research method was an exploratory survey directed to residents of vernacular buildings across Cumbria. Surveys generally involve questionnaires that can be filled out on paper, via telephone or, more commonly now, online (Ruel et al., 2016). Surveys are identified by Yin (2014) as being useful for answering questions about what, where, and how many. Surveys are valuable for gaining a broad view of a topic and for answering well defined questions (Ruel et al., 2016). One of their chief benefits is that a larger sample size is possible than for more in-depth methods such as interviews (Theirbach et al., 2020; Andres, 2012). Surveys can seek statistical generalisability, which is based on sampling which aims to select a ‘random sample’ which is representative of the ‘population’ under study (Andres, 2012). This generalisability is different to what Yin (2014) terms analytical generalisability, which is the likelihood of results in one context applying to other similar contexts.

There are many barriers however to achieving a truly random sample, such as accessing sufficient data about the population under study to be able to identify an appropriate sample (Ruel et al., 2016; Andres, 2012). There is no data, for example, on how many buildings in Cumbria were constructed before 1940, so identifying a statically representative sample of these buildings would be problematic. Therefore, in this research, the survey was not designed to provide statistical generalisability but rather to provide analytical generalisability and an understanding of the views, values and behaviours of a larger number of residents than that which could be achieved through individual interviews (Andres, 2012). The survey in this research can therefore be termed an exploratory survey, which provided breadth for investigating the research questions, while the nested case studies provided depth (Theirbach et al., 2020; O’Sullivan and Howden-Chapman, 2017). It also helped to corroborate or challenge the findings of the nested cases because the survey examined similar topics for a larger number of residents, thereby increasing the analytical applicability of the research findings (Theirbach et al., 2020).

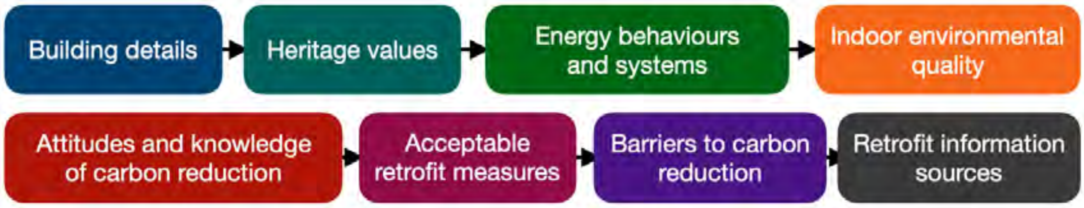
Survey design

The survey was developed for online distribution and was targeted to residents of vernacular buildings. The research was described as investigating energy, carbon, and heritage values. No mention was made in publicity of 'heritage' or 'vernacular' buildings, only 'older Cumbrian buildings' so as not to discourage any respondents who might have particular definitions of these terms. Older buildings were described as those constructed before 1940 as these were highly likely to be vernacular.

Five scoping interviews were undertaken with Cumbrian conservation and sustainability professionals to inform the survey development and identify key areas of interest in the local context. All interviews took place in person at each professional's place of work. The interviews lasted between one and two hours and the interview schedule and participant consent form are available in Appendix A. These interviews highlighted confusion in the definition of heritage buildings, and the perceived importance of planning policies, especially within the National Parks. Local materials were identified as important to a Cumbrian setting and tensions between retaining heritage and retrofitting to reduce carbon, were confirmed as important.

Eight sections were created, informed by the interviews and literature review (Figure 3.3). The full survey can be seen in Appendix B. Surveys can include both closed questions with pre-set answers which can be analysed numerically and open questions which can be analysed more qualitatively (Theirbach et al., 2020). As is common with surveys, most of the questions were closed. Each section also contained at least one open question to encourage respondents to elaborate on the pre-set answer in their own words, or to provide further pertinent details (Theirbach et al., 2020; Yin, 2014). Almost all questions also had an ‘other’ option to allow for variation from the pre-set answers if required (Andres, 2012).

Figure 3.3: The eight sections of the survey



The first page of the survey set out the study information, provided researcher contact details, and requested informed consent to participate in line with Open University research ethics procedures. The survey was fully anonymous, and no identifying personal details were gathered. It was approved by the Open University’s Human Research Ethics Committee (HREC). The first page also included a question on whether respondents were happy for data such as anonymous quotes from the survey to be shared in publications and/or presentations. The survey was designed using the JISC online survey tool, which is fully compliant with the General Data Protection Act (GDPR) and stores all data within the EU.

The requested building details included: the age of the respondents’ buildings; building form (detached, semi-detached, etc); building type (cottage, townhouse, castle etc); building designation (Listing, National Park etc); whether it was owned or rented; and the district of Cumbria, to form a picture of the types of buildings that respondents occupied and to provide comparison with secondary data on the Cumbrian built environment. There was an option in the district question of ‘Not in Cumbria’, if respondents ticked this, they were redirected out of the survey to a page thanking them for their time but explaining that this research focussed on Cumbria.

Section six asked respondents to consider a range of retrofit options and indicate whether they already had them, or if they would be willing, might be willing or would not be willing to enact each measure. The list of measures was developed from the literature on heritage retrofitting and included both fabric (Table 3.1) and system improvements (Table 3.2).

Improvements to the building fabric through the addition of insulative materials is one of the most common energy retrofit measures (Carratt et al., 2020; Fisk et al., 2020; Sesana et al., 2019). Insulation can be added to all the main opaque elements of a building, including walls, floors, and roofs/lofts. The insulation of solid walls is often a key measure for reducing energy demand from vernacular buildings. However it may also have a significant impact on the building's heritage values and its ability to manage moisture (Glew et al., 2017; Bristol City Council, 2015; Harrestrup and Svendsen, 2015). Both internal and external insulation were considered as they have different potential benefits and challenges in terms of heritage values, practical issues such as space reduction, and hygrothermal risks to the building fabric (Morgan, 2019).

After wall insulation, improvements to the performance of windows, either through replacement or alteration, is considered a key retrofit measure for older buildings although it can also be a significant source of tension with the retention of heritage values (Ginks and Painter, 2017; Bakonyi and Dobszay, 2016). The benefits of window replacement in reducing heat loss are often highlighted, although in designated heritage buildings the replacement of windows is frequently prohibited (Curtis, 2010). Research has indicated that traditional additions to windows such as curtains and shutters, or the use of secondary glazing, may have similar heat loss reduction potential as window replacement (Litti et al., 2018; Bakonyi and Dobszay, 2016; Wood et al., 2009). Both window replacement and several window additions were therefore considered.

The air permeability of buildings is a key aspect in their energy performance (Hubbard, 2011). Studies have found that draught proofing activities such as closing off chimneys and draught stripping windows, doors, and floors can significantly reduce uncontrolled air infiltration (Gillott et al., 2016; Teekaram, 2013), although adequate ventilation pathways must be maintained (Morgan, 2019). Finally some studies have identified the potential benefits of wall hangings for reducing energy and improving comfort (Khan, 2018; Pracchi et al., 2017). There is limited research on this topic but significant historic precedent to suggest its validity (Pender and Lemieux, 2020; Khan, 2018). Wall hangings were therefore included in the list of potential retrofit measures.

Table 3.1: Fabric improvement measures

Fabric improvement measures	Reference studies
Loft or floor insulation	(Iyer-Raniga and Wong, 2012)
Floor insulation	(Glew et al., 2019)
Internal Wall Insulation	(Bjarløv et al., 2015; Harrestrup and Svendsen, 2015)
External Wall insulation	(Jensen et al., 2020; Zagorskas et al., 2014)
Window replacement with wood, metal or UVPC frames	(Litti et al., 2018; Menzies, 2013)
Secondary Glazing	(Bakonyi and Dobszay, 2016; Curtis, 2010)
Interior or exterior shutters	(Bakonyi and Dobszay, 2016; Wood et al., 2009)
Thermal curtains	(Wood et al., 2009)
Draught proofing	(Gillott et al., 2016; Wood et al., 2009)
Chimney balloons	(Hubbard, 2014; Teekaram, 2013)
Thick wall hangings	(Khan, 2018; Pracchi et al., 2017)

The other common area of retrofit interest is the improvement of building energy systems and the decarbonisation of energy sources through renewable technologies (Fisk et al., 2020) (Table 3.2). Several authors have examined the opportunities for the heritage sensitive use of solar PV and solar thermal panels for heritage buildings as they can have a clear visual impact (Cabeza et al., 2018; Cellura et al., 2017; López and Frontini, 2014). Other micro-renewables can include hydropower, and ground, air, or water source heat pumps which are an area of increasing policy focus because of their potential to decarbonise heat (BEIS, 2021a). The use of biomass boilers is also a potential measure to decarbonise heat (Rafique and Williams, 2021), although its sustainability is dependent on the source of the biomass. Biomass may be more appropriate in rural areas such as Cumbria (BEIS 2021a). Other common improvements, often promoted by government initiatives, are the replacement of current boilers, lights, and appliances with more efficient models (Shove, 2018) although it is expected that many respondents may have already enacted such measures (Gram-Hanssen, Georg, et al., 2018).

Table 3.2: System improvement measures

System improvement measures	Reference studies
Solar Photovoltaic panels	(López and Frontini, 2014)
Solar thermal panels	(Cabeza et al., 2018)
Air, ground, and water source heat pumps	(Cabeza et al., 2018)
Hydropower turbine	(Pokharel et al., 2020)
Energy efficient lighting	(Cellura et al., 2017)
Energy efficient appliances	(Morgan, 2019)
Boiler replacement	(Hamilton et al., 2016; Tagliabue et al., 2014)

A final page of the survey asked if respondents would care to be involved in further research and have their building developed as a nested case study. Respondents were encouraged to contact the researcher on the email address provided if they were interested. This option was preferred over having respondents provide their own contact details, as it reduced unnecessary handling of personal information. As well as being a method in its own right, the survey therefore also acted as a tool to help develop nested case study opportunities.

Survey piloting

The use of piloting has been identified as an important strategy to help develop data collection methods (Yin, 2014). Piloting can provide opportunities for testing and reflection on methods and on practical and logistical aspects (Yin, 2014).

The survey was piloted with a number of Open University academics and Cumbrian vernacular building residents. This process helped to ensure that the language of the survey was clear to a non-specialist audience and identified areas which needed clarification. It also highlighted some different ways that the questions were understood. This was an iterative process; initial pilots, sometimes called 'pre-testing' (Ruel et al., 2016), were done in person with the researcher and physical copies of the survey, and questions took the form of an informal discussion and instant feedback as participants went through the survey. After further development from this feedback, later pilots involved participants remotely accessing the actual online survey and giving feedback on the usability of the tool as well as the questions' content. This iterative process helped to develop both the content and the ease of use of the survey and provided time between stages for critical reflection. Piloting has been identified as particularly important for surveys because respondents do not have the same opportunity to request clarification as they do with other 'in person' methods (Ruel et al., 2016; Sapsford, 2007).

Survey distribution

The survey ran from the 28th of October 2019 to the 10th of January 2020. It was shared via the snowballing technique (Sapsford, 2007) and contacts were made with a number of organisations in October and November 2019 who were asked to share details with their members (Table 3.3). The survey was also shared with local personal contacts and leaflets were displayed at a local museum and taken to three local events.

Table 3.3: Organisations approached for survey distribution

Organisation	Brief description	Type of contact	Result
Cumbria Action for Sustainability (CAfS)	Local sustainability organisation	Personal contact in person and via email	Shared on two occasions in electronic newsletter (01/11 and 01/12 2019)

Organisation	Brief description	Type of contact	Result
Friends of the Lake District (FOLD)	Organisation dedicated to conserving the Lake District's character	In person communication at offices	Shared with members in electronic newsletter (date unknown)
Cumbria Vernacular Buildings Group	Local interest group	Email communication to secretary	Emailed to members (date unknown)
ACTion with Communities in Cumbria	Rural community council and rural community development organisation	Personal contact	Announcement and leaflets during community buildings sustainability workshop (28/10/2019)
Association of Environmentally Conscious Builders (AECB)	Cumbrian group of the national AECB	In person communication at event	Leaflets at event and information shared with contacts (October)
Kendal Museum	Local museum	Personal contact in person	Leaflets displayed at museum and shared at event for volunteers (November 2019)
Society for the Protection of Ancient Buildings (SPAB)	National organisation	Email with named introduction	No response
National Trust	National organisation which rent out a lot of residential property in Cumbria	Email with named introduction	No response

Information leaflets providing an invitation to participate and a link to the survey were also hand delivered to 750 older buildings across Cumbria (Figure 3.4 and Figure 3.5). These leaflets were delivered in the evening and at weekends when potential respondents were considered most likely to be receptive to completing the survey. A dynamic assessment was made of the likely age of each property based on its external appearance and leaflets were only delivered to those that appeared to have been constructed before 1940, or where residents were in gardens and could be consulted. Leaflets were only delivered to homes that appeared to be permanently occupied, not to the high numbers of holiday and second homes in Cumbria.

Figure 3.4: Survey information and invitation leaflet (L front of leaflet, R back of leaflet)

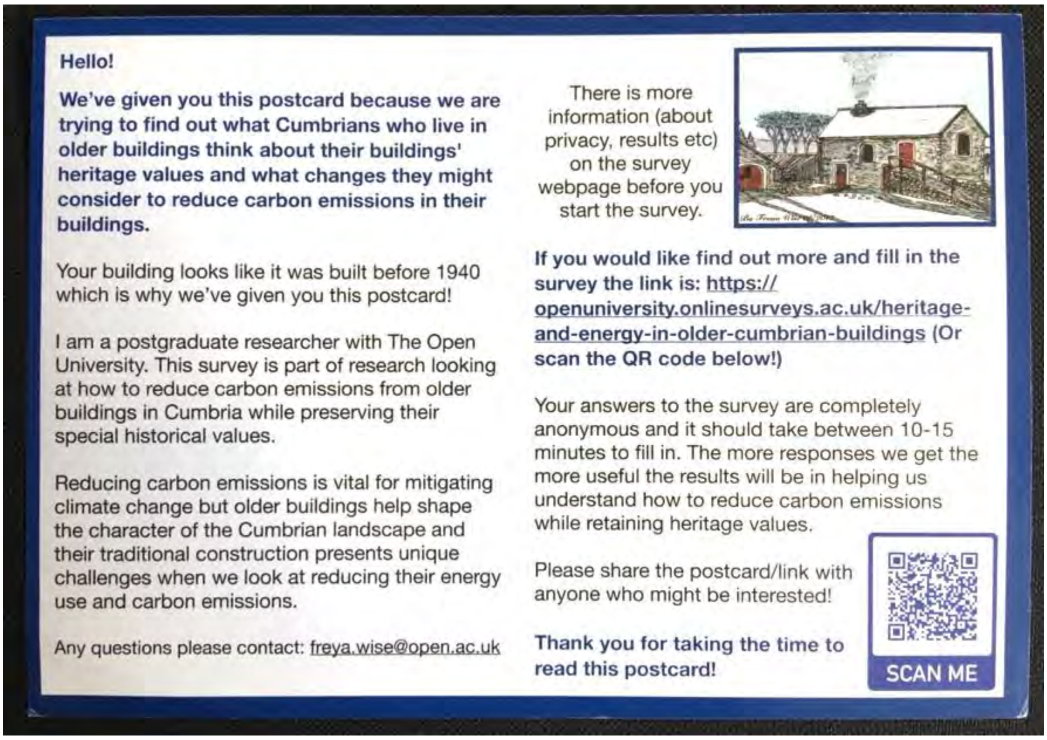
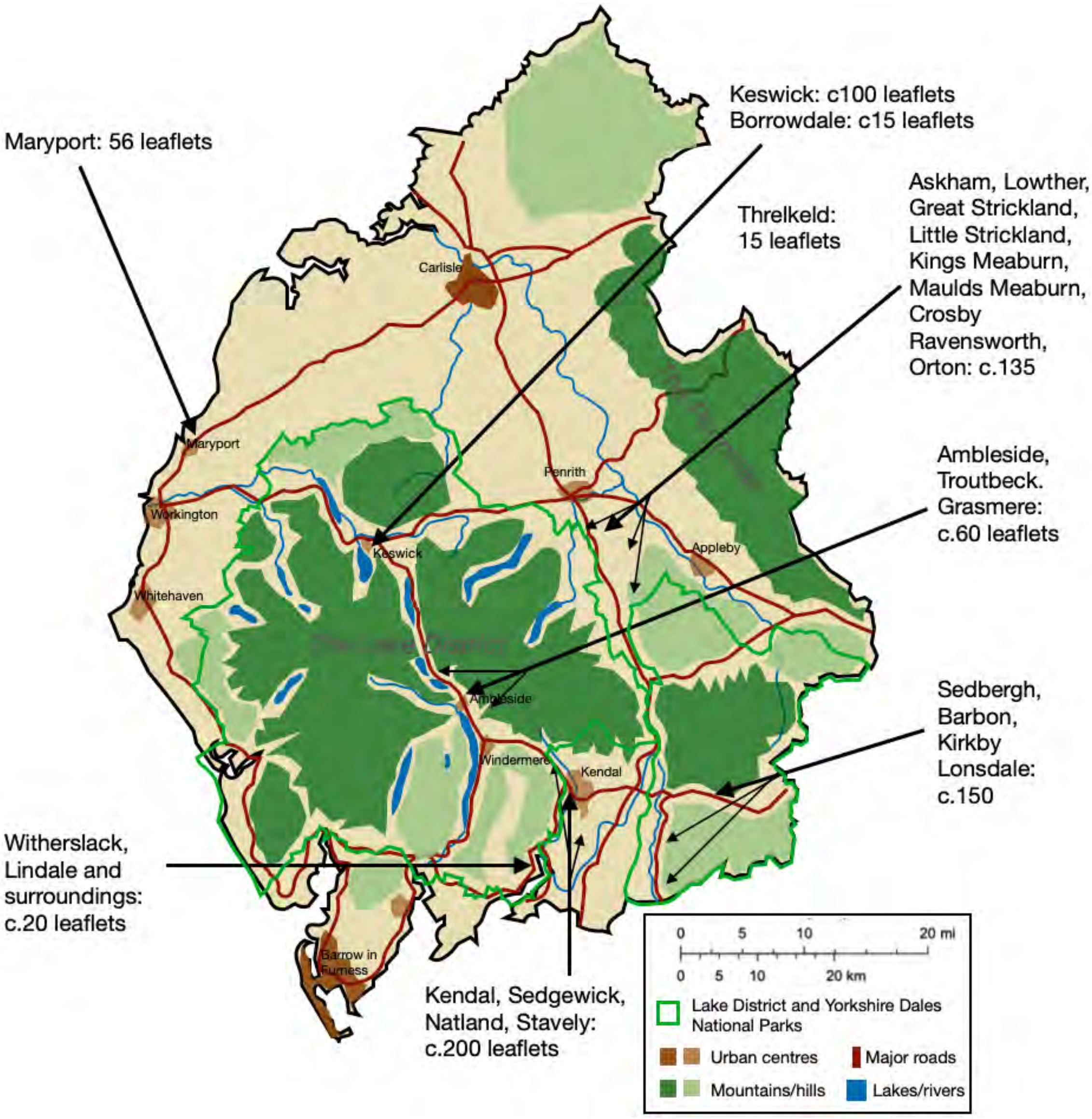


Figure 3.5: Survey invitation leaflet distribution



As a result of the varied distribution channels, it was not possible to determine how many people in total had the opportunity to complete the survey. 484 people accessed the first page of the survey, 37 dropped out part way through the survey, and one person was screened out because they did not live in Cumbria. In total 147 respondents completed the whole survey and submitted their responses. Respondents were submitted by residents across Cumbria with a range of different building types and ages which were reasonably representative of the Cumbrian building stock (Appendix K).

Survey analysis

Many forms of statistical analysis can be used to assess the numerical results of surveys (Ruel et al., 2016; Andres, 2012). However, if surveys are not designed to be statistically representative then only limited statistical analysis is considered appropriate. This includes the development of descriptive statistics, cross-tabulations and basic inferential statistics (Andres, 2012; Sapsford, 2007). The use of more complex inferential statistics such as multivariate analysis or regression analysis is generally deemed inappropriate for non-statistically representative survey research (Andres, 2012; Sapsford, 2007).

The survey data was exported into SPSS (IBM Corp, 2017) where it was cleaned, and descriptive statistics were produced. Various cross tabulations and a small number of inferential statistics (using independent sample t-tests and Mann-Whitney U tests) were developed for key results to help inform the descriptive analysis. Free text responses to open questions were imported into NVivo (QSR International Pty Ltd, 2019) where they were analysed thematically. Five respondents asked for their free text comments not to be published and this request was honoured.

As part of the sequential and abductive research design, the survey informed the selection of the nested case studies, questions for the nested case interviews, and the development of the energy diaries.

3.3 Nested case studies

Nested case piloting

An additional case was selected as a pilot for the interview, retrofit matrix and building tour elements of the nested case study. This pilot helped to develop the interview questions and confirmed the ability of the building tour to provide rich and relevant information. It also provided thorough testing of the recording equipment and retrofit option matrix. The pilot participants were asked for their feedback on the process, which helped to refine the interview questions. The audio recording was transcribed, and a summary was created to test the transcription process and to enable reflection on the quality of the data. Reflection on this piloting and the data from the survey led to the development of energy diaries for participants to complete, thus increasing the understanding of residents' energy behaviours. This was consistent with the abductive research design. Data from the pilot case study on heritage values was included in Chapter Four, other pilot data was not included as the questions and methods developed between the pilot and rest of the cases.

Nested case recruitment

The nested case study participants were recruited from the respondents to the survey who were invited to contact the researcher if they were interested in taking part in further research. Nested case participants were not linked to their survey response, which was completely anonymous. 24 respondents expressed interest in being a nested case and, after assessing initial information, this number was reduced to 18. It was decided that all those who were willing to take part would be developed as case studies to cover a diverse range of building types, ages, locations, household compositions and energy demand and to explore the research questions in a range of different contexts (Yin, 2014). This selection was consistent with Flyvbjerg's (2006) theory of maximum variation selection, meaning that if findings held true across the various nested cases then they were highly likely to have wider applicability.

Prospective participants were given information about the process and had the opportunity to ask questions before signing the ethical consent form which was approved by the University's ethics committee (for information sheet and consent form see Appendix C).

As a result of the Covid-19 pandemic two participants dropped out during the research process. A total of 16 nested case studies were therefore developed. For simplicity the nested case studies will be referred to just as 'case studies' or CS throughout the remainder of the thesis and the case study of Cumbria will be delineated as the 'overarching case study' (Table 3.4 and Figure 3.6).

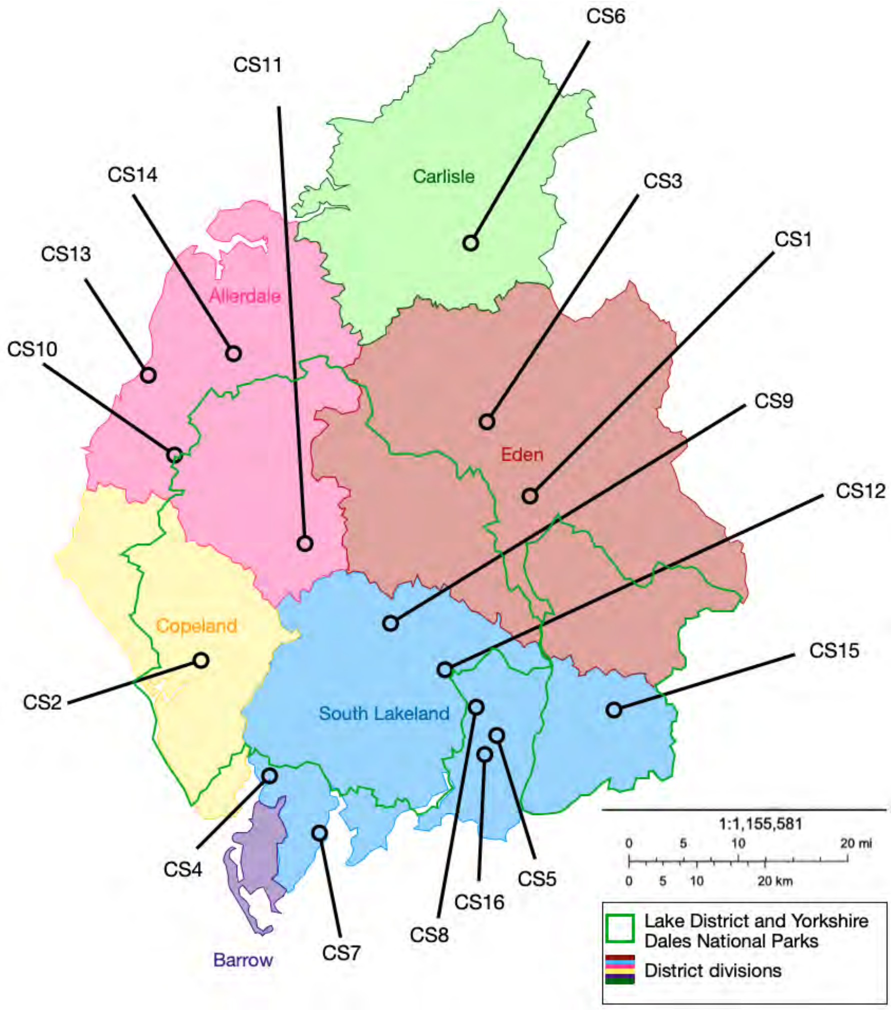
Table 3.4: Summarised details of nested case studies

Nested Case study	Location	Building age and designation	Description	Heating system	Household
PCS1*	Rural, South Lakeland	C.1676 Undesignated, Corner of L shaped farmstead	Former farmhouse, limestone	Biomass central heating.	(4) 2 adults, working. 2 children under 15
CS1	Hamlet, Eden	1820s with earlier elements Grade II Listed. Semi-detached	Georgian Squire's house. Sandstone	Oil central heating	(2) 2 adults, retired
CS2	Rural, Lake District	1740s. Grade II* Listed curtilage. Detached	Miller's cottage. Pink granite	Storage heaters with hydropower	(2) 2 adults, working
CS3	Town, Eden	1928. Conservation area. Semi-detached	Stately home in miniature. Red sandstone.	Gas central heating	(5) 2 adults, working. 3 at university
CS4	Hamlet, South Lakeland	1850s, on site used since 13th century. Undesignated. Detached	Mill building with some machinery still extant. Siltstone	Gas central heating	(2) 2 adults, retired
CS5	Village, South Lakeland	1897 with earlier elements. Undesignated. Detached	Late Victorian house, former chapel. Limestone	Gas central heating	(2) Two adults, retired
CS6	Village, Carlisle	Early 1700s with Victorian extension. Conservation area. Detached	Large, detached former farmhouse. Rendered sandstone	Gas central heating	(2) 2 adults, semi-retired
CS7	Hamlet, South Lakeland	1789. Undesignated. Detached	Large Georgian farmhouse. Rendered fieldstone	Oil central heating	(2) 2 adults, semi-retired
CS8	Town, South Lakeland	1871. Conservation area. Mid-terrace	Four storey Victorian townhouse. Limestone	Gas central heating	(2) 2 adults, retired
CS9	Large village, Lake District	1896. Conservation area. Mid-terrace	Small late Victorian house. Slate	Gas central heating	(2) 2 adults, working
CS10	Rural, Allerdale	Undesignated. Semi-detached	Part of former mill building. Sandstone	Propane gas central heating	(4) 2 adults working, 2 children under 10

Nested Case study	Location	Building age and designation	Description	Heating system	Household
CS11	Hamlet, Lake District	1760s. Undesignated. Mid-terrace	Small cottage. Slate	Wood stove in living room	(1) 1 adult, working
CS12	Village, South Lakeland	1600s/1700s. Conservation area, mid-terrace	Very small terrace, limestone	Gas central heating	(3) 2 adults working, 1 child under ten
CS13	Coastal town, Allerdale	1834. Grade II listed. Semi-detached	Georgian, former courthouse. Sandstone	Gas central heating	(2) 2 adults, working
CS14	Rural Allerdale	1770s. Undesignated. Semi-detached	Georgian farmhouse. Sandstone/cobble	Gas central heating	(4) 2 adults, working. 2 children under 10
CS15	Small town, South Lakeland	1850s, Conservation area. Semi-detached	Victorian town house. Siltstone	Gas central heating	(1) 1 adult, retired
CS16	Village, South Lakeland	1700s, Undesignated, Detached	Large farmhouse, limestone	Gas central heating	(4) 2 adults, working. 2 children under 15

*Pilot nested case study included the interview, retrofit matrix and building tour only

Figure 3.6: Distribution of nested case studies across Cumbria



The case study site visits took place in late February and early March 2020. Each visit included a semi-structured interview and retrofit matrix, participant led building tour, technical building survey and the collection of energy data from utility bills or discussion with participants about taking meter readings to gather energy data.

Semi-structured interviews

Each of the nested cases included a semi-structured interview with residents. This involved the preparation of an interview schedule (Appendix D.1) with the list of questions or topics to be covered, although these were approached in a flexible manner depending on the participants' responses (Given, 2008).

Semi-structured interviews are considered to be a useful method for developing an in-depth understanding of the area of interest while retaining a greater level of focus than completely unstructured interviews (Theirbach et al., 2020; Given, 2008) (Figure 3.7). Semi-structured interviews can also provide opportunities to ask follow up questions and delve more deeply into participants' answers than would be possible through the use of a survey (de Chavez et al., 2017; Given, 2008). The use of multiple semi-structured interviews also provides opportunities for the answers to similar questions across different interviews to be compared to identify similarities and contrasts (Given, 2008).

Figure 3.7: Case study interview topics

These types of interviews can be used in research on residential buildings to provide an understanding, not only of what residents do but of why and how they do it (de Chavez et al., 2017). Interviews can add richness and depth to the understanding of residents' views, details of how they behave in their homes and why they engage in these behaviours (de Chavez et al., 2017). Interviews have been identified as a useful part of a mixed method and case study research design because they provide specific and in-depth knowledge (Theirbach et al., 2020; Yin, 2014). Interviews were conducted with one or sometimes two household members, dependant on residents' choice (Nowicka, 2022; Sunikka-Blank and Galvin, 2016) (Table 3.5).

Table 3.5: Number of case participants taking a substantial part in site visit

Participants	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
No.	2	2	1	1	1	1	2	1	1	1	1	2	2	1	1	1

The interviews were audio recorded using the Voice Record Pro 7 app for iPhone (Dayana Networks Ltd, 2021). Once recorded the interviews were transcribed by the researcher, using the program Express Scribe to slow the recording for ease of typing (NCH Software, 2019). The completed transcript was sent to participants to give them the opportunity to correct any errors and confirm that they were happy with the details recorded.

Interview transcriptions can be analysed in a variety of ways depending on the purpose of the analysis and the questions being addressed (Arksey and Knight, 1999). Thematic analysis was used to identify patterns and themes in the data set, thus allowing overall conclusions to be drawn from the individual interviews (Fugard and Potts, 2020; Braun and Clarke, 2006). Summaries were created of the completed transcripts, and these were analysed individually and across cases to identify themes, similarities, and differences. Thematic analysis requires extensive familiarity with the data and the use of comparison both to similar topics within interviews and to similar topics in other interviews to help develop themes and sub-themes (Fugard and Potts, 2020). Themes were developed until 'saturation' was reached which is when no new themes are discovered through the acquisition of additional data (Fugard and Potts, 2020; Braun and Clarke, 2006).

The use of interviews within a case study research design is therefore considered a useful way to add depth to the research (Theirbach et al., 2020; de Chavez et al., 2017) It can help to answer how and why questions and allows more detail than more structured survey methods (Yin, 2014).

Retrofit option matrices

In addition to the interviews, participants were invited to complete a sheet providing a matrix of retrofit options. The retrofit matrix used the same list of retrofits as the survey, with the addition of wind turbines, heating control improvements and four potential behaviour changes; reducing heating temperatures, not heating bedrooms, turning heating off when away and only heating actively used spaces. These additional measures were identified through the survey. Participants were asked to indicate for each measure, whether they had it already or, if not, whether its effect on heritage values or aesthetics, planning constraints, its cost or any practical implications would be an issue for them. These potential barriers were identified from the literature as likely to commonly influence residents' retrofit decisions (Sunikka-Blank and Galvin, 2016; Mallaband et al., 2013). They were also asked to state overall whether the measure would be something that they would consider or not and if there were any other issues that would affect their decision. The matrix can be seen in Appendix D.2.

The use of this matrix is akin to the use of more structured interview techniques or surveys (Given, 2008) and was useful because it produced data in a format which was readily comparable between different nested cases and which could be assessed both quantitively and qualitatively. This matrix was developed from the concept of visual elicitation methods and acted as a stimulus to prompt a more thoughtful response than verbal questioning alone could have achieved (Crilly et al., 2013). The use of a structured physical document can help to focus discussion about a common framework. This was considered useful for a complex topic such as retrofitting decision making. The matrix was used to prompt participants to think through at least some of the common factors which the literature identified as likely to influence residents' decisions.

Participants were also asked to describe their thought process as they completed the matrix, this was audio recorded and transcribed in the same way as the interviews. The transcript and retrofit matrices were used in tandem to create a colour coded, digitised version of the retrofit matrix for each case summarising their choices and reasoning. Completed matrices were sent to participants to confirm that their data sheet had been interpreted correctly. The retrofit matrix acted as a complementary element to the wider interviews, helping participants to articulate their opinions more clearly (Crilly et al., 2013).

Building tours

During site visits to the nested cases, participants were asked to lead a 'tour' of their building, identifying features which they considered pertinent for heritage, energy, and comfort. These tours were designed to encourage participants to elucidate more general comments from the interviews with specific points about individual and contextual features. This method was designed as a form of place based interviewing which is considered useful for gaining a greater awareness of participants' attachment to a space (Riley and Holton, 2020). This technique is particularly appropriate when participants' buildings, and the values that they invest in them, are topics of interest (Sunikka-Blank and Galvin, 2016). The process of moving from place to place, or room to room, and being 'in-situ' has been recognised as acting as a prompt to develop more detailed data about people's experiences and views (Riley and Holton, 2020).

The building tours were audio recorded and, in addition, general photographs of rooms, and specific photographs of heritage and energy features were taken, except for CS1 who did not give permission for indoor photography. After each site visit, details from tours and photographs were combined to answer a checklist of questions (Appendix D.1) on energy behaviour and building details for each case. Online historic maps for each case study area were consulted where available to inform the understanding of the buildings' development. Where buildings were listed or in conservation areas the listing information and/or character appraisal document were consulted for additional historic information. These details were compiled in building summaries for each case and complemented the interview data.

This method provided additional opportunities to understand how residents felt about, and used, space within their buildings than could have been gained solely through interviews (Riley and Holton, 2020). It also provided an opportunity to understand the building's form and clarify specific details.

Energy diaries

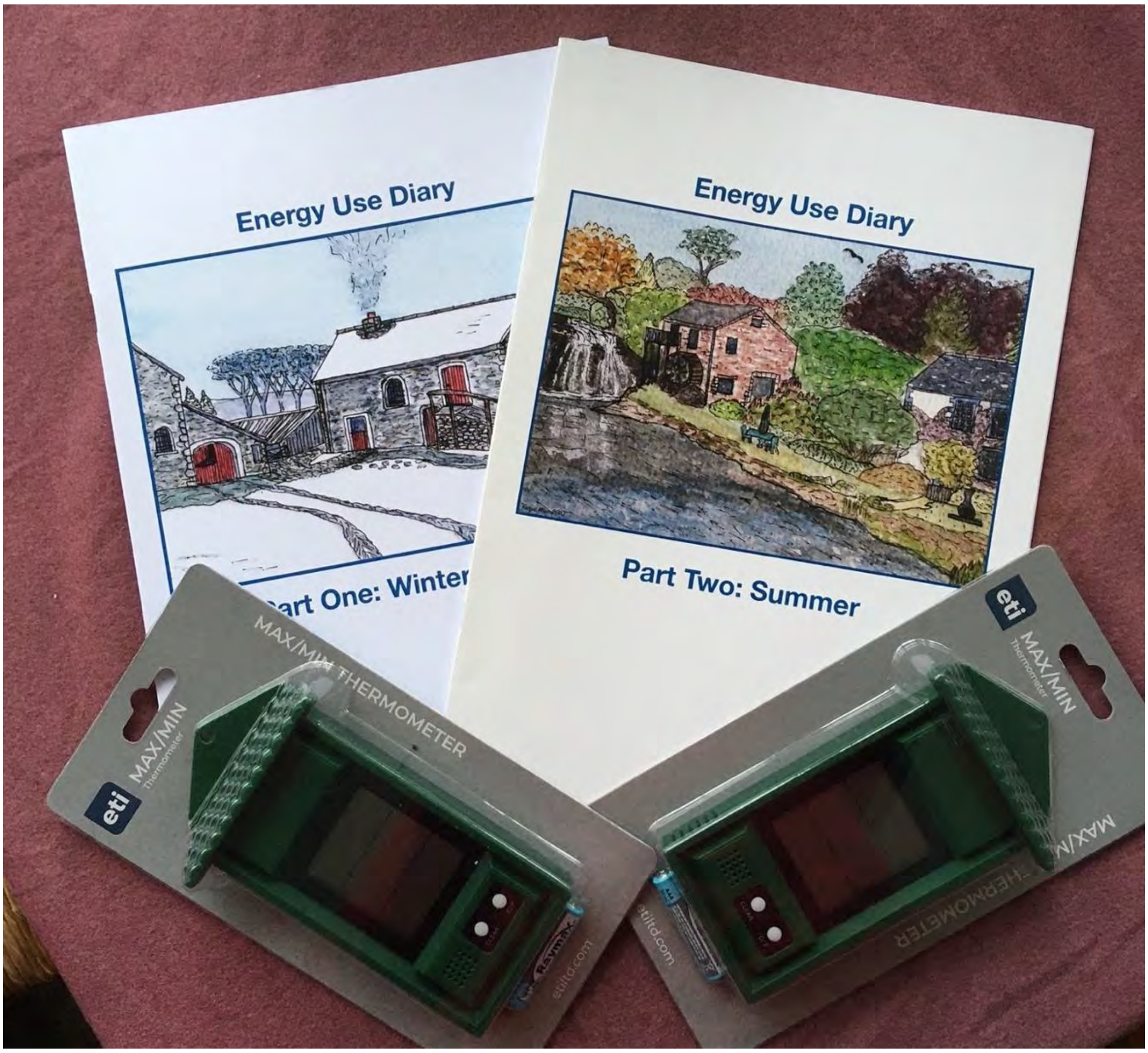
During the site visit participants were also presented with the first of two energy behaviour diaries. These diaries were developed to help increase understanding of participants' daily behaviours. Interviews take place at a specific point in time and therefore rely on memory when considering previous events and activities (Alaszewski, 2020). The use of research diaries can therefore help to gain more time relevant and detailed information about actions that are not easy to otherwise observe (Alaszewski, 2020). While data in diaries is still filtered by participants, it may provide more immediate and therefore potentially 'authentic' information than interviews (Alaszewski, 2020). Diaries may also provide more detail about everyday activities which would not be considered important enough for participants to discuss in interviews but which may nonetheless have significant relevance for research (Bennett, 2014).

Structured diaries, where participants are given a clear format to fill out, have been used, for example, in time-use studies, to understand energy use in buildings (Ibrahim et al., 2019; Anderson, 2016; Hiller, 2015). The completion of diaries at different times of year is considered useful when there is a focus on seasonal behaviours such as heating (Ibrahim et al., 2019; Adekunle and Nikolopoulou, 2014). For this research one diary was completed in winter/early spring and one in summer/early autumn. The diary was to be completed for five days in each period. Participants could choose the most appropriate days for them, with the proviso that a weekend and three weekdays were covered (Hiller, 2015). Because the nested cases were spread across Cumbia it was not considered necessary for participants to complete the diaries synchronously as climatic conditions were likely to vary in any case.

The energy diaries were piloted prior to deployment by members of the researcher's family. This took place over several days and several changes were made to make the diary clearer and more user friendly as a result. Participants were contacted before the site visit and asked if they would prefer to complete a physical or electronic version of the diary. A sample day from the diary can be seen in Appendix E. They were given the opportunity to read through the diary and ask any questions while the researcher was onsite and encouraged to follow up by email if necessary.

The use of technical measurements such as data loggers or similar in concert with participant diaries has also be identified as useful in energy research (Kane et al., 2015; Hong et al., 2009). Diary participants were therefore also provided with two digital thermometers (Figure 3.8). These recorded maximum, minimum and current temperatures and could be reset each day to gain an indication of internal and external temperature ranges (Electronic Temperature Instruments LTD, 2020). The use of data loggers could have provided more granular and accurate temperature, and potentially energy, use data. However budgetary constraints precluded the use of this more advanced technology, with one data logger having a similar cost to approximately ten thermometers. Because of the number required (two per case study) data loggers were therefore not affordable within the project budget. The thermometers provided less detail and were only accurate to within +/-1ºC but still provided a useful impression of general temperature variation which helped to develop understanding of the case studies' environment and performance.

Figure 3.8: Physical energy diaries and digital thermometers



Participants were asked to place one thermometer in their main living space and one outside their building. They were requested to check both the thermometers at a similar time every day, note down the three values and then reset the thermometer's memory. Participants were asked to place their indoor thermometers away from any heat sources such as stoves, televisions or computers and the outdoor thermometers in a sheltered location, out of direct sunlight. One participant developed a creative solution to sheltering his external thermometer (Figure 3.9). The importance of placing the thermometers in the same location for the second diary was also stressed. Advice on thermometer locations was provided to participants during the site visits. These thermometers have limited accuracy and variations in location and time that readings were taken meant that they provided only indicative values of general temperature trends.

Figure 3.9: CS3's 'Patented mk. II thermometer shelter''

Participants were not asked to take daily meter readings during the diary period because it was felt that this might be too demanding if meters were not easily accessible. However, when the winter diaries were returned several participants had provided daily meter readings. For the summer diary, participants were therefore encouraged to take meter readings if possible and a table was provided for them to note the figures. A number of participants who could not easily access their meters nonetheless provided a reading at the beginning and end of the diary period as an indicative value. The other alteration to the summer diary was the addition of a question on artificial lighting in all periods of the day. For the winter diary this had only been included for the evening period.

When the diaries were returned, all data was digitised, and summaries based on this data were created for each case study. The use of diaries and technical measurements alongside interviews has been identified as providing broader and richer data on the energy behaviours and comfort perceptions of residents than could be achieved by any of these methods alone (de Chavez et al., 2017).

3.4 Baseline energy modelling

Quantitative building surveys

Building energy simulation models are often used to assess current building energy performance and to model changes such as retrofitting to assess their potential impacts without needing to enact them (Carratt et al., 2020; Jain et al., 2020; Kane et al., 2015). This provides obvious advantages in terms of time, flexibility, financial cost, and disruption, in comparison to physically testing changes. However models may not provide accurate predictions of future performance if they do not reflect current performance, and are likely to be subject to a range of uncertainties around input data (Carratt et al., 2020). This can lead to what is termed, the 'performance gap' between actual and modelled performance (Jain et al., 2020; Tüysüz and Sözer, 2020). There is often a trade-off between the level of data collection and input required, and the scale of the performance gap (Jain et al., 2020; Pracchi, 2014).

Technical building surveys were undertaken of each of the case studies, following the participant led building tours, to provide sufficient data to create baseline energy models which reflected current energy performance. Input data for the models included building dimensions, construction materials and build-ups, operational systems, and details of occupant behaviour (Carratt et al., 2020; Jain et al., 2020). Measurements of internal building dimensions, orientations, and thicknesses and details of building constructions were gathered to create detailed plans for each case. Details of energy systems were noted during the survey and informed by participants' comments. Construction materials and build ups were determined from visual observation and information provided by participants -such as floor or wall construction identified during previous building work- as it was not possible to use destructive investigative techniques (Akkurt et al., 2020; Roberti et al., 2015; Pracchi, 2014). Details of residents' energy behaviours were gathered via the interviews, building tours and energy diaries.

Measured energy and carbon data analysis

A number of authors have identified the need to calibrate energy simulation models with actual data, both quantitative and qualitative, to increase accuracy and minimise the uncertainty inherent in models (Carratt et al., 2020; Tüysüz and Sözer, 2020). A common calibration method is to compare measured and predicted energy use. Smaller time steps, such as monthly instead of annual data, can provide increased calibration (Carratt et al., 2020; Federal Energy Management Program, 2015).

Energy use for the case studies was analysed using utility bills, residents' records, and meter readings. This data was provided by participants either during or after site visits, either in the form of original bills which were photographed or through copies of participants' records. This generally consisted of electricity and gas bills and most residents were able to provide data over multiple years, increasing the granularity of the data and allowing averages to be calculated that reduced skew from particularly warm or cold years. Utility bill data is official data that can provide an authoritative measurement of the actual energy use of metered fuels, (Carratt et al., 2020; Jain et al., 2020; Kane et al., 2015).

CS1 and CS7 used oil and CS11 used wood for their heating but all kept detailed records of their fuel use which enabled energy demand to be calculated. CS2 and CS15 provided detailed meter readings in place of energy bills but were unable to provide a full year of data, the assumptions made for estimating their annual energy use are described in Appendix H.2. Some participants also provided information on secondary, unmetered fuel such as log fires or stoves. This was not possible for all participants, so this energy use was not quantitively assessed although information on the frequency of secondary heating was examined to develop an understanding of this heating use.

Secondary data comprising official governmental, or intergovernmental, data such as building information from censuses or nationally produced energy statistics was also used in this research to provide authoritative and nationally recognised key statistics (MacInnes, 2020). This included information on the Cumbrian and UK building environment, average energy use for UK households and national carbon factors for different fuels (BEIS, 2021b; ODYSSEE-MURE, 2021a). This data can therefore provide a wider comparable context and, with the measured energy data, allowed the carbon emissions for each of the case studies to be calculated.

RdSAP energy modelling

EPCs for existing UK residential building are produced using RdSAP and, as discussed in Chapter Two, EPCs are increasingly being used as a policy tool to promote retrofit (BEIS, 2020a; European Commission, 2020). EPC certificates also include recommendations on potential building improvements and the UK Committee on Climate Change has recommended that all residential buildings should reach EPC band C by 2028 (CCC, 2020). A recent review commissioned by the government identified that RdSAP, is commonly used as the de facto modelling tool to inform many retrofit projects (Godefroy et al., 2021). An assessment of this tool was therefore considered valuable, especially in relation to other research findings about the potential inaccuracy of EPC modelling tools for older buildings (Gram-Hanssen, Georg, et al., 2018; Sunikka-Blank and Galvin, 2012).

Certification as a domestic energy assessor was undertaken to develop methodological competency with the tool, which is only available for use by certified assessors through proprietary interfaces developed by certification organisations. A three-day training course and further portfolio work was undertaken to achieve certification. Once certification was complete, a different certification organisation, Quidos, kindly provided access to their training tool which had all the functionality required for the research.

Using data gathered during the building survey and following the official conventions (Quidos, 2020; Department for Communities and Local Government (DCLG), 2017) EPCs were produced for each of the case studies. This ensured that the research assessments were comparable with actual assessments. These conventions include various details, for example on when basements should be included, how dimensions should be measured and what evidence on insulation is acceptable.

Following the creation of the RdSAP models, predicted energy demand was compared with the actual measured energy data provided by participants. Carbon emissions were also compared with current emissions, calculated using UK carbon factors for 2021 (BEIS, 2021b). EPC ratings from predicted energy use and official recommendations for improvements for each building were identified. It does not appear possible to produce EPC ratings from energy demand alone as they are effected by a range of other factors including energy costs (BRE and DECC, 2014) and the process is opaque. The RdSAP modelling was the first modelling element undertaken.

SBEM energy modelling

The second tool assessed was the Simplified Building Energy Model (SBEM), which is the UK tool for producing EPCs for non-domestic buildings (BRE, 2018). Unlike RdSAP or full SAP, a freely accessible version of the SBEM software was available from the National Calculation Methodology website and was used for the research (BRE, 2020a). SBEM requires increased data entry compared with RdSAP, but it is possible to define specific materials and to use more detailed building dimensions.

After completing the domestic energy assessor course, it was clear that RdSAP would not have the functionality required to produce detailed building energy models. Because the full SAP version was not publicly available, SBEM, as a more detailed official UK energy tool, was assessed as part of the abductive research process.

SBEM models were created for three of the case study buildings, CS1, CS5 and CS14, which provided a good range of different materials, constructions, and heating systems. These cases were modelled, using the data gathered during the case study site visits, to test the capabilities of the tool (see Appendix G) and help to answer research sub-question 2c. However, the outputs produced by the tool had low useability and it was not possible to model specific occupancy, heating, and equipment schedules, meaning that models could not be calibrated with actual usage. In addition, data entry was very time consuming, with the area and orientation of every internal and external wall, and every opening, needing to be manually defined and calculated. The three test cases were deemed sufficient to test the capabilities of this tool and compare them with the functionality and useability of both RdSAP and Design Builder.

Design Builder energy modelling

Building simulation tools can be steady state, where calculations are made on a monthly basis, or dynamic, where calculations are made on much shorter time frames, often half hourly. RdSAP and SBEM are both examples of steady state simulation models (Godefroy et al., 2021; Pracchi, 2014). Energy Plus meanwhile is a commonly used dynamic building simulation tool which was developed by the US Department of Energy and has been identified as one of the most commonly used tools for research involving building energy simulation (Carratt et al., 2020). Dynamic modelling is generally more accurate than steady state modelling but requires much higher levels of input (Godefroy et al., 2021; Pracchi, 2014).

Design Builder is a highly detailed, dynamic modelling tool utilising a 3D modelling environment, it acts as a user interface tool for the Energy Plus simulation engine (Carratt et al., 2020; Pohoryles et al., 2020). Using the data collected during the case studies, baseline energy models were created for each case using Design Builder. In addition to the actual building data, a number of assumptions were also required for the Design Builder models and can be seen in Appendix H.1. As a dynamic modelling tool, Design Builder requires hourly weather data for use in the simulations which determine the heating demands of the model. Because this level of detail was not available for individual case study sites, data from the closest weather stations -taking account of topography and climatic variation- was used for each case (more details are provided in Appendix H.3).

The Design Builder models were calibrated by comparing the predicted figures with the measured energy data from fuel bills and meter readings. Step-wise alterations to the model were then made on individual inputs where there is uncertainty (Tüysüz and Sözer, 2020), this could include for example, rates of air infiltration if these have not been assessed (Hubbard, 2011). Only one parameter was altered at a time to enable the impact of each change to be identified (Tüysüz and Sözer, 2020). It is also possible to perform sensitivity and uncertainty analysis to identify the influence of different input parameters, although this requires greater computing power than was available for this research. Further details on the calibration process can be seen in Appendix H.3.

3.5 Lifecycle assessment of retrofit potential

Lifecycle assessment (LCA) of the range of retrofit measures identified in the survey and retrofit matrices was undertaken to identify their potential carbon impact. Standards for LCA are covered in ISO 14040 and include the need to set out clear system boundaries describing what is included and excluded from the LCA (BSI, 2020). Variations in the system boundaries chosen can mean that the results of different studies are not directly comparable (Vilches et al., 2017; BSI, 2012). Only carbon was assessed for the lifecycle analysis because this impact had the most available data.

The LCA in this research followed the conventions for construction LCA set out in European standard BS EN 15978 (BSI, 2012). This includes a number of conventions, such as how on-site renewable generation should be reported. It also provides details on which processes should be included within an LCA and which should be excluded, for example transport of construction workers to and from site should generally be excluded but transport of materials and waste included. As with ISO 14040, BS EN 15978 emphasises the importance of describing the assumptions made during the LCA process. BS EN 15978 uses a process analysis method where the specific materials, components and processes involved are assessed (Birgisdottir et al., 2017; Moncaster and Symons, 2013). This is the most common method for LCA, although it will underestimate the full lifecycle impacts due to inevitable truncation errors where auxiliary services, such as the aforementioned transport of tradespeople, are considered outside the system boundaries (Moncaster and Symons, 2013; Crawford et al., 2010).

This modelling was a cradle to grave assessment in which lifecycle stages A to C were assessed (Table 3.6), cradle to grave is generally considered to provide the most comprehensive picture of lifecycle impacts (Birgisdottir et al., 2017). Following common practice, the embodied and operational impact of the retrofit measures was assessed over a 50-year period (Pomponi and Moncaster, 2016). However, because of the heritage nature of the building and uncertainty about lifespan, buildings were not considered to be demolished at the end of the assessment period. Stage C impacts were therefore only assessed for the removal of any current material when the retrofit measure was installed and for the end-of-life impact of any measures that required replacement within the 50-year assessment period. Because of the limited number of end-of-life impacts that fell within the assessment period, and the uncertainty around potential recycling opportunities, module D impacts around recycling and reuse were not included in the assessment.

Table 3.6: Retrofit lifecycle stages assessed

A1-A3			A4-A5		B1-B7						C1-C4				D
A1 raw material extraction	A2 Transport	A3 Manufacturing	A4 Transport	A5 Construction/installation	B1 Use	B2 Maintenance	B3 Repair	B4 Refurbishment	B5 Replacement	B6-B7 Operational impacts	C1 Deconstruction	C2 Transport	C3 Waste processing	C4 Disposal	Re-use/recycling beyond lifecycle
X	X	X	X	/	X	/	X	NA	X	X	X	X	X	X	NA
X = included in assessment, / = partially included, NA = Not assessed															

LCA is the key method for the assessment of lifecycle impacts for construction and retrofit (Moncaster et al., 2019; Birgisdottir et al., 2017). It is subject to international standards which emphasise the importance of clearly stating assumptions about what is and what is not included within system boundaries. The operational and embodied stages of the LCA are described in the following two sections.

Operational retrofit modelling

All simulation models involve the simplification of reality to some extent, and this is particularly true for heritage buildings. It is however still possible to create models that have a sufficient level of accuracy to usefully inform retrofit if these models are calibrated with measured performance data (Akkurt et al., 2020; Carratt et al., 2020). The use of energy simulations can therefore help to predict the potential carbon saving opportunities of retrofitting and help to inform decision making.

After an assessment of the capabilities of the three energy modelling tools, Design Builder was chosen as the tool to assess the operational (lifecycle stages B6-B7) potential of the retrofit measures. A specific package of measures based on EPC recommendations for each of the case studies to reach band C were also modelled in RdSAP to assess the effect of this policy. RdSAP additionally provides outputs on the effect of making all recommended changes to the building, which may produce a rating higher than C. These outputs were compared with actual energy demand and with the more detailed retrofit modelling. A sub-selection of the retrofit options was also modelled in SBEM, and these results can be found in Appendix G.

The main retrofit modelling took place in Design Builder using the calibrated baseline energy models to examine the operational energy and carbon potential of a range of retrofit measures. The retrofits modelled were mainly similar to those used for the retrofit matrix described above. Three insulation materials were modelled for each element of the building envelope to allow a comparison between different materials for the most common thermal retrofits. These included a ‘natural product’, a ‘standard’ or commonly used product and a ‘technical’ or rarer product. For ceiling insulation and internal wall insulation an additional ‘heritage sensitive’ product was also modelled.

The annual operational energy and carbon impacts of the retrofit measures were calculated, alongside the lifecycle assessment of operational carbon over fifty years. The UK electricity grid has decarbonised significantly in recent years and this trend is predicted to continue (BEIS, 2020c). This decarbonisation will affect the carbon savings from retrofit which includes electricity demand over the assessment period. Future grid decarbonisation has been accounted for when considering operational electricity savings over 50-years. Government forecasts were available until 2040 (BEIS, 2020c), after which an evenly distributed reduction until 2050 was assumed with zero emissions after 2050, in line with international carbon targets.

In addition to the individual retrofit measures, the lifecycle impact of measures combined into several packages was also assessed. These packages are described in detail in Chapter Nine and more details on the retrofit modelling can be found in Appendix I.

To ensure that the insulation materials/products modelled were realistic a small number of built environment professionals were asked to identify their top three products for each type of insulation. Results between professionals were compared and the most commonly listed products were chosen (Table 3.7). Both double glazed and triple glazed replacement windows were also modelled. Where possible, specific products for all the retrofit measures were modelled as more detailed performance data was then available.

Table 3.7: Insulation materials for retrofit modelling

Insulation Type	Cold roof	Warm roof	Internal wall	External wall	Solid floor	Suspended floor
Natural material	Sheep's wool	Woodfibre	Woodfibre	Woodfibre	Recycled foamglass	Recycled paper
Natural product	Thermafleece Cosywool	Gutex Thermoflex	Gutex Thermo-room	Gutex multitherm	Geocell foamglass	Thermofloc
Standard material	Recycled plastic	Mineral wool	Mineral wool	Mineral wool	Phenolic foam	Mineral wool
Standard product	Thermafleece Supersoft	Knauf Rocksilk	Knauf Omnifit	Knauf EWI Rocksilk	Kingspan Kooltherm	Knauf Omnifit
Technical material	Enhanced sheep's wool	Aerogel	Aerogel	Hempcrete blocks	Aerogel	Aerogel
Technical product	Thermafleece Ultrawool	Spaceloft	Spaceloft	Isohemp	Spaceloft	Spaceloft
Heritage material	N/A	Cork lime plaster	Cork lime plaster	N/A	N/A	N/A
Heritage product	N/A	Diasen Diathonite	Diasen Diathonite	N/A	N/A	N/A

Generic data from Design Builder templates was used for ground source heat pumps (GSHP) and air source heat pumps (ASHP) because there was a lack of manufacturer data in the correct format. Attempts to convert manufacturer GSHP data into an appropriate format failed. The GSHP heat pumps were therefore oversized for the peak heating demand of several of the case studies. However, this is likely to only have a limited effect on technical system performance. The financial cost of the system will be affected but detailed financial aspects are not being assessed in this research.

Some retrofit options such as wall hangings, curtains or similar measures that can be termed ‘soft retrofits’ may be challenging to model in simulation tools (Pender and Lemieux, 2020; Khan, 2018) or it may only be possible to model some aspects of their performance. Wall hangings, for example, have been shown to have significant thermal comfort benefits in terms of reducing draughts and increasing the temperature of surfaces (Khan, 2018; Pracchi et al., 2017) thereby reducing occupant heat loss to cold stonework, analogous to the improved comfort of a carpet on a cold stone floor. These types of changes are therefore likely to result in greater benefits than would be expected from their improvements to u-values and results of energy simulation models (Pender, pers communication, 2021).

The importance of considering the hygrothermal performance - which is the movement of heat and moisture through materials- of heritage buildings has been identified, as retrofit activities can disturb the moisture balance within the building envelope (Akkurt et al., 2020; Harrestrup and Svendsen, 2015). Due to the complexity of assessing hygrothermal performance many studies focus on individual building elements instead of whole house assessments, often focussing on wall insulation, which has the most potential for harm (for example Jensen et al., 2020; Litti et al., 2015; Zagorskas et al., 2014).

In Design Builder it is only possible to conduct hygrothermal assessment for one element of a construction build-up at a time. This was considered impractical for the scale of modelling required and hygrothermal assessment has therefore not been undertaken in this research. In compensation, appropriate thicknesses of insulation materials, especially in wall build-ups, have been chosen, following guidance in Morgan (2019) and the AECB’s Carbon Lite Retrofit course (n.d.) on moisture sensitive retrofit. At least one moisture permeable insulation material has also been modelled for each envelope element. Further investigation of retrofits' hygrothermal impact should be carried out before any measures are put into practice (Morgan, 2019).

Embodied carbon assessment

The embodied carbon assessment for the retrofit measures covered lifecycle stages A, B1-5, and stage C and followed standard EN 15978. LCA information was based on specific product Energy Performance Declarations (EPDs) which provide at least cradle to gate LCA for individual products such as insulation materials or heating system components (Birgisdottir et al., 2017). There are national and international databases of EPDs which follow the international standards described above (Anderson, 2022a), such as The International EPD System (EPD International, n.d.). EPDs also include information on product lifespans. Where no EPD was available generic product data was used, for example for biomass boilers. For some measures, for example curtains or shutters, where no data was available, a proxy product with similar characteristics was used. Some applicable data was identified using the software OneClickLCA (OneClickLCA, 2021), which can be used to select products from EPDs, national databases and lifecycle material inventories, alongside other input data, to aid the development of building LCA.

Lifecycle stages A1-A4 were assessed for all the materials. Construction impacts (A5) such as groundworks for the GSHP or scaffolding for the installation of external wall insulation were not assessed because of data availability. Additional products required for installation such as putty for window replacement was however included in the assessment, as was a 2% wastage factor for all materials. For retrofit the construction/installation stage was considered to have a limited impact on overall embodied carbon. Maintenance (B2) was included where specific data was available from product EPDs, such as for cleaning for wall hangings, or repainting for wooden windows. Refurbishment (B4), which relates to replacement due to choice, such as redecorating rather than the end of a measure's lifespan (De

Wolf et al., 2017), and re-use/recycling of products (D) were not assessed due to uncertainty around timespans and outcomes.

No information is included in the standard around the modelling of alternative future scenarios to the retrofit considered (BSI, 2012). In common with approaches in the literature, the embodied emissions that would take place in the baseline building over the assessment period if retrofit was not undertaken, such as the replacement of boilers, structural or floor coverings, and similar is therefore not included in the assessment (Asdrubali et al., 2019; Iyer-Raniga and Wong, 2012). This is partially because the scope of the LCA only considers processes relevant to the retrofit measures and partially because of the uncertainty in predicting future building changes. It is likely, for example, that residents will replace their existing boiler at least once within the 50-year period. However, CS1's boiler is currently over 40 years old and came to them as a recycled product from another house. Furthermore, in the context of decarbonisation policies, the replacement of boilers is likely to require replacement with low carbon heating systems in the next decade (BEIS, 2021a), but what this system would be for a specific building is uncertain. The only non-retrofit scenario considered was the continued use of compact fluorescent (CFL) lightbulbs rather than their replacement with light emitting diode (LED) bulbs because there was more certainty in the alternatives available.

Biogenic carbon is that which is present in natural materials such as wood. In the context of retrofit this could include wooden shutters or curtain poles. The carbon is stored in the material for the duration of its lifespan and is then re-emitted when the material is disposed of. It is therefore properly a carbon delay, rather than a carbon saving. Because the case study buildings are not considered to be demolished at the end of the 50-year assessment period, biogenic carbon is reported separately. Further information on the LCA process and the assumptions made can be found in Appendix J.

3.6 Research timeline and covid impacts

Covid-19 adjustments

Some adjustments to data collection were required as a result of the Covid-19 pandemic. All case study site visits had been scheduled between the 24th of February and the 30th of March 2020. 12 of the 18 visits had been completed by the 17th of March, however the remaining six visits then had to be postponed as a result of the pandemic in the UK. Two of these cases where unable to continue participating in the research because of changed circumstances due to the pandemic.

Visits to the remaining four cases however were finally conducted virtually in late 2020 and early 2021. It was not possible to conduct quantitative building surveys for the virtual cases, meaning that retrofit potentials were not modelled for three of these cases. A personal connection with the participants of CS12 however meant that it was possible to conduct a building survey in a covid secure manner, when they were away for several weeks, leaving their building empty and following a risk assessment. The other elements of the site visit for CS12, interview, retrofit matrix and building tour then took place virtually.

Virtual visits were conducted using Microsoft Teams or Zoom, dependant on participants' preferences. Two of the virtual visits (CS10 and CS12) were split into two parts to fit around childcare commitments. The same questions were asked in the virtual interviews as in the physical interviews to increase comparability although there was an additional question about the effect of the pandemic on energy behaviours. The virtual interviews were audio recorded. To enable the completion of the retrofit matrices the researcher shared their screen and acted as scribe for the participants as they talked through their choices. Virtual building tours worked surprisingly well, and participants' broadband connections were robust enough in most areas of the buildings, with only minor problems. Tours were recorded using Teams'/Zoom's record function. As part of the analysis the tours were transcribed, and appropriate frames were taken from the recording in lieu of photographs. Once this had been completed the recording itself was securely destroyed.

Optional Photo elicitation

During the delay resulting from the pandemic, in the summer of 2020 an optional photo elicitation activity was presented to the case study participants. Photography is often used to help elucidate contexts and intangible feelings that are hard to convey verbally and is becoming an increasingly popular tool for interdisciplinary and collaborative research (Pauwels, 2020; Lapenta, 2012). Photo elicitation was also used by Fouseki et al (2020) in the context of identifying residents' heritage values.

Participants were invited to take 1-3 photos of heritage features of their building which they valued and to write a short explanatory paragraph for each photo. They were encouraged to consider both tangible and intangible values as part of the activity and to define heritage value in the broadest possible sense (see Appendix F for information sheet). All participants gave permission for their photographs and textual explanations to be shared in research publications and acknowledged that this might mean their buildings were more easily identifiable. To increase anonymity the photos and quotes are included using pseudonyms which are not linked to the case study numbers. Seven of the 16 cases participated in the photo elicitation activity.

The use of visual elicitation by participants can often be more participatory than other forms of research, allowing participants the freedom to identify and frame their visual material, although there is still clear researcher influence through the brief provided (Mannay, 2014). Participants may be encouraged by this method to provide opinions more freely that they may do verbally (Pauwels, 2020). Not all participants may be comfortable, or have the time to engage in image production however (Mannay, 2014) which is why this activity was framed as optional. It provided an additional and useful opportunity to elucidate residents' views from a different perspective and to help to identify more complex and specific heritage values.

Covid-19 impacts on case study energy use

The pandemic also required some of the winter energy diaries to be postponed until winter 2020/2021 rather than late winter/early spring 2020. Summer diaries and winter diaries after March 2020 were posted to participants rather than delivered as part of the site visit. Accompanying instructions were sent and participants were encouraged to ask any questions about the completion of the diaries via email. Participants very kindly arranged to post completed diaries back to the researcher. It was not possible for CS13 to complete their summer energy diary.

An additional question was included in the summer energy diary, and added to later winter diaries, about the impact that Covid-19 and the National lockdowns might have had on participants' energy behaviours throughout the diary period. Most participants stated that their behaviours hadn't changed that much although some adjustments were highlighted (Table 3.8). Many participants already worked either partially or completely from home prior to the pandemic. This is representative for Cumbria which has a high percentage of home working and retiree households (Cumbria Local Enterprise Partnership, 2019).

Table 3.8: Covid-19 effects on case study energy use reported in diaries

	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
Reduction in going away		X	X		X		X	X	X			X			X	
Increased screen use from online meetings	X		X			X	X			X		X	X	X		X
Increased home working			X			X				X		X		X		X

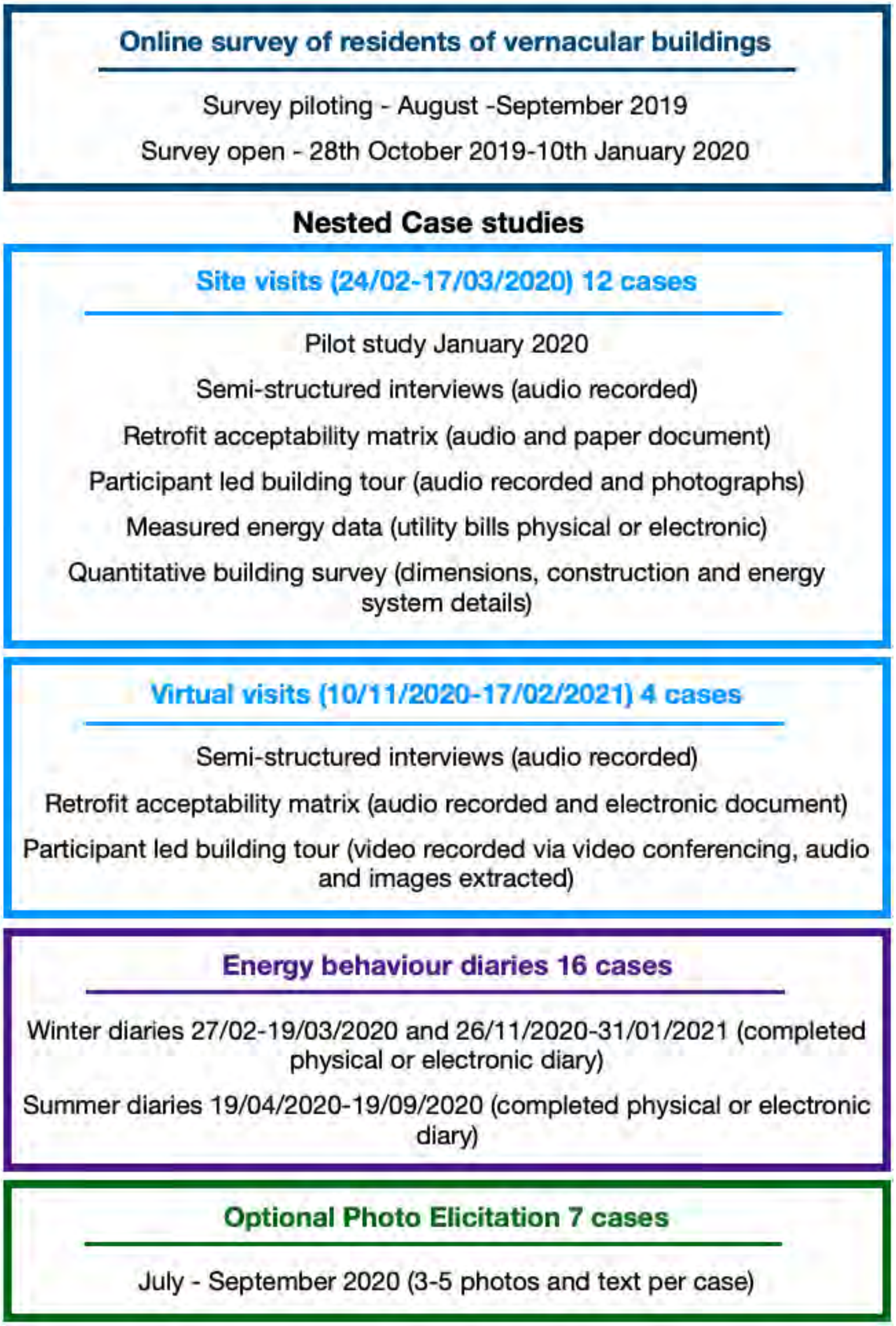
	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
Increased frequency and temperature of clothes and dishwashing	X							X								
Increased daytime occupancy										X		X		X		X
Increased occupancy*			X			X										

*CS3 had full occupancy (all five members of the household) for a longer period of time than typical, resulting in increased energy use.
*CS6 had significantly increased heating use from March to December 2020 due to the presence of an elderly relative.

Research timeline

The various types and sources of data, and the timelines of data collection can be seen in Figure 3.10.

Figure 3.10: Research timeline and data points



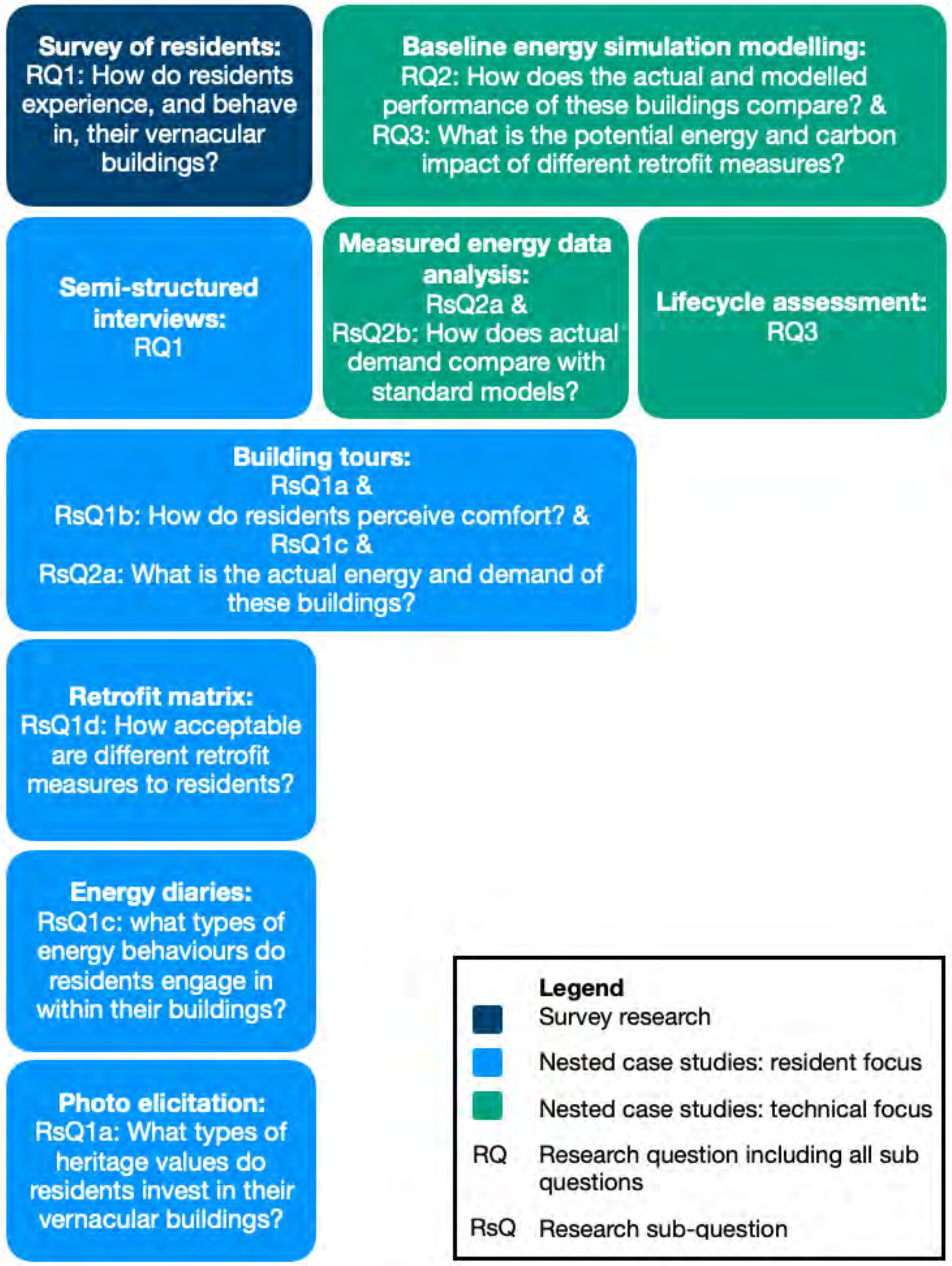
3.7 Mapping research questions and methods

This research used a range of different methods within a case study design to provide multiple points of evidence (Byrne, 2020; Yin, 2014). The use of these multiple methods enabled interdisciplinary research questions to be addressed and provided both breadth and depth to the understanding of the topic (Theirbach et al., 2020; de Chavez et al., 2017; Doyle et al., 2016). The research methods can be mapped onto the research questions identified Chapter Two (Figure 3.11).

The exploratory survey provided an overview of the experiences and views of a large number of Cumbrian residents (Ruel et al., 2016). The multiple methods included in the nested case studies complemented each other and provided a rich and in-depth understanding of residents' experiences, attitudes and behaviours (Theirbach et al., 2020; Yin, 2014). The detailed understanding of the nested case studies then allowed the potential of a range of retrofits to be assessed in a real-world context through the energy simulation and lifecycle assessment.

The survey results informed the development of the nested case studies. The energy modelling was dependant on the data collection from the nested case studies and the retrofit assessment was informed by the understanding of residents' views, values and behaviours that was developed through the survey and nested cases. Three phases of energy modelling were undertaken because the results of the first two phases were assessed as insufficient. An additional method involving optional photo elicitation was also developed during the process of the research to provide an extra point of evidence.

Figure 3.11: Research methods mapped onto the research questions



The multiple points of data gathered in this research complemented each other and provided the breadth and depth of information around the complex relationship between residents and their buildings to allow the potential of retrofit measures to reduce carbon while retaining heritage to be assessed.

This interdisciplinary, mixed methods approach thus addressed the research aim.

Some material in this chapter has been previously published in (Wise, Jones, et al., 2021; Wise, Moncaster, et al., 2021)

Figure 3.12: CS1 and CS2

Chapter 4. Heritage values

4.1 Introduction

The attention paid to heritage value in retrofit projects is often limited to an awareness of the constraints that planning policies may have on alterations for designated buildings (Cassar and Fouseki, 2014). Residents appear to invest their own values in their buildings, however, and these values are varied and individual, but often overlooked (Sunikka-Blank and Galvin, 2016). Understanding the heritage values of residents' may affect, not only the acceptability of different retrofit options (examined in Chapter Five) but also how residents view their buildings, their behaviours within them and the types of information and guidance that they may access. It also has implications for how many homes are nationally recognised as heritage buildings and thus how they may need to be approached for retrofitting.

This chapter uses data from the survey, the case study interviews and building tours and the photo elicitation activity to identify the heritage values that residents invest in their buildings (research sub-question 1a (RsQ1a). It explores the link between residents' values and official heritage designation. The importance of a broad range of both tangible and intangible values that residents invest in their building is examined before four themes are explored in more detail. Finally, the ways that these values effect residents' connection to, and perception of, their homes is considered.

Throughout the rest of this thesis those who completed the survey will be referred to as respondents, while those who took part in the case studies will be referred to as participants. Residents will be used as an overarching term to refer to all those who took part in any aspect of the research.

4.2 Relationship between residents' heritage values and official values

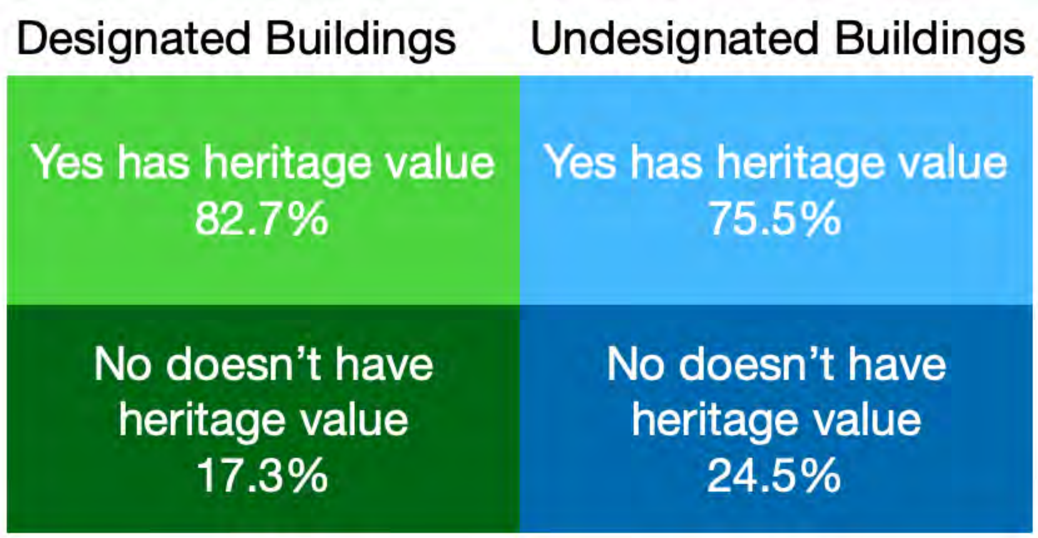
Heritage buildings are often identified by their official designation in policy, including individual Listed buildings which are deemed to have exceptional heritage value, and conservation areas where a certain grouping of buildings is considered to provide value. National Parks may also provide recognition of buildings because of their impact on the wider landscape. However many undesignated buildings can also have important heritage values (Herrera-Avellanosa et al., 2019).

Residents in this research occupied a range of both designated and undesignated buildings of different ages and types (Case studies: Table 3.4, Survey: Appendix K). All of the participants in the 16 case studies were found to invest heritage value in their homes. More broadly the majority (80.7%) of the 147 survey respondents also considered their buildings to have heritage value. These values can relate to a range of different aspects (Chapter Two), so for the survey, the following example of heritage value was provided:

'Heritage value can include things like: historic value; uniqueness; aesthetic values; values for the local community (i.e., a local landmark); forming part of a distinctive landscape; etc, although this is not exhaustive.'

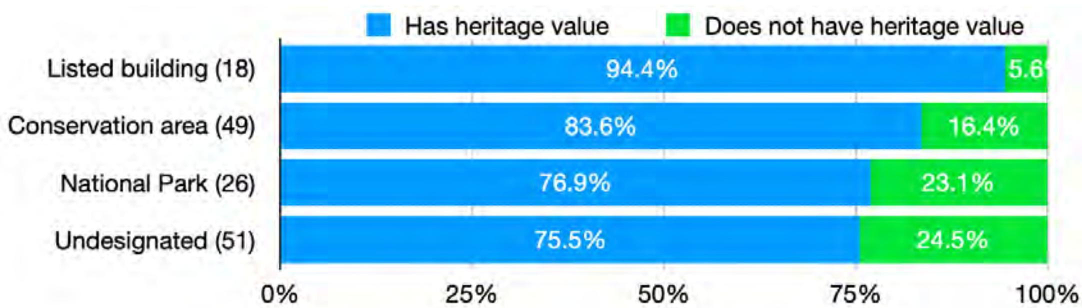
As would be expected the percentage of survey respondents who identified heritage value differed somewhat by levels of designation. However over three quarters of the respondents in undesignated buildings still felt that their buildings had heritage value, only 7.2% less than respondents in designated buildings (Figure 4.1).

Figure 4.1: Survey respondents heritage value response in designated and undesignated buildings (N = 147)



Considering more detailed designation categories, only 8% less respondents in undesignated buildings ascribed heritage value to them than respondents in conservations areas, while values for respondents in national parks are very similar for undesignated buildings (Figure 4.2). The 28 respondents who did not recognise heritage value in their buildings lived in a range of building types, ages, and designations (Appendix L.1). This suggests that values may be related to respondents' perceptions and not only a product of building characteristics.

Figure 4.2: Survey heritage value responses across different designation groups.



These survey results clearly indicate that the majority of respondents invest heritage value in their homes and that these values exist independently of official designations.

Participants in the nine designated and seven undesignated case studies all identified that their buildings had heritage values. A distinction did appear however in how participants defined their building. Several participants in undesignated buildings expressed uncertainty as to whether their home was a heritage building or not, often citing a lack of designation (CS5, CS7, CS10, CS14, CS16).

CS5: Possibly not... I don't know how you would define a heritage building but it's not listed… [undesignated]

CS16: It's got a lot of history…, I don't know, it depends on the definition... [undesignated]

This distinction may be related to the fact that a number of participants in undesignated buildings appear to associate the term 'heritage building' with listed or significant older buildings and felt the need to emphasise the modest nature of their own homes (PCS1, CS5, CS7, CS14).

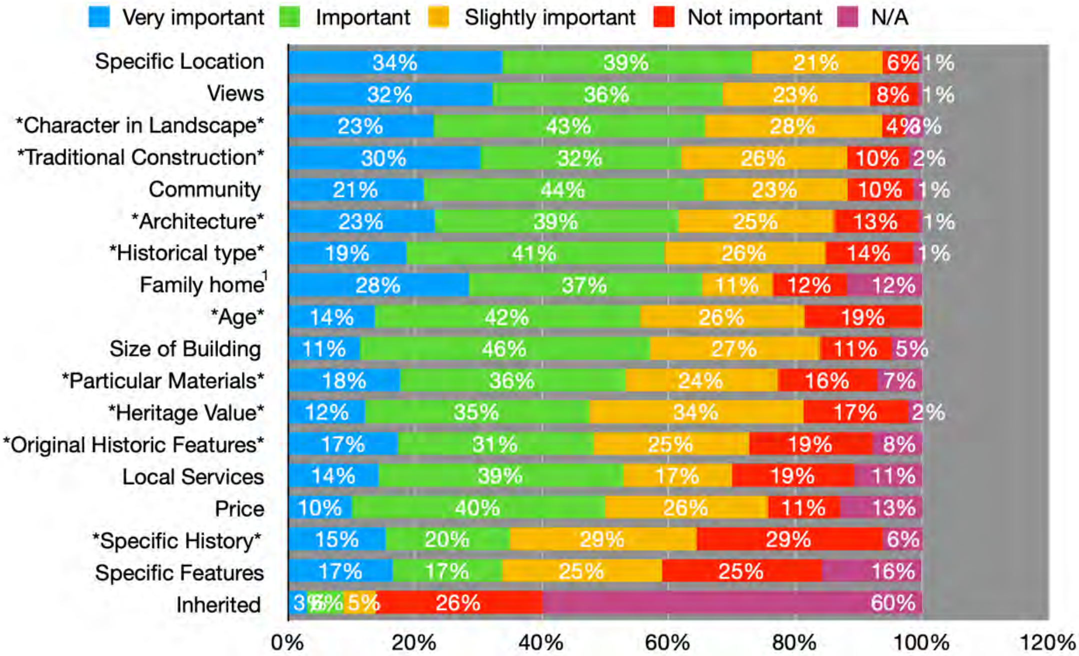
CS14: I suppose it is [a heritage building], but I don't personally think of it in that way… I'm not sure I would have applied the word heritage to it… it sort of implies a certain importance and one of the things that I like about this building is that it doesn't have delusions of grandeur.

In contrast, participants in designated buildings appeared more thoroughly convinced of their homes' heritage status (CS2, CS3, CS8, CS9, CS13), although CS12 and CS15 both felt that their home might only be 'a modest heritage building' (CS15). Designation therefore appears to have a limited influence on residents' perceptions of value, although the case studies suggest that it may influence how residents define their buildings.

4.3 What do residents' value? An overview

The survey respondents were asked how important a range of different heritage and non-heritage aspects of their building and its locality were to them (Figure 4.3). The two aspects considered most important by the highest number of respondents overall were 'specific location' and 'views', while the two *heritage* aspects identified as most important by the most respondents were ‘character in the landscape’ and ‘traditional construction’. Of the nine aspects that the majority of respondents identified as the most important (down to and including ‘age; in Figure 4.3), five were related to heritage value. Meanwhile only three of the nine least important aspects were heritage related, indicating that most respondents considered heritage related aspects to be important qualities for their homes.

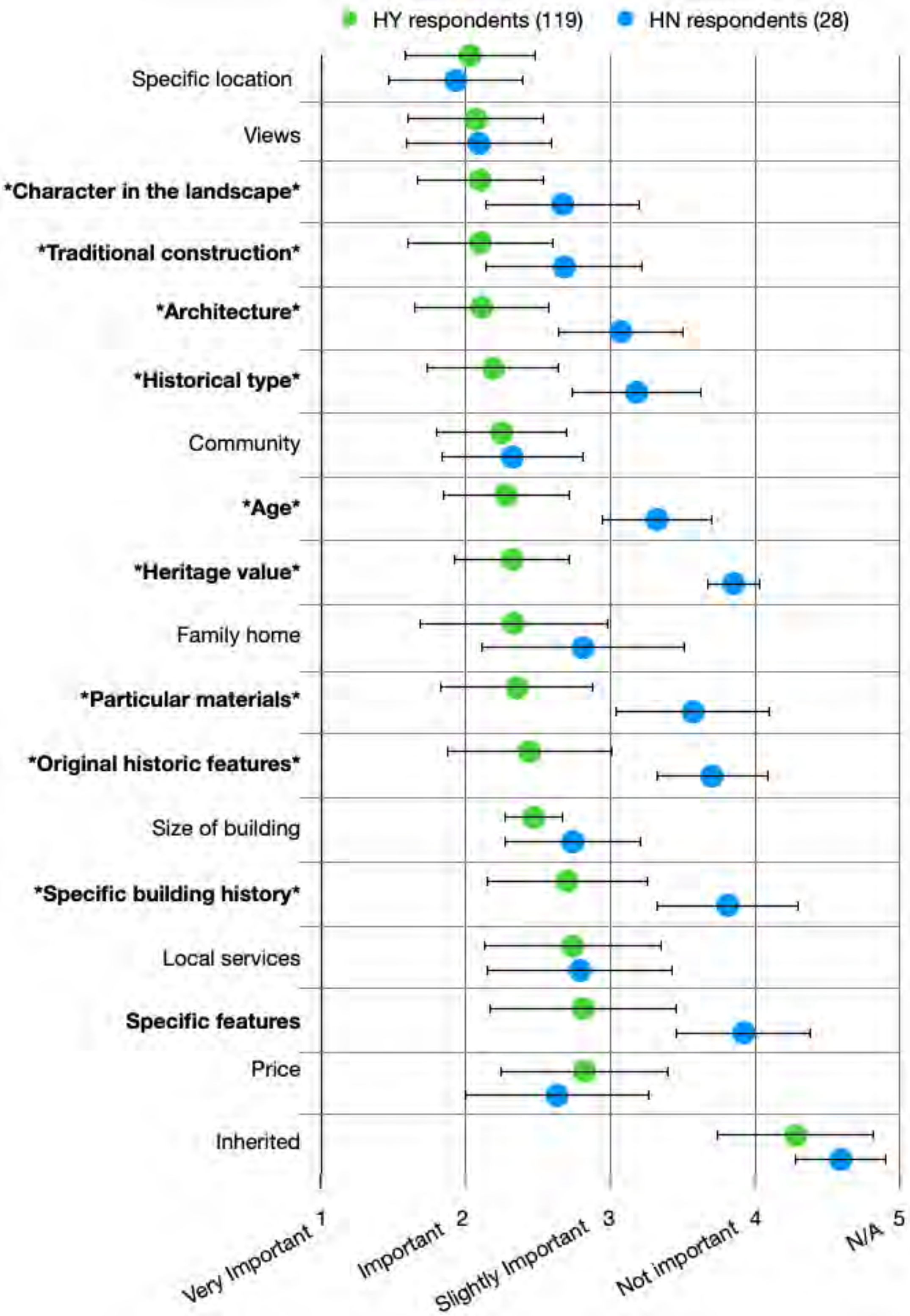
Figure 4.3: Valued aspects of survey respondents’ buildings and locality, arranged in order of mean value (N = 147)



xxx indicates specifically heritage aspects (note that these aspects were not emphasised in any way to respondents.
1. based on initial interviews and piloting, many people value their buildings as ‘family homes’ i.e., ‘its a great home to bring up a family’, compared with those who may value their home because it is inherited.

The importance of these valued aspects can also be compared between respondents who perceive heritage values in their buildings (referred to as HY) and those who do not (referred to as HN). The mean scores for the valued aspects were compared for the two groups, ordered by the HY group (Figure 4.4). The aspects with bold titles are those which showed a statistically significant difference between the two groups when assessed using both independent T-tests and Mann-Whitney U tests (for test choice discussion and results see Appendix L.2). As can be seen, there appear to be clear differences between the groups which map onto those aspects related to heritage values.

Figure 4.4: HY and HN survey respondents, cross tabulation of means for valued aspects with standard deviation as error bars.



‘Architecture’, ‘historic type’, ‘age’, and ‘heritage values’ become more important than community and family home when just the HY group is considered. These values include both tangible aspects such as architecture as well as less tangible values such as age. Not perhaps surprisingly for Cumbria and the Lake District, ‘specific location’ and ‘views’ were the most important values for both groups while ‘character in the landscape’ and ‘traditional construction’ remained the most important heritage aspects for the HY group. A range of heritage values therefore appeared to be important to the survey respondents.

Free text comments from the survey and data from the case studies provided further details about the values that residents identified and considered most important about their buildings. Several themes were identified around these values and are explored in more detail in the following sections.

4.4 What do residents value? Location and context

A recognised, although intangible, aspect of heritage value is a sense that a building adds to, or is an integral part of, its surroundings. ‘Character in the landscape’ was the most important heritage aspect identified in the survey. It was the third most important value overall and may be related to a strong ‘sense of place’, akin to the place based values highlighted in Chapter Two. Case study participants in both designated and undesignated vernacular buildings felt that their homes fit into the landscapes and added character to local areas (CS2, CS6, CS7, CS9, CS10, CS11, CS16). CS9 thought that vernacular buildings were much more sympathetic in the landscape than modern buildings while CS10 considered this aspect to be a key part of their building’s heritage value:

> *CS9: A photo of this part of town with the fells behind, or Elter water, where it’s all stone-built, a photograph of that and the hills is just so much more, I don’t know, satisfying than a photo of [a modern development] and the hills… [Conservation area]*

CS10: If we say to someone, 'oh, we live in the mill'… they'll have a story, like the guy who is coming to build the wall, he used to go past it on his bus route to school. It's so significant, that it's part of people's journeys… everyone knows where it is, it's a landmark [undesignated]

Some participants also identified the reciprocal nature of this relationship, with the local context increasing the heritage value of the individual building in addition to the building adding to its context (CS8, CS12, CS13, CS15). Cases in terraced houses often felt this the most strongly, identifying the effect of the wider streetscape on the character of their homes, although natural landscapes also played an important role. The role of the streetscape is more likely to be recognised in designation, for example through conservation areas, than the sense of the role of the building within its wider landscape. The frontage of CS13's house for example is listed because it is part of the streetscape, and this is something that CS13 recognises and values.

CS13: But really with the location as well, [it's] been like this since, probably the 1850s, I think. And when you see old pictures of the market square you see our house looking pretty much like it does now, so in that sense it's part of the town heritage as well as the building itself [Grade II]

This aspect was also supported by free text comments from the survey with participants who identified their homes as landmarks, or a part of the character of the area.

focal point of mining village throughout 19th Century

Traditional terrace… in town centre. Very much of the ethos

Our house is a Victorian barn conversion adjoined by the Victorian farmhouse and various farm labourers' cottages. The whole complex is important in the streetscape as an example of the Victorian conversion of a Victorian farm on the edge of an expanding town.

Many residents therefore appeared to value the 'sense of place' that they feel that their building has in the landscape. This may also be related to 'views' and 'specific location' being identified as the most important non-heritage aspects for survey respondents and suggests that place based values may be important for Cumbrian residents. This sense of the building fitting within its landscape can also be linked to the values that residents identified around traditional construction and materials, which provide a tangible link to locality.

4.5 What do residents value? Materials and construction

'Traditional construction' was identified as the second most important heritage aspect by the survey respondents (Figure 4.3). This aspect seemed to relate to an appreciation of local construction techniques and traditions, which were also highlighted by many of the case study participants. This included aspects such as local traditions and decorative styles which participants had identified.

CS3: [The doors] were designed to be painted and the consequence is, when some of it was removed, you see the infill panel here, is darker? …apparently it's very, very local, the doors manufactured on this side of Shap are any old wood but on your side, they are matched.

CS16: That [decoration], if you go to the Mason's Arms at Strawberry Bank, that's the same thing, it's not a Fleur de Lys but that type of style… suggesting that it is a local mason's way of doing things… [Figure 4.5]

Figure 4.5: CS16's fireplace decoration, a feature replicated in other local buildings

Note: image taken from recording of online visit.

Some survey respondents also identified a range of traditional features, layouts, and local connections in the construction of their buildings.

> *Believe that some cupboard features in this house also match those in other Lowther houses and were taken from Lowther castle when it was decommissioned*

> *Traditional layout with 'firehouse' and 'downhouse', cross-passage, 'mell', 'heck', open hearth, spice cupboard, scullery, pantry (including massive slate shelf) and dairy under large 'outshut', 17th century oak panelling and doors.*

> *Traditional Lakeland stone structure using reclaimed ships timbers from Whitehaven*

The spice cupboard mentioned in the second quote is a common feature of Cumbrian farmhouses from the 17th and 18th centuries. These built in cupboards were located near the hearth to keep contents such as spices and salt warm and dry (Woodcock, 2010). Of the case studies only PCS1 still has an original spice cupboard although CS5, CS11, CS14 and CS16 have features that may formerly have been spice cupboards and CS11 has created a new door for their cupboard space in the traditional style (Figure 4.6). Spice cupboards commonly had initials and dates carved onto their decorative doors and these often related to significant events such as marriages or inheritances (Denyer, 1991). These cupboards therefore provide an example of tangible heritage value which can also provide information on the history of the building and links to previous occupants.

Figure 4.6: L: PCS1 original spice cupboard (initials S M, dated 1674). R: CS11's replica spice cupboard

Residents therefore appeared to appreciate the traditional construction elements and local traditions associated with their buildings. Some residents also identified these aspects in terms of their distinctive character, and the 'special' quality that they perceived them to give to their buildings for example, CS9 highlighted the uniqueness of their garden fences, or one of the survey respondents who felt that a certain level of knowledge was required to appreciate their building.

> *CS9: between the gardens, they have slate fences, I love them! And I've not seen them anywhere else except the very far north of Scotland… My ex-husband's dad used to work at [a local slate mine], he used to cut the slate, so there's a family connection there as well.*

These features would be identified and understood by anyone with knowledge of the Cumbrian vernacular but to others would perhaps just look 'old'

Although materials were not one of the most important aspects in Figure 4.3, they still appeared to be appreciated by respondents who perceived heritage value in their buildings (Figure 4.4). Materials are an integral part of traditional construction and free text comments highlighted a range of local materials reflecting the geological diversity of Cumbria (Table 4.1).

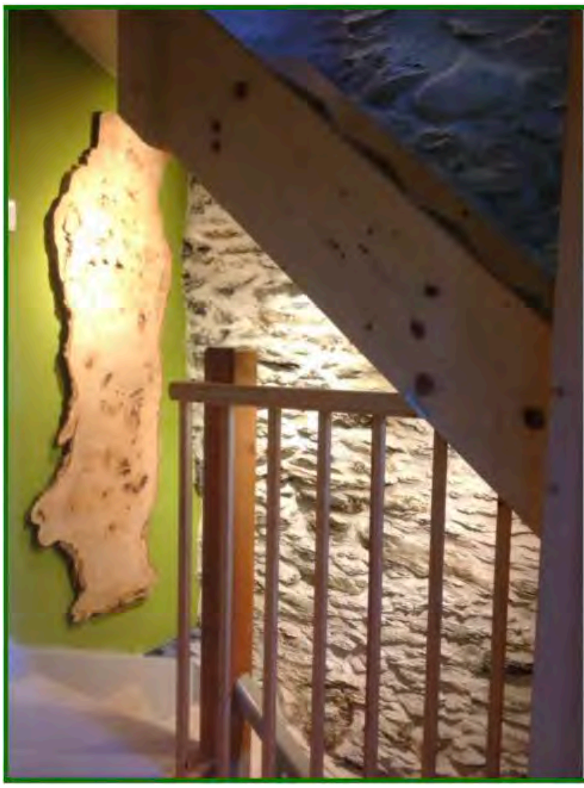
Table 4.1: Survey free text comments on local materials

Area of Cumbria	Survey free text comments
Probable location based on geology is also shown	
Southern central Lakes	Local stone built (Borrowdale volcanic stone) under Westmorland slate
Central Lakes	Typical local Lakeland slate construction
Unknown	Local stone from quarry 100ft up the road
Northern, eastern or the west coast	House is built out of locally quarried sandstone
Unknown	Westmorland slate, local stone walls, sandstone ridge stones
North central	Weather-shot* Towse Yat Skiddaw slate
Southern	It is made out of local limestone from the fell on which it stands
*Weather shot construction is where slate wall courses are sloped slightly downwards on the exterior so that water hitting the slate is shed away from the building. The mortar is set back within the wall giving the impression that it is mortarless (Brunskill, 2010).	

The case study participants also invested value in the local and natural materials used in their homes (PCS1, CS2, CS3, CS9, CS11, CS12, CS13, CS14). Some participants highlighted sustainable aspects of using local materials, while in the photo elicitation activity participants identified their enjoyment of textures (Figure 4.7), natural materials (Figure 4.8), and human connections to those materials (Figure 4.9).

CS2: It's built out of the pink granite that comes from this valley, so, it's obvious that, in times gone by, we used local materials, and this is a flagship of that isn't it?

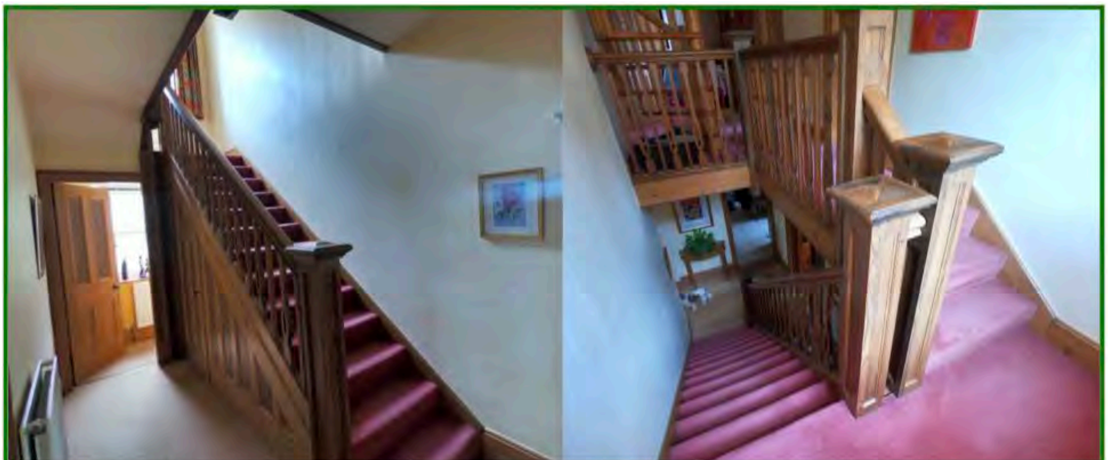
Figure 4.7: Photo elicitation: Textures in Sarah's house



Sarah: Our house has a lot of texture. The house has been done up but has retained a lot of original features & exposed old stonework of the house. I like the contrast of the texture of the stone wall, smoothness & Natural-ness (!) of the plank of wood & the vibrancy of the green. This is on the stairs so it isn't a place you look at much as you are passing through.

*Note that, as discussed in the Chapter Three, pseudonyms were given to the photo elicitation participants to increase anonymity.

Figure 4.8: Photo elicitation: Graham's 'most important piece of furniture'



Graham: I like the staircase very much. Apart from the handrails, the wooden panels and casing were probably painted originally (as were the doors, frames, skirting and picture rails in the house). The wood colours of the panels vary as were not expected to be visible. A man took eight days to strip off the layers of paint for us around 1996. He described the staircase as the most important piece of furniture in the house. Probably constructed in situ by the (local) house-builder

Figure 4.9: Photo elicitation: Brenda's initialled stones

Brenda: Names carved into the stones at the front of the house. They start in 1911 and I love the fact that the house is stone built and the human relationship to the stone, whilst it was being quarried, sorted, built with and then lived in and written on.

The vernacular construction of residents' buildings, using local traditions and materials therefore seemed to be appreciated by residents, with evidence that this may add a distinctive character to their buildings. These values are very context specific and may provide residents with a sense of connection to their individual locality.

4.6 What do residents value? Quality and character

Another important theme was the value that residents placed in the quality of their homes. This was often highlighted by participants in contrast to the perceived features and architectural quality of modern buildings (CS1, CS2, CS4, CS5, CS8, CS9, CS11, CS12, CS13, CS14). Participants felt that their buildings had better architectural quality than modern, mass construction.

CS8: Generally speaking, I like the way that this style of Victorian house has been designed, I like the square rooms, I like the tall ceilings… and none of that you get in a modern house… they are all rabbit hutches I think

CS9: There's a history there which, you know, I suppose is important from an architectural point of view because after a certain point in British architecture, if you've got any building with any sense of style it is really expensive. General standard housing just stopped having any architectural value really

There was also a consistent link with an ephemeral sense of 'character' which participants were not necessarily able to elucidate or to relate to specific features but which they nonetheless described as extremely important. One example of this is the space, light, and proportions which participants ascribed to their homes (CS1, CS6, CS8, CS16), (Figure 4.5).

CS1a: 'It's the space, it's the whole proportion I think' CS1b: 'the height of the rooms, the light in it'

Figure 4.10: Photo elicitation: Edward's internal spaces

Edward: Internally I enjoy the airy spaces in the ground floor rooms

While high ceilings and light were emphasised by many participants, others in contrast, were more likely to focus on the 'character' and 'cosiness' of small rooms and low ceilings (PCS1, CS11, CS12, CS14). Despite valuing opposing architectural aspects, these participants also made comparisons with modern construction.

CS11: [I like] The character, the low ceilings, it feels so incredibly cosy, I love the textures of traditional materials. Going into a new house, it's just this square, characterless box, you know, regular, I think I'd struggle to live in a place like that….

There is clear variation here, resulting from the varied architecture of the case study buildings, but both groups emphasise the importance of character and contrast it with more modern buildings, summarised in this survey comment.

Character, a combination of things you don't get in modern boxes -good proportion to the rooms, traditional details and materials, a history however modest.

Original windows were identified by several participants as features that added to the distinctive character of their homes (CS1, CS3, CS5, CS8, CS9, CS12, CS14). Participants and survey respondents highlighted a range of different window styles from 'sashes' through 'stone mullions', 'stained glass' and 'quatrefoil windows', to one respondent who had 'shutters unique in England (according to Eng. Her.)'. The values that residents invest in their windows may therefore relate more to the original nature of the windows, the traditionally manufactured glass, and the overall character that they bring to the building rather than to a specific window type.

CS3: On the front they are leaded windows. I really like the leaded windows a lot from both inside and outside… That reflection of trees in the leads, I love

CS9: There are just so many things that make it, not unique but special, you know, the windows, the beautiful window lights, and the beautiful windows… it's wonderful, it's wobbly glass… I like the fact that I can look at it from different angles and see a different shape outside! [Figure 4.11]

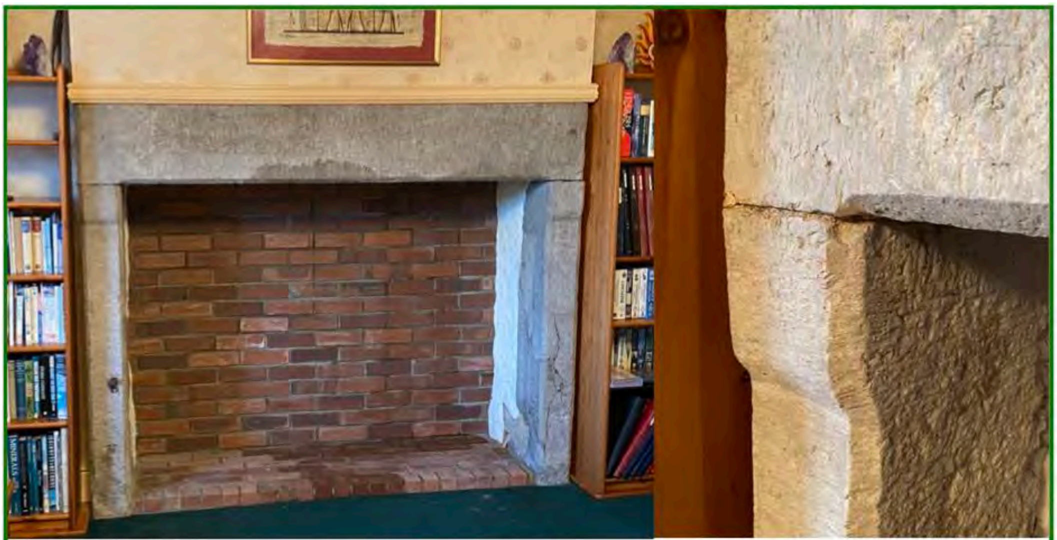
Figure 4.11: Case study original windows

Participants also felt that the craftsmanship of original internal features added to the quality and character of their homes (CS1, CS2, CS3, CS7 CS8, CS11, CS12, CS14, CS16). A somewhat eclectic range of features was highlighted during site visits and in the photo elicitation activity. Once again, these features were often compared, either explicitly or implicitly, with modern alternatives (
Figure 4.12).

> *CS8: Well for instance, if you look at the wainscoting, modern wainscoting is very small and thin and made of some sort of cheap wood, this is rather larger, and I like tall wainscoting.*

> *CS11: I love these, these doors are original 18th century, these are handmade by a blacksmith, all different. As a craftsman myself I appreciate that sort of thing, that's it's lasted so well. Yeah, I think about the guys who built it at times, and the tools that made the marks on here, the adze marks… I feel I belong here.*

Figure 4.12: Photo elicitation: Steve and Caroline's fireplace and fireplace detail



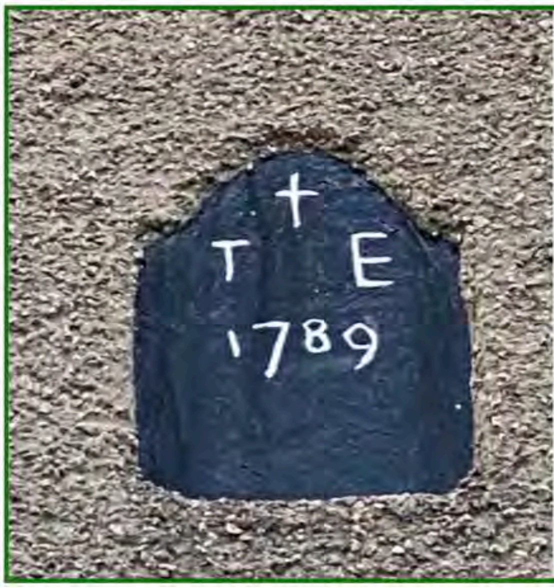
Steve and Caroline: This large kitchen fireplace is so simple, just three large plainly dressed columns of limestone, but it is made with precision and complete suitability for its purpose. There is a worked bevel around the outer edges, only about half an inch wide but hand cut with accuracy and uniformity that machinery could not better. The surface finish is rough and natural, yet flat and true, without perceptible fault. There is a simple corbelled form near the top of the uprights that gives it style and presence beyond expectation.

4.7 What do residents value? History and connections

The majority of participants also valued the history and connections to the past that their home provided, again, associating these with the elusive 'character' (CS1, CS2, CS4, CS5, CS6, CS7, CS9, CS11, CS12, CS14, CS16). These values related both to their actual knowledge of past events and occupants, and to a more intangible sense of the history and evolution of the building, along with their own sense of belonging within it (Figure 4.13 and Figure 4.14).

> *CS2: I like the fact that I live in historical buildings, because I like the social history that's happened before, it makes the building interesting, it gives it character, yeah, for me, I feel that I'm part of that history now.*

Figure 4.13: Photo elicitation: date stone on Steve and Caroline's house



Steve and Caroline: We often wonder what life would have been like when the house was built. What was going on in the world? The French Revolution; George III was on the throne; William Pitt the Younger was prime minister; mutiny on the Bounty, etc.

Figure 4.14: Photo elicitation: the story of the past that Tony's building tells

Tony: I like the way an old house tells the story of past use. An intriguing feature is this blocked up old window, low down on the south elevation. The lintel is oak and very old and the size and position of the opening don't fit the current house layout. I think it shows our house was built on the recycled ruins of a former building.

Specific features were identified by some participants (CS3, CS4, CS7, CS12, CS14, CS16) as giving them a sense of connection to previous residents and helping, as Tony said, to ‘tell the story of past use’. A variety of features were identified, some of which were still in use although others had become decorative.

CS3: [the house] was built for some people in the big house next door who wanted to get rid of their 34-year-old son… although it was built in 1928 it was still built as a miniature stately home with servants, as you see up there, we have the bells! …this was actually below stairs originally…. And it was literally a green baize door [

Figure 4.15].

Figure 4.15: CS3's 'servants bells' no longer function

CS14: Things that I fell in love with, were like, this table, which must have been assembled in situ as you can see, they would never have got it in! (laughter) And there's about three ages of construction in [it] [Figure 4.16]

Figure 4.16: CS14's in-situ table

Steve and Caroline identified a cheese press (Figure 4.17) and a mounting block (Figure 4.18) as features that they valued because of their connection to previous occupants. They also had an old photograph of their house showing some of the previous residents and their animals (Figure 4.19).

Figure 4.17: Photo elicitation: Steve and Caroline's cheese press

Steve and Caroline: A simple farm cheese-press, no machinery or screws, just a heavy stone with a lifting bar, that has lost its wooden handle. It is shaped to suit a family-sized cheese. The base is flat with a circular groove and drain channel for the whey

Figure 4.18: Photo elicitation: Steve and Caroline's mounting block

Steve and Caroline: At the front of the house in what would have been the farmyard, is this mounting block made of massive, dressed limestone blocks. We have a picture taken maybe 100 years ago, with people standing in front of the house, and a carthorse, but we assume these steps were for riders to mount more slender animals. Was it their standard mode of transport to the nearest town?

Figure 4.19: Vintage photo of mounting block and carthorse outside Steve and Caroline's property

Participants were often interested in what could be termed the 'micro-history' of their building, such as details of previous residents, why certain layouts exist and what certain features may have been used for.

> *CS16: [For] people who worked on the house, it was considered good luck to leave a woman's shoe or a child's shoe under the floorboards… so we found an old clog and a child's clog under the floorboards in the loft, so they just went back where we found them, so these little signs of the people who lived here.*

Engagement with local memories and recent, previous residents enabled some participants to discover that the unusual layouts of their buildings had resulted from property divisions as a result of inheritance settlements. CS13, for example only owns half of the first floor above their ground floor footprint but they own almost all the outdoor courtyard space behind the house. They discovered that this was because when two sons inherited their father's house and carriage business, one received the business and a smaller portion of the house while the other received the larger house but gave up their share in the business. CS7 and CS12 had similar scenarios with property layouts resulting from inheritance, although in CS7's case they had recombined the original farm complex through several purchases over the course of their long ownership.

Several participants had invested a lot of time in researching the previous history and usage of their homes. Many had identified a range of former uses although they often struggled to identify how old their homes might be with any certainty (Table 4.2). This was especially challenging for buildings constructed before the development of large-scale maps in the late 18th and early 19th centuries. A lack of detailed knowledge did not however appear to reduce participants' appreciation of their buildings' sense of age and history. Many participants were interested in history more generally and CS4, CS6 and CS7 were all members of the Cumbria Vernacular Buildings Group.

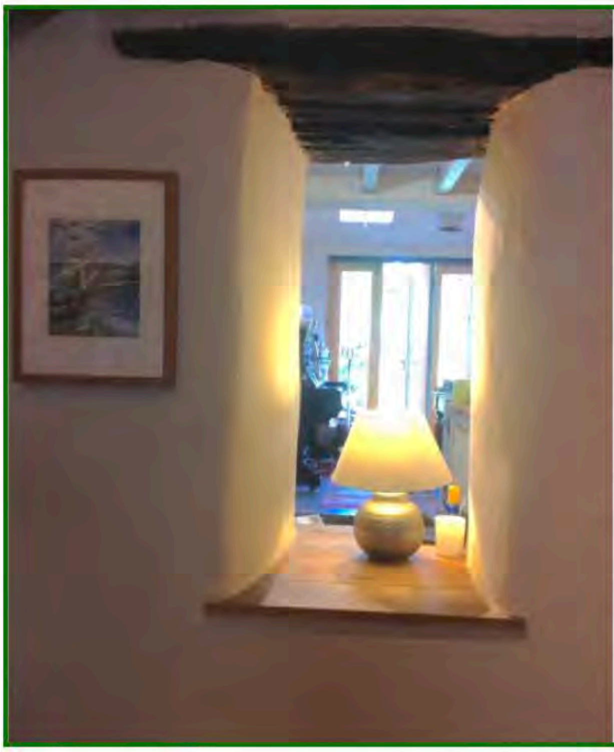
Table 4.2: Former use and potential age of case study buildings

Case	Former use	Probable age
PCS1	Farmhouse	At least 1674 (based on spice cupboard)
CS1	Squire's house (extended on older farmhouse)	c.1820s with much earlier elements
CS2	Miner's cottage	At least 1740s
CS3	Gentleman's home	1928
CS4	Mill	Mill on site since 1290, current footprint mid 19th century.
CS5	Possible chapel	1897 with earlier elements
CS6	Farmstead, land belonged to local priory until reformation	Unclear, at least early 1700s with Victorian extension

Case	Former use	Probable age
CS7	Farmhouse and outbuildings	At least 1789 based on date stone
CS8	Townhouse	1871 dedicated housing
CS9	Terraced house	1896 dedicated housing
CS10	Mill	Unclear, at least 1826 as appears on map, likely to be older.
CS11	Terraced house	Unclear, c.1760s based on construction
CS12	Terraced house	Unclear c.1700 based on features
CS13	Courthouse, carriage business	1834 based on maps and records
CS14	Farmhouse	At least 1770s has some earlier features
CS15	Possible weaving workshop and dwelling	At least 1850s based on original deeds
CS16	Possible weaving workshop, farmhouse	Unclear, at least c1800 and possibly older

The survey respondents meanwhile reported a diverse range of building uses, including a headmaster' house, shops, public houses, barns, laundries, workshops, farmhouses, and dwellings. In addition to building uses, respondents also highlighted a range of former occupants, including authors, musicians, locally important families, generations of craftsmen, game keepers and even border reivers. Residents therefore appeared to value their connection to local events and micro history, even if they had only fragmentary knowledge. Sarah identified a window in the former rear wall of her home as making her think of, and feel connected to, previous occupants, with her thoughts focused by the UK lockdown for Covid-19 (Figure 4.20).

Figure 4.20: Photo elicitation: Previous back wall of Sarah's house



Sarah: the original back wall window, which is now 2 extensions away from the current back wall of the house. It reminds me of how small people's houses were, how full of people they must have felt and this makes me think about how they lived in such small places, what the constraints were, perhaps with only one set of best clothes, a lot of washing required, hard to get away from others if you had fallen out, hard to have private intimacy when so many in such a small house, nowhere to store the 'stuff' most of us have today, and how we see things differently from one generation to the next. Did people get on better as well as fall out more often?!

The history that participants identified and valued in their buildings was not necessarily more widely important, relating to special events or people of national interest. It related more to the micro and domestic history of the building and the daily usage of features that were still present. The sense that: 'I am a part of a sequence of people for hundreds of years who have lived here' (CS14) or a connection because 'you feel the history as you walk around' (CS2). This appreciation of the age and history of the building is illustrated by the photos that George took of three beams to show the impact of his building's use over the centuries and the values that he associates with this sense of age. (Figure 4.21, Figure 4.22 and Figure 4.23).

Figure 4.21: Photo elicitation: George's beams 1

George: A beam at the foot of where the stairs to the upper floor used to be, the interesting bit is the way the beam is worn rounded due to the miller and anyone else coming down just touching it to steady themselves with their hand, I wonder how many years of wear that represents.

Figure 4.22: Photo elicitation: George's beams 2

George: This shows where a beam has been worn away by the chain which drove the sack hoist which the miller used to raise sacks of grain and flour or animal feed through the floors of the mill and the repairs done by the miller - when it got too worn he just nailed a new bit of timber on the old beam, crude but effective.

Figure 4.23: Photo elicitation: George's beams 3

George: This last one shows to the left a cut out in the beam where one of the hoppers that fed grain from the top floor into one pair out of the four pairs of mill stones and also wear marks where the rope which engaged the sack hoist system was pulled by the operator. A pull on the rope engaged the drive and the chain driven sack hoist capstan in the roof rotated to wind up the sack hoist and sack through trap doors in each floor which would bang shut after the sack had passed through, release the rope and the sack would fall back onto the floor at the correct level, hoist it to the top and there was a trip mechanism to stop it over-winding.

In summary then, specific aspects that residents' value are varied and individual. However, many of them appear to evoke a sense of the building in its context, a respect of its local construction and materials, an admiration of its quality and craftsmanship and an appreciation of the building's history and sense of age. These aspects can all be related to the overall 'character' that residents strongly recognised in their buildings. A clear sense is developed of how much residents value the individuality and authenticity of their homes, especially in contrast to the characteristics that they perceive for modern construction, as summarised by CS5:

[It's] off a catalogue, a book they have with 'the Marlborough' (laughter), there's kind of a street but basically, it's the same across the country… The design [of modern buildings] is just, pathetic, I'd like to see some decent architects, designing aesthetically pleasing houses, not, 'mock Tudor, executive homes.' (CS5)

4.8 Reasons to purchase and reside

The length of time that participants had resided in their buildings ranged from one to 52 years (Table 4.3) The average length of occupancy was 22 years, although four participants had been living in their homes for over forty years. A number of participants who had lived in their houses for a long time felt a definite sense of ownership and emotional investment in the building (CS1, CS3, CS4, CS5, CS7, CS11). CS11 has lived in their home for 46 years and has a very strong attachment to it because they inherited it from their grandmother whom they spent summer holidays with as a child. CS1 meanwhile felt a strong connection to the building because:

CS1b: The fact that our family has grown up here, I think. CS1a: We've put a lot of ourselves into it. (32 years occupancy)

Table 4.3: Participants' years of occupancy

Case	PCS1	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
Year	22	32	1	25	52	41	21	40	10	27	1	46	12	2	18	6	11
Average occupancy 22 years																	

Age and heritage value was a significant decision factor for nine of the case study participants when looking to buy or move to their homes. PCS1, CS1, CS2, CS4, CS5, CS8, CS9, CS12, CS14 were all specifically looking for an older building, 'something with a bit of character' (CS1). CS7 and CS13 meanwhile both looked at a variety of houses but quickly came to realise that an older building was what they wanted.

CS4: I was an engineer and mills fascinated me… the fact that it still had the machinery in it was a big attraction.

CS13: We looked at couple of more modern houses and just, the room sizes and garden sizes weren't really doing it… the whole feel of the building really, and a lot of that is the heritage … we came to see this one, walked in the front door and it was like visiting a relative's house, you know? It's not quite coming home but it's a familiar place

Three participants meanwhile (CS6, CS15 and CS16) did not feel that age was a major factor in their decision making when they decided to purchase their homes. CS15 was mainly influenced by the location and CS16 by the practicalities that the house's space and layout provided. CS6 meanwhile purchased their house:

…on the strength of what they'd done to the kitchen… we prefer an older building, but it wasn't a major factor in the decision making. [Figure 4.24]

Figure 4.24: CS6's kitchen in the modern part of their house

Note: At the time of the site visit there were also decorators in the house, hence the dust sheets visible in this image.

CS3 had spent time in their house prior to purchase as the previous occupants were family friends. They liked everything about the house, so when the opportunity arose, they bought it. CS10 meanwhile was offered the house by friends and bought it because of the rural location and because an attached holiday let would provide them with a pension in the future. However, although the heritage nature of the building did not enter into their decision making at the time of purchase, a year on:

> *CS10: Now, we love it because it's an old building but when we were buying it, it was irrelevant... But that's why we love it so much now, definitely! … I think I didn't let myself love it until we were actually in it. [Figure 4.25]*

Figure 4.25: CS10 now love their house because of its heritage despite buying it for practical reasons

Note: Photo extracted from recording of online visit

The heritage nature of the buildings was therefore a factor in many of the participants' purchasing decisions. Even those for whom this was not a factor however had come to appreciate and value the heritage aspects of their homes. The survey did not ask people why they had chosen their properties, but three respondents mentioned this in their comments, highlighting the traditional materials, building age, and location as purchase factors:

> *My wife and I always wanted to live in a stone-built house. Rural village location was also important purchase factor.*

> *Moved to this property due to location and right rental price*

We have been in the house for 5 weeks but really want to learn more about the history and the people who lived here before us. The age of the house was what drew us to buying it.

4.9 Discussion

Residents' heritage values have been explored, to build on existing research and present new findings to contribute to an understanding of the type and nature of these values.

The majority of residents in this study invested heritage value in their buildings, regardless of their official heritage designation. Formal designation is therefore not the only, or most important, factor, in residents' appreciation of heritage value in their buildings. If this is representative of residents of vernacular buildings more widely it could suggest that up to eight million (28%) of the UK's homes are perceived to have heritage value by their residents. This compares with approximately 1% of UK buildings which are listed. The effect of designation on participants' definitions of their homes as heritage buildings may however have implications for how information should be directed to residents of these buildings, for example around heritage sensitive retrofit measures.

Addressing research sub-question 1a, it appears that residents invest a broad range of both tangible and intangible values in their buildings which contribute to an overall sense of character and connection to the building. Some aspects which are often recognised in heritage designations, such as historical importance, architectural styles, building streetscapes, and particular materials are important to residents. There are however other aspects and features valued by residents which are rarely recognised in designations, including contrasts with modern mass construction, quality and craftsmanship, and a broader range of personal and cultural connections with place, geography, and history.

The values that residents invest in their homes relate directly to the connection that they have with their buildings. These values were individual and specific but had a strong relationship with local landscapes, materials, construction traditions, and history. This sense of heritage has motivated many participants to attempt to find out more about their buildings' history and this knowledge has contributed to residents' appreciation of their buildings and their ongoing relationships with them. However, a lack of specific knowledge did not inhibit residents' appreciation of their homes' value or their sense of the buildings' age. A sense of connection to previous occupants, and the place of the building in past contexts, is also an important aspect for residents, both as part of the general character of the building and in relation to specific features. In common with findings by Eriksson (2018), when residents' values were examined in more detail, intangible values around context and character appear to the most important, with specific features valued more for their sense of connection to more abstract concepts rather than necessarily as individual objects.

It is therefore clear that such values and connections are important to residents and, as will be seen in later chapters, have a significant influence on how they live in their home, as well as how they maintain and change it as part of an ongoing relationship. At the very least, the evidence suggests that it is important to engage with residents to understand the values they see in their properties and, in particular, the need to look beyond only designated buildings and official interpretations of value. This has implications in a number of areas around policy, operation, and retrofit of these buildings, which in turn can have a significant impact on carbon reduction in residential vernacular buildings

4.10 Conclusion

This chapter has examined the types of values that residents invest in their buildings (RsQ1a). All case study participants and the majority of the survey respondents in both designated and undesignated buildings considered their homes to have heritage value. Official designations appeared to have little influence on residents' recognition of heritage value but potentially influenced the designations that residents associated with their homes.

Residents invest a range of both tangible and intangible heritage values in their homes and while these values may fit general themes, they are also specific and individual. The location and context of their home as part of the wider landscape or streetscape was considered important by most residents. Traditional construction and local materials of vernacular buildings were also valued by residents, perhaps enhanced by the geological diversity of Cumbria. The quality and craftsmanship of these buildings was also a key factor particularly in contrast to modern mass construction. The sense of history and connection to previous residents was the final theme identified, with residents valuing the age and histories of their buildings, however modest, even if they knew only limited details. All the case study participants came to invest heritage values in their homes, even if heritage aspects had not been an important factor in their purchase decisions.

Overall, many of these values appeared strongly related to a sense of connection that residents had with their buildings, which was linked to a sense of the character of their homes and influenced by context, construction and sense of history, place, and locality. This level of connection and significant investment of value is highly likely to affect residents' views and behaviours and thus their interrelationship with their buildings. It is also likely to affect the retrofit measures that they may consider acceptable and will therefore enact.

Some material in this chapter has been previously published in (Wise, Moncaster and Jones, 2022; Wise, Jones, et al., 2021; Wise, Moncaster, et al., 2021)

Figure 4.26: CS3 and CS4

Chapter 5. Acceptability of, and barriers to, retrofit

5.1 Introduction

This research has demonstrated that residents invest significant, and varied, tangible and intangible heritage values in their buildings (Chapter Four). This chapter considers how these values effect the retrofit measures that residents consider acceptable (RsQ1d) and the barriers that they perceive in reducing carbon from their vernacular buildings (RsQ1e). Because domestic retrofitting is largely instigated and managed by residents, the acceptability of these measures and the barriers that residents consider important are critical to the likely enactment of retrofit projects.

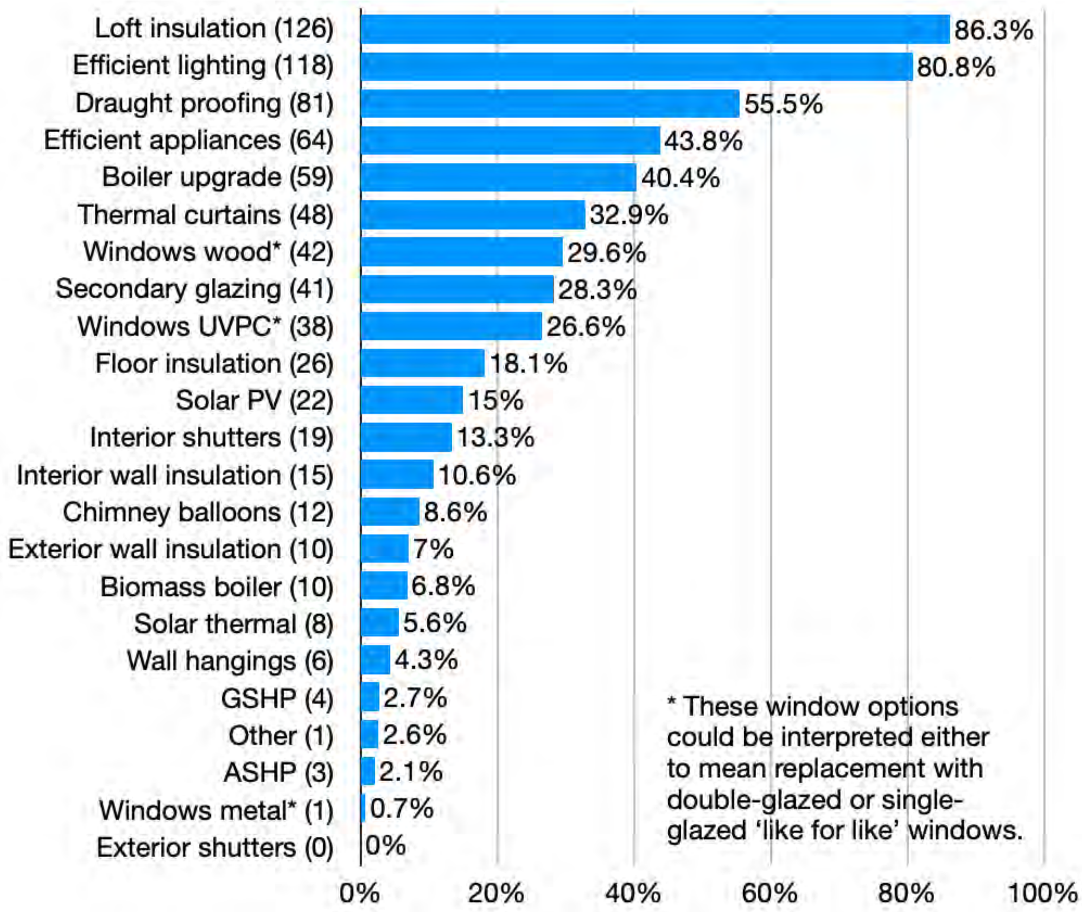
These questions are examined by drawing on the survey and the case study interviews, retrofit matrices and building tours. The retrofits that residents have already undertaken, and their assessment of their effectiveness, are explored. The measures that they might consider in the future are examined and the barriers that they perceived to be important are identified. The information sources that respondents might access and their satisfaction with these sources is also examined.

5.2 Previous retrofits

The survey respondents were asked to indicate the retrofits that they already had from any of the 23 potential retrofits identified in Chapter Three (Figure 5.1). Like the vast majority of existing buildings, those belonging to respondents had already had various levels of alterations, refurbishments and retrofits over their lifespan, undertaken by either current or previous residents, all of which affect their energy performance.

The retrofits that had already been installed by the majority of respondents were measures such as loft insulation (86.3%) energy efficient lighting (80.8%), and draught proofing (55.5%), while energy efficient appliances (44%), boiler upgrades (40%) and thermal curtains (33%) had been installed by over a third of respondents. These measures are amongst those that have been commonly promoted and supported by various government initiatives over recent decades and this will have influenced installation rates (Fawcett and Topouzi, 2020). However, these measures are also some of the least likely to have a substantial visual impact or to require the removal of existing material. They may therefore also be less likely to adversely affect residents' heritage values.

Figure 5.1: Percentage of survey respondents who had already installed retrofit measures (N = 147)



Comparatively few respondents had installed renewable technologies, with the most common being solar PV at 15%, followed by biomass and solar thermal at 7% and 6% respectively. Very few respondents currently had heat pumps. Comments suggested that those who had installed GSHPs were likely to have done so as part of a larger, whole house retrofit package including insulation and other renewables. The types of alterations that they had made suggested twin concerns with carbon reduction and the compatibility of retrofit materials with vernacular construction.

> *I have installed a ground source heating system and rendered the outside walls with diathonite [insulating lime/cork plaster] and lime render. If I need further heat, I light one of my two wood-burning Clearview stoves… The logs come from timber on my own land.*

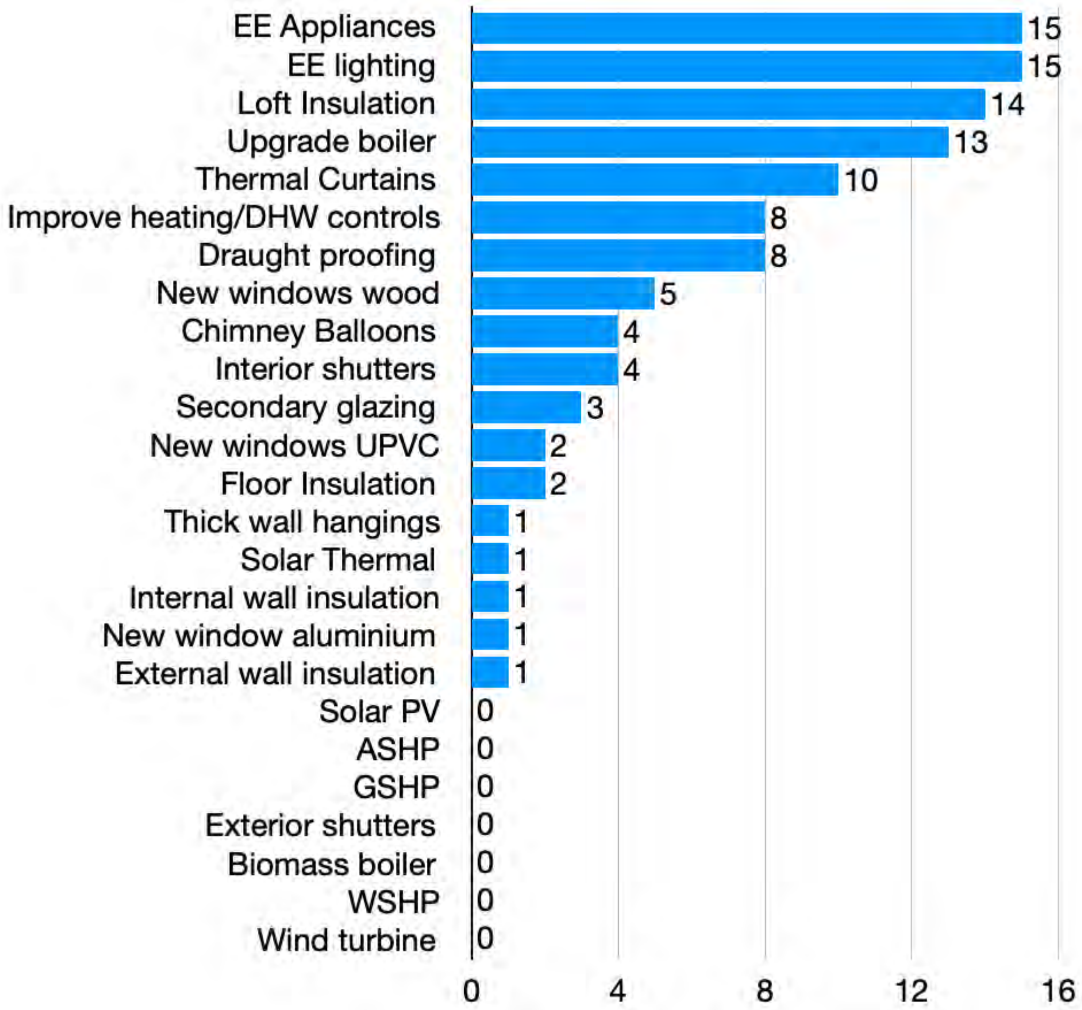
> *I tried to keep any old feature… I placed on the external walls a 10cm gap on the inside and filled it with wool insulation… I did not want to burn fossil fuels so looked around for any alternative, in the end I put in Ground source heat energy, with a log burner to boost when necessary. Not the cheapest option, but morally there was no argument. Finally, as the cottage faces SSW, I have 12 PV panels on the roof.*

Original windows are often considered a focal point in designated heritage buildings and are also something that residents in this research were found to value, with 14% of respondents specifically mentioning the importance of their original windows in comments on heritage value (section 4.6). Approximately 40% of respondents still have at least some original windows in their building, 30% have at least some replacement wood framed glazing and 27% have UPVC framed glazing while only 1% have glazing with metal frames. Around a third of respondents have thermal curtains (33%) and secondary glazing (28%), while 13% have interior shutters.

Internal and external wall insulation, which are other common retrofit measures, had only been installed by 11% and 7% of respondents respectively. Window replacement and wall insulation are measures that are likely to have a substantial visual impact and may therefore negatively affect residents' heritage values. The lower take up of these measures may suggest that respondents' choice of retrofits is influenced by their heritage values.

Considering the measures that case study participants have already installed shows a similar picture to the survey (Figure 5.2). Energy efficient lighting and loft insulation were once again the most common measures, followed by boiler upgrade, although more of the case study participants had energy efficient appliances. Participants were asked to consider a very similar list of measures, the only difference being the addition of water source heat pumps (WSHP) and wind turbines as additional renewable technologies, and the improvement of heating/domestic hot water (DHW) controls based on suggestions in the survey responses.

Figure 5.2: Case study retrofit measures already installed (N = 16)



Many of the participants had resided in their properties for a significant period of time and had therefore made, or at least considered, a range of retrofit measures. Only CS10 did not currently have energy efficient lighting throughout and were in the process of swapping out failed bulbs for LEDs. CS10 was also in the process of getting their loft insulation replaced because the current insulation had been installed incorrectly. CS11 was the only participant unwilling to install loft insulation; this is because their roof forms the ceiling of the bedrooms and has the original lathe and plaster and reused medieval beams visible (Figure 5.3). Most participants felt that they had replaced their boilers fairly recently; a term which they appeared to associate to a timeframe of the last ten years. CS1 and CS3 were both planning to replace their boilers in the next 12 months. CS7 however felt that they were unlikely to replace their 12-year-old boiler until it stopped working because they thought that this would be wasteful.

Figure 5.3: CS11's reused medieval beams and lathe and plaster ceiling

Nearly all participants had made some attempt at draught proofing, but most felt that there was more that could still be done. Eight of the participants felt that they had 'done' draught proofing, including CS1 who felt that the effect had been: 'massive, for the front door… we've had several goes at the front door!' CS14 is cautious about additional draught proofing as they felt that the ventilation provided by the draughts is important for moisture management, which is something they have challenges with (section 6.6).

Some participants have installed wall or floor insulation but only in some rooms. CS1 and CS5 have floor insulation in their main sitting room and CS7 in their garden room, all having taken advantage of the need to replace damaged floors. CS6 has internal wall insulation in the bathroom in their Victorian extension. They have found this insulation beneficial, and they are planning to extend it into the rest of the Victorian section.

CS6: It was a cold, cheerless room… we put in the wall insulation, and it made a huge difference.

In common with the insulation measures, several of the participants have partially replaced, or added to, windows. CS4 and CS16 have wood framed double glazing throughout and CS6 and CS10 both have UPVC framed double glazing throughout. CS6's UPVC double glazing is a conservation product that is designed to look similar to the previous sashes (Figure 5.4). The remainder of the participants were found to all retain at least some of their original windows although the proportions vary. CS7 has one original sash with the remaining windows replica double-glazed timber, CS8, CS9 and CS13 have original windows in their main building and double glazing in their extensions. Five participants (CS2, CS3, CS5, CS11 and CS14) have original windows throughout.

Figure 5.4: CS6's UPVC replica sashes and shutters in the Victorian bathroom with internal wall insulation

Three of the case study participants, CS2, CS12 and CS16, had undertaken more extensive retrofitting to varying levels of effect. CS2's property was extensively retrofitted just before they moved in, although fewer changes were made than originally planned due to project costs. The stonework was repointed externally, a new concrete ground floor was laid, the loft was insulated, and the original windows were refurbished and draught proofed. A new heating system based on high efficiency modern storage heaters with a woodburning stove as a booster system was installed. A thermal storage tank for hot water was also added. An electric heating system was installed because the cottage benefits from a micro-hydropower system so onsite electricity generation can cover part of the building's heating demand. The residents feel that post retrofit, the cottage is significantly better than it would have been previously, however they are unhappy with the heating system as they find it that it uses significant electricity while not meeting their needs in terms of timing or temperature.

CS12 made significant alterations to the more modern extensions to their house. They externally insulated and re-rendered the 1970s main bedroom extension with wood fibre board and lime and constructed their own super insulated timber frame dining room extension in place of a former concrete outhouse. They also insulated the sloped ceiling in the loft space, which is used as an office, although they only installed a limited thickness of wood fibre insulation as they wanted to keep the original beams visible. They feel that these changes have made an 'amazing' difference to their level of comfort, and also solved damp issues that were extant in the main bedroom. Their main regret was that they did not insulate and install underfloor heating in the living room floor in the main house, as they did in the dining room extension, because they find it very beneficial.

When CS16 bought their home ten years ago it required significant work. As part of an eight-month project they installed thermal plasterboard, added a new concrete ground floor, and replaced all the windows and the roof. They also installed a new heating system and solar thermal panels, remarking that 'We probably used up our carbon footprint for decades!' They felt that the retrofit made a substantial difference overall and are pleased with the performance of their solar thermal panels, which prevents them needing to use their boiler for hot water for long periods in the summer. A side effect of such a substantial retrofit however is that they now feel that it may be a barrier to investing time and effort in making further changes.

CS16: It was a huge project ten years ago so it's a mental shift to think, ok, we need to carry on improving from where we are… it's having the capacity to explore it and see the benefit and get on and do it.

5.3 'Soft' retrofit measures

So far in this chapter, the measures discussed have been mostly technical improvements to the building fabric or its energy systems. However, what could be termed fixture retrofits which are attached to primary or secondary buildings elements (and which are easily reversible), and fitting retrofits which are not fixed to the building fabric at all, may also have a useful role in reducing energy use and improving comfort. This can include traditional measures such as wall hangings or innovative products such as thermoelectric fans, which are not normally considered in retrofit approaches (Chapter Two). The term ‘soft retrofits’ is chosen in this research for these types of measures and some of those already used by participants appeared to have a good effect.

A number of the case studies had window additions such as shutters, thermal curtains or secondary glazing and the majority of those with original windows had also had at least some of them refurbished and draught sealed so that they functioned more effectively. Four participants (CS1, CS5, CS8, CS11) have secondary glazing on some of their windows which they feel has made a positive difference to their buildings and some are actively considering installing more.

CS8: Probably this year we're going to do the back as well… I think the secondary glazing would tackle any draught problems there.

Three of the case studies (CS1, CS14, CS15) made use of existing original internal shutters on some windows, which they feel are exceptionally good at reducing heat loss. CS6 has original shutters downstairs in the main house and was so impressed that they installed similar ones upstairs when they retrofitted their bathroom (Figure 5.4). CS16 meanwhile has modern louvre style shutters and CS12 has what they describe as a ‘glazed shutter’ for their living room window. This is a double-glazed unit which can be folded back in summer and was designed so that the window dividers match those on the original (Figure 5.5).

CS1b: we've got functioning shutters in two of the downstairs windows which is great… they are very good; they make a massive difference.

Figure 5.5: Case study shutters

10 of the 16 case studies already had thermal curtains or similar, at least in part, and felt that they were beneficial.

CS7: They're not thermal curtains but they are heavy and lined and the rooms do get warmer quicker [when we close them]

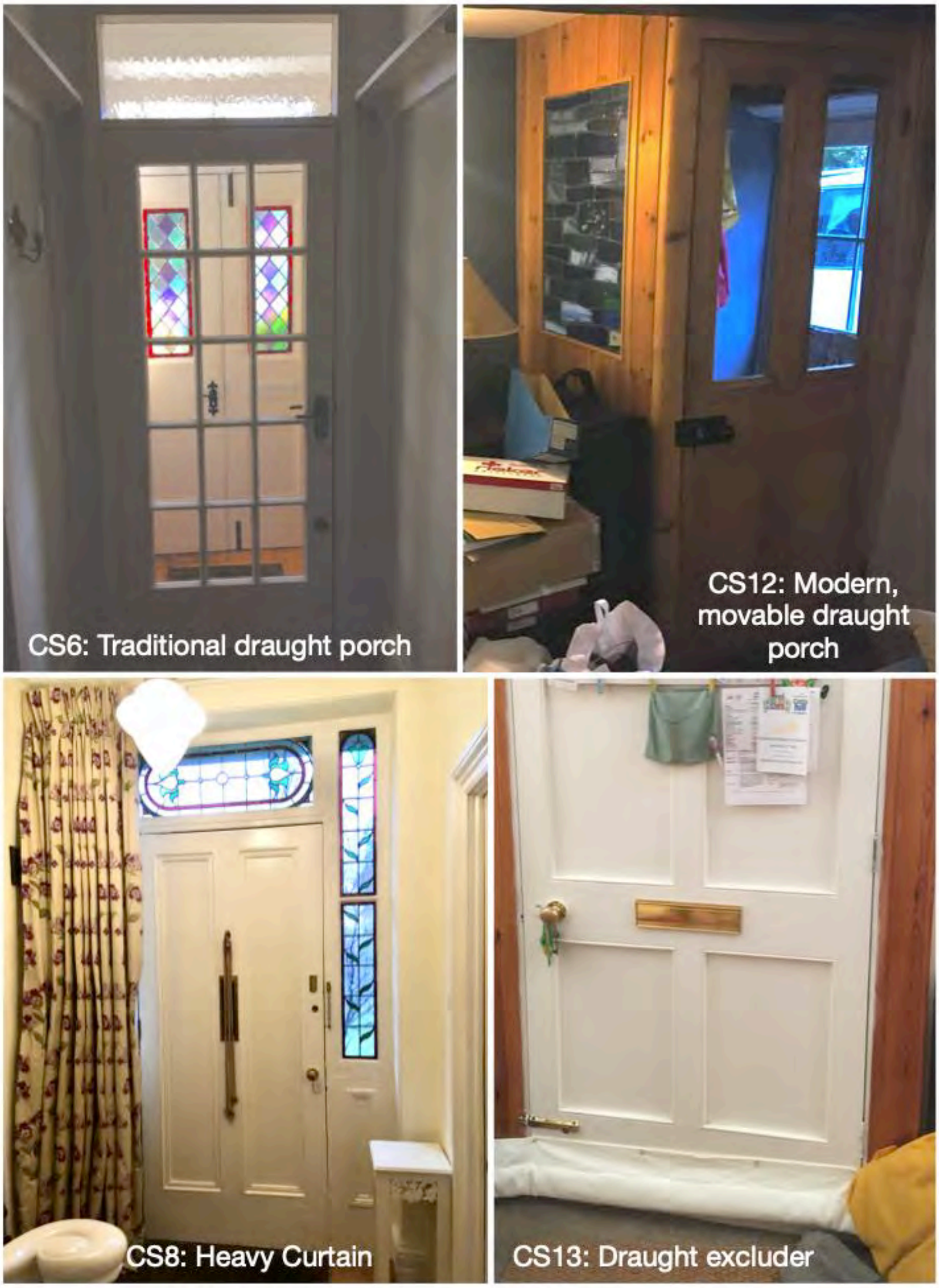
The potential of other types of soft retrofit can be illustrated through measures taken or utilised by a number of the case study participants. CS1 for example actively manage their conservatory for solar gain, including using traditional wood slat blinds commonly used in southern France to manage overheating in the summer.

CS1: Because we've got a south facing conservatory, certainly from mid spring, we get solar gain, which is fantastic, and even today

[February], once the snow had stopped and the sun came out, that conservatory gets really warm, we open the door and all that heat comes into the house, it's really great.

Many participants identified front doors as a source of draughts. CS6 and CS15 benefit from their original draught porches, while CS12 has installed a wooden draught porch- which can be easily removed if large objects need to be bought in- for their front door, which opens onto their living room. CS8 make use of a heavy curtain on windy days to cut draughts from their front door and CS13 have created a movable draught excluder to keep the prevailing sea wind from penetrating their front door which opens directly into their living room (Figure 5.6).

Figure 5.6: Case studies door draught solutions



Internal draughts are also managed to keep heat in occupied spaces. CS9 uses a curtain to close off their living room (which is in their cellar), from the ground floor of the house which can be draughty, thus keeping the heat from the wood burner in the living room, and CS10 have curtains in their hall to reduce heat loss to unheated areas:

CS10: We've put two curtains in, one at the top of the cellar door, one in between the front door and stairs that go up to the kitchen and we have a few draught excluders in strategic places.

CS4 have taken this one step further and have a curtain across the room, dividing their living room from the open plan dining room space that they only rarely use. They reported that this has resulted in them being able to have the same level of comfort in their living room while turning their thermostat setting down by 4ºC. They also have a large wall hanging which they find reduces heat loss to their cold stone walls, thus increasing their comfort. As a final example, CS2 have a small wood stove, used daily to supplement their storage heaters, but which they feel is undersized. Rather than buying a larger stove at considerable financial and environmental cost, they are now using two thermoelectric fans to disperse the heat from the stove more evenly around the room, and indeed, the rest of the ground floor.

CS2b: it even makes a difference in here [kitchen], if the door's open, doesn't it? The heat now comes through here from the stove. CS2a: They've been brilliant, we've noticed a massive improvement

[Figure 5.7]

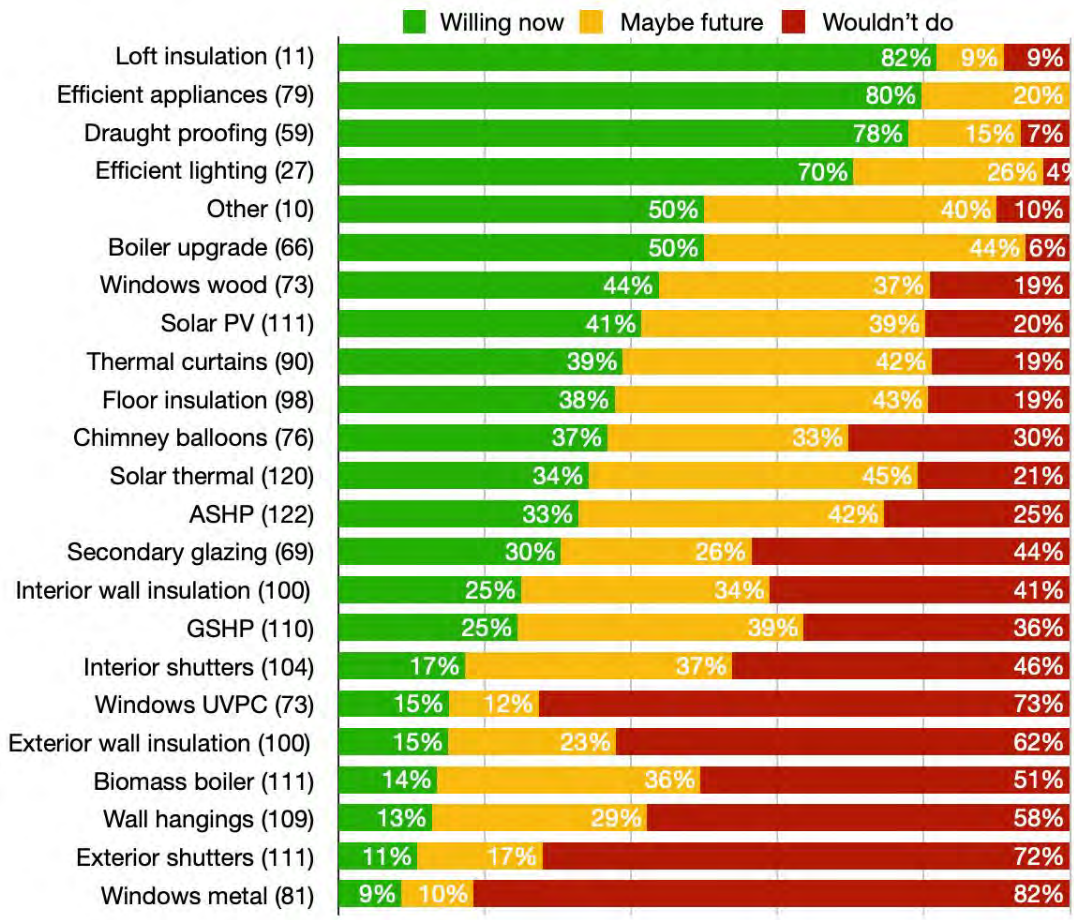
Figure 5.7: CS2's thermoelectric stove fans

Residents therefore appear to already have a range of common technical retrofits, as well as making use of a variety of less permanent 'soft' retrofits. The next section considers the acceptability of potential future retrofits.

5.4 Acceptability of future retrofits

To understand the sort of retrofit measures that residents might be willing to enact, the 147 survey respondents were asked whether they would consider installing any of the retrofit measures in the list that they did not already have (Figure 5.8). This meant that the number of respondents, shown in brackets in the figure, varied for each measure. Respondents were asked to only consider the impact of the measures on their buildings' heritage value, and to ignore planning and cost constraints.

Figure 5.8: Acceptability of retrofit measures to survey respondents



The six most acceptable retrofit measures were those which were unlikely to have a visual or physical effect on the building, such as energy efficient lighting and appliances, draught proofing, or boiler upgrades. These measures were therefore less likely to affect the values that respondents invested in their buildings however, they were also measures that the majority of respondents already had.

Loft insulation was the most acceptable insulation measure although the vast majority of survey respondents (86%) already had it. Over a third of respondents (38%) were willing to have floor insulation now and another 43% might be willing in the future. Despite wall insulation being a commonly recommended retrofit for vernacular buildings neither internal (IWI) nor external wall (EWI) insulation was attractive to respondents, although the proportion of those who would definitely not install EWI (62%) was significantly higher than those who would not install IWI (41%). This may be related to the increased external visual impact of EWI, especially in Cumbria where many vernacular buildings have bare stone façades.

‘Windows wood’ was the most acceptable window alteration (44% willing now), and thermal curtains were also popular with 39% of respondents willing to install them now, while 30% were willing to have secondary glazing. Despite the effectiveness of shutters reported by the residents that already had them, only 17% of respondents were currently willing to install interior shutters but 37% might be willing in the future. These measures could all be said to be heritage sensitive, through their use of sympathetic materials or because they have a limited visual impact. Conversely, the majority of residents would not be willing to install UPVC windows (73%), exterior shutters (72%) or metal windows (82%) which may have a more substantial effect on heritage values.

Considering renewable energy technologies, solar PV panels were the most acceptable (41% willing) followed by solar thermal panels (35% willing), suggesting that visible renewables may be more acceptable to respondents than other externally visible measures, and in contrast to their planning acceptability in designated buildings. ASHP and GSHPs, which are a key part of UK government's plan to decarbonise heat, were less attractive, although around 40% of respondents were usure and might be willing to consider them in the future. Only 14% of respondents were currently willing to install biomass boilers and this was something that just over half of respondents (51%) would not do.

The 'other' category provided respondents with the opportunity to describe additional measures that were not included in the current list. Six respondents felt that the traditional construction of their buildings precluded certain measures, such as wall insulation or heat pumps. Four respondents mentioned either domestic or community wind turbines and four described challenges with window replacements around planning and cost constraints:

> *I would very much like to be able to install double glazing units into our existing traditional sash windows. This is technically possible but not under conservation area rules.*

> *[someone needs] to design [replica] Georgian wooden sashes that are draught proof and double glazed… that are affordable.*

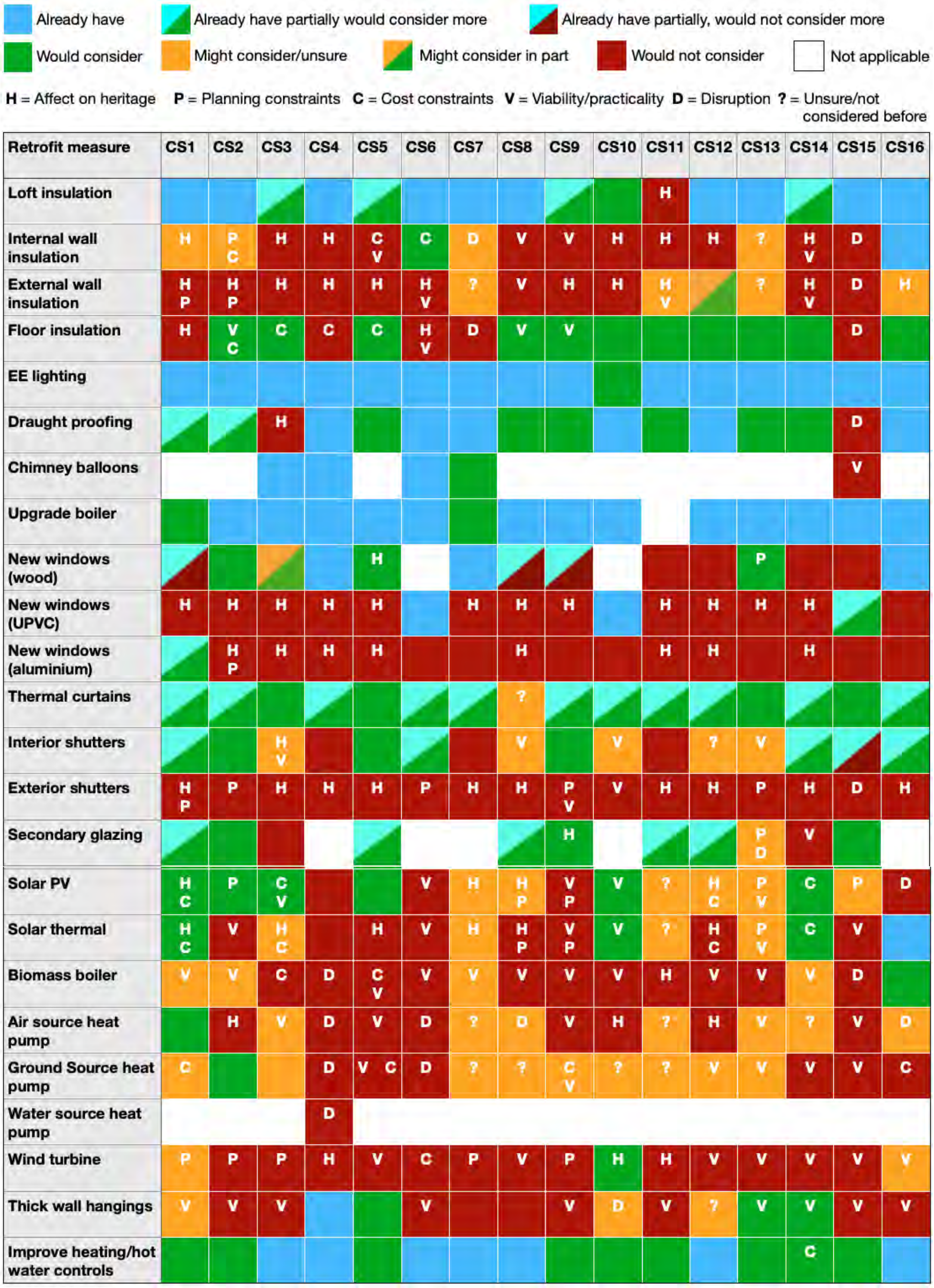
Three respondents mentioned the financial viability of measures. Two suggested underfloor heating as a useful measure, something also supported by the case studies. Two respondents expressed confusion about what some of the suggested retrofits were but felt that: 'if it helps energy conservation – yes.' This suggests that respondents were willing to engage in activities which might reduce their energy and carbon emissions.

The most acceptable changes therefore appear to be those with little or no visual or material impact. Externally visible changes such as window replacement and external wall insulation are unacceptable to the majority, although visible renewables such as solar panels were more acceptable to respondents.

The case study participants completed a retrofit matrix (Chapter Three) covering a similar list of retrofits, as discussed in section 5.2. As they completed the matrix, they were asked to describe any challenges that they considered pertinent for each retrofit. Four broad categories, impact on heritage/aesthetics; planning constraints; cost of measure; and practical issues, were provided as prompts, although participants were also encouraged to describe any other issues. They were also asked to state whether, in summary, each measure would be something that they would consider or not.

The retrofit matrices and accompanying recorded summaries for each case study have been condensed and summarised (Figure 5.9). The colours in the chart below show the overall acceptability of each measure for each case, the 'not applicable' category was for measures such as chimney balloons if participants did not have open fires, or secondary glazing if all windows were already double glazed. The letters indicate the primary and secondary constraint or challenge which influenced the overall decision, where this was elucidated by the participants. In addition to the four categories considered above, disruption, and a need to think further because a measure was not something that they had previously considered, were additional categories that emerged during the analysis.

Figure 5.9: Condensed retrofit acceptability matrix for case studies, showing acceptability and key constraints



Retrofit measure	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
Loft insulation											H					
Internal wall insulation	H	P C	H	H	C V	C	D	V	V	H	H	H	?	H V	D	
External wall insulation	H P	H P	H	H	H	H V	?	V	H	H	H V		?	H V	D	H
Floor insulation	H	V C	C	C	C	H V	D	V	V						D	
EE lighting																
Draught proofing			H												D	
Chimney balloons															V	
Upgrade boiler																
New windows (wood)					H								P			
New windows (UPVC)	H	H	H	H	H		H	H	H		H	H	H	H		
New windows (aluminium)		H P	H	H	H			H			H	H		H		
Thermal curtains								?								
Interior shutters			H V					V		V		?	V			
Exterior shutters	H P	P	H	H	H	P	H	H	P V	V	H	H	P	H	D	H
Secondary glazing									H				P D	V		
Solar PV	H C	P	C V			V	H	H P	V P	V	?	H C	P V	C	P	D
Solar thermal	H C	V	H C		H	V	H	H P	V P	V	?	H C	P V	C	V	
Biomass boiler	V	V	C	D	C V	V	V	V	V	V	H	V	V	V	D	
Air source heat pump		H	V	D	V	D	?	D	V	H	?	H	V	?	V	D
Ground Source heat pump	C			D	V C	D	?	?	C V	?	?	V	V	V	V	C
Water source heat pump				D												
Wind turbine	P	P	P	H	V	C	P	V	P	H	H	V	V	V	V	V
Thick wall hangings	V	V	V			V			V	D	V	?	V	V	V	V
Improve heating/hot water controls														C		

Looking at those retrofits that participants would not consider, the majority found changes with a visible impact, such as wall insulation and window replacement, unacceptable, generally attributing this to their impact on heritage value. Renewable technologies were more acceptable and more likely to be affected by viability/practicalities, although heritage impact was still an important factor for many participants. Window additions such as curtains or internal shutters, and floor and loft insulation were more acceptable to most participants, as were changes such as energy efficient lighting and boiler upgrades, although most had already enacted these. Impact on the heritage values that residents invested in their buildings appeared to be a key determinant of a measure's acceptability. There were significant variations between what different participants considered acceptable for their specific contexts as will be explored below. However the overall pattern of acceptability is similar to that of the survey respondents.

Several participants were interested in applying measures only to parts of the building, such as CS11 who was considering a small area of insulating external render on the already rendered façade of their home, or CS3 who felt that it might be acceptable to replace their single glazed sashes on the north side of their house with double glazing but were determined to keep the original leaded windows on the south façade. CS13 meanwhile was interested in applying either internal or external wall insulation to their modern rear extension but not to the main building. Because this was a modern extension, they felt that it did not present heritage concerns.

Participants were already familiar with most of the measures listed but some were new to them or were things that they had not considered in the context of their own building. For some of these measures they identified the need to consider them further before they could come to a decision, although for some, they were able to immediately give an opinion. Unfamiliar measures included thermal curtains for CS5 and CS8, secondary glazing for CS9 and internal or external wall insulation for CS7. Several participants were unclear on how heat pumps actually worked and a discussion of the technology and its level of efficiency in a UK climate was required before they could complete the matrix. Wall hangings were also a measure that was less familiar to participants but which they quickly understood.

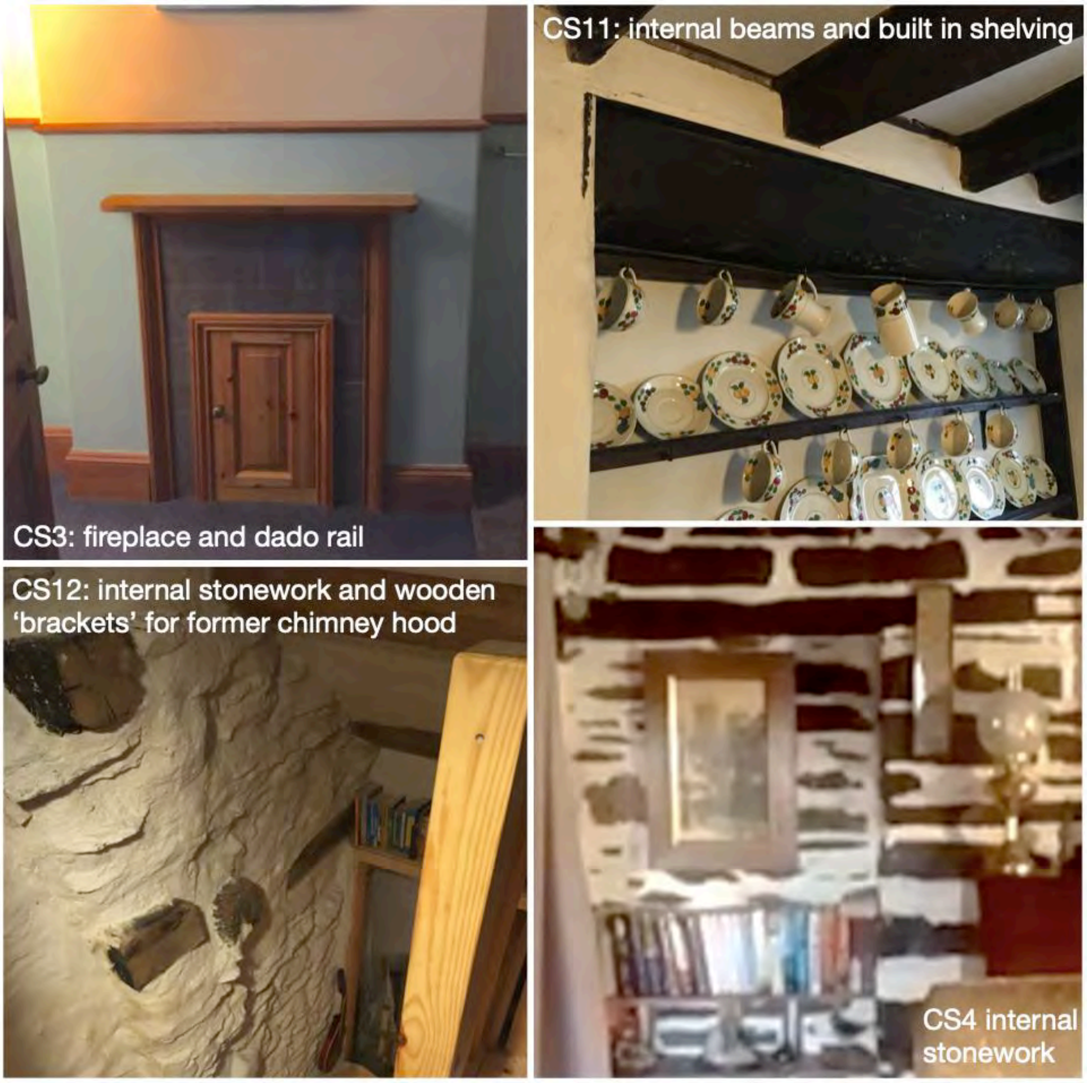
5.5 Barriers to retrofitting

Participants identified a range of different reasons why particular measures might be either unacceptable or challenging to deploy.

Impact on heritage value was a key consideration for the majority of participants. Rather strangely, six participants were willing to consider solar PV panels while only three would consider solar thermal. CS3, CS5, CS8 and CS12 were concerned as to whether solar thermal panels would 'fit' the character of their buildings, sentiments that they did not express nearly as strongly for solar PV. IWI was slightly more acceptable to participants that EWI because it had less external impact. However, in addition to concerns about space reduction, several participants had internal features whose heritage value would be detrimentally affected by wall insulation (CS1, CS4, CS5, CS10, CS11, CS12) (Figure 5.10). CS11 for example, appreciated the texture of their lime plastered walls and contrasted them with the characterlessness of drylining in places that they had visited.

CS11: This wonderful old stonework and they've drylined it… I'd rather be cold than that!

Figure 5.10: Case study internal wall features



Participants also exhibited concern about the cultural appropriateness of measures, with all participants for example feeling that exterior shutters were unacceptable to their heritage values. This was because these shutters were not considered appropriate in a Cumbrian context despite acknowledgement that, in other regions, they would be acceptable, and even desirable, with CS16 noting that: 'In the south of France everywhere has got shutters…' while CS4 characterised them as 'too continental'. In contrast, seven participants felt that interior shutters would be appropriate, with a further five usure. Several participants felt that reinstating interior shutters would actually contribute to enhancing their building's heritage value

CS13 'In terms of heritage it would look great with the house… it's what the building should have.'

Disruption was an issue that emerged as a barrier in the analysis, in terms of the scale of work, such as lifting floors for underfloor heating (CS6) or redecorating after installing IWI (CS7), and also because of personal circumstances. CS4 and CS15, where all participants are over eighty years old, were concerned about the level of disruption and effort that a measure might entail. They were unsure whether this made sense in a cost benefit analysis because they did not feel that they would enjoy the benefits for very long. CS4, for example, had looked into whether they could get their original waterwheel to provide hydropower, and while this did appear to be feasible, they decided that it would not be worthwhile for them at their current life stage. Meanwhile CS16, who have young children, felt their capacity as a household was too limited at present for them to invest time and thought into exploring further potential retrofit measures.

The viability and practicality of measures was also of concern to participants. Some of those with small homes identified practical space challenges with IWI (CS2, CS5, CS9), fuel storage space for biomass boilers and the commitment that feeding a biomass boiler might require (CS4, CS9). CS2 and CS10 also noted challenges with the reduction of headroom that could result from solid floor insulation. Other participants were concerned about the compatibility of measures with the fabric of their building, CS6 and CS11 for example, were concerned about the weight of solar panels on their original roofs and CS14 felt that wall insulation would be unsuitable given the levels of moisture in their building.

CS3 was interested in the potential of wall hangings but was concerned about the cost of maintenance because of the experience of their friend who had just had heirloom medieval tapestries cleaned by specialists for an exorbitant sum. This highlights the way that decisions are influenced by personal knowledge and experience. A further practical issue with wall hangings was also identified by CS13 and CS14 who were very interested in the concept but felt that there might be challenges.

CS13: The only problem with thick wall hangings is that you get thick cats climbing up them…

Planning was a constraint for participants with designated buildings (CS1, CS2, CS3, CS6, CS8 CS9, CS12, CS13, CS15), especially for listed buildings (CS1, CS2, CS13). CS2 for instance felt that solar panels would be acceptable to their heritage values but did not think they would get permission from the Lake District National Park (the planning authority), because they are within a grade II* listed curtilage. CS13 was interested in seeing if they could get slimline double glazing to replace their current, modern single glazing on their grade II listed façade but thought permission was unlikely.

In the conservation areas there was some confusion about the types of measures that would be acceptable and how guidance could be accessed. CS15 for example, thought that they would have to pay a fee just to find out if they would need permission for solar panels or not. While this is unlikely to be true, participants perceived challenges with accessing information about whether changes would be acceptable in planning and highlighted discrepancies in planning decisions. Inconsistency in decisions and how planning regulations were applied was also noted by survey respondents.

Cost was the final constraint that participants identified, especially for measures such as renewables and window replacements or secondary glazing, although it was something that they did not emphasise as strongly as other issues when discussing the retrofit matrix. Several participants (CS6, CS12, CS16) had investigated GSHPs and concluded that they were too expensive to be viable, especially given the heating system changes that would be needed to make them effective in their buildings. The 'heritage premium' of more sensitive measures was also emphasised by several participants. CS1 and CS3 had both investigated secondary glazing and received quotes in excess of a thousand pounds per window, although both were potentially willing to pay this figure. CS9 meanwhile noted that a hardwood double glazed sash window that they had specifically made for their bathroom extension was:

Quite eye wateringly expensive but… if we can afford it, we have the right thing done.

Residents therefore appeared willing to pay more for measures that they felt were more acceptable to their heritage values. Several residents identified a range of measures as ‘expensive but worth it’, suggesting that while they saw cost as a constraint, it was not, per se, a barrier that would stop them considering a measure, although it might limit the time frame in which they could enact it. CS14 for example, was interested in investigating renewable technologies for their home but currently did not have the capital. Their summary on cost constraints however was that:

CS14: If we had the money, I don’t think cost would be an issue.

A number of the case study participants are actively planning a variety of retrofit measures in the short term, while others are considering potential changes in the more medium future. For measures that participants are actively considering cost is a clear barrier. These measures are summarised in Table 5.1 and include improvements to heating systems (shown in green), windows (blue), and insulation (red), while one participant is considering removing a previous maladaption (purple).

Table 5.1: Case study planned and considered retrofits

	Planned, planning in progress, or definite statement of intent.	Measures that are being considered
CS1	Planning new heating system, considering air source heat pump or possibly biomass.	Replacing current poor quality double glazing with high quality replica sashes
CS2	Would like to improve heating system by replacing storage heaters	Possibly secondary glazing for windows.
CS3	Replacing boiler in next year is ‘in progress’	Possibly replacing or restoring single glazed sashes on north side with ‘like for like replacement’
CS4	Nothing planned	Nothing planned
CS5	Nothing planned	Possibly replacing two windows in poor condition with like for like single glazing
CS6	Nothing planned	Nothing planned

	Planned, planning in progress, or definite statement of intent.	Measures that are being considered
CS7	Nothing planned	Nothing planned
CS8	Secondary glazing for rear of house in the next year is ‘in progress’	Nothing planned
CS9	Nothing planned	Nothing planned
CS10	Replacing inappropriate loft insulation and fixing current heating controls ‘in progress’	Considering low carbon alternatives to LPG heating.
CS11	Insulating intermediate floor above living room, for insulation and fire security. Refurbishing upstairs windows.	Potentially removing cement render covering one facade and installing lime based external insulation.
CS12	Nothing planned	Nothing planned
CS13	Taking up modern living room floor to expose original floor (if present) and insulating	Possibly slimline double glazing for replica single glazed sashes on front façade
CS14	Nothing planned	Would like to remove impervious paint from external walls and replace with lime. Would like to get original sashes reconditioned
CS15	Nothing planned	Nothing planned
CS16	Nothing planned	Nothing planned

Some of the measures that participants are considering are things that they would like to do but feel are not possible at present. Because CS2’s participants work at home and are in their house all day, they feel that their storage heaters do not provide heat for a long enough duration or deliver it efficiently. They are therefore very keen to install a different heating system, ideally utilising underfloor heating powered by a ground source heat pump. The costs of such a system however are prohibitively expensive. Cost was also a barrier for CS14 in their desire to replace their impervious external paint and restore the original lime render to help their building to manage moisture better.

Beyond the specific context of the retrofit matrix, the case study participants were also asked what they considered the key barrier to carbon reduction from their building was for them (Table 5.2). Many of the comments were related to knowledge of suitable options and understanding appropriate solutions. These appeared to be related to residents’ feelings that, because of their heritage values, standard solutions are not acceptable to them, and they are unaware of any suitable alternatives (CS1, CS3, CS5, CS6, CS9, CS10, CS11, CS12, CS14). CS5 for example, feels that because of their building's heritage values, internal wall insulation would be the only major measure that they could consider and that practically this would cause too significant a reduction of internal space, and effect internal features of value.

Table 5.2: Case study participants' perceived barriers to carbon reduction from their homes

	Barrier 1	Barrier 2	Barrier 3
CS1	Suitable options for traditional construction compatible with heritage values		
CS2	Cost of measures	Planning restrictions for visible renewables	
CS3	Changes that work with the current building fabric (retaining chimneys etc)	Heritage appropriate options	
CS4	Age of residents and cost and disruption benefit analysis		
CS5	Heritage appropriate solutions	Practicalities, for example size reduction from internal insulation	
CS6	Cost of measures	Heritage appropriate solutions	Disruption
CS7	Absences of personally motivating drivers	Not getting around to it	
CS8	Knowledge from trustworthy sources		
CS9	Not getting around to it	Cost	Knowledge from trustworthy sources
CS10	Knowledge of suitable options for traditional construction	Helping the building to function efficiently	
CS11	Knowledge of the best solutions		
CS12	Heritage appropriate solutions	Location and form factor preclude further sensitive changes	Cost benefit analysis 'is it worth it?'
CS13	Maintaining a base heating level		
CS14	Cost of measures	Practical considerations around moisture management	Knowledge from trustworthy sources
CS15	Age of residents and cost and disruption benefit analysis		
CS16	Time capacity to consider available options		

Another theme is the importance of accessing knowledge from trustworthy sources (CS8, CS9, CS14), with residents feeling that they do not want to be to be ‘sold to’ and identifying this as one of the problems with getting the companies that would do the work to do the assessment of what is needed.

> *CS14: Because if you get someone in to look at damp, you’re actually getting someone to sell you some damp proofing… even if they are not ‘money grabbing horrors’ they are still committed to what they’re doing so they’re interested in it… If you’ve got a physical problem and you go to see a surgeon, he will want to do surgery, you know? Because that’s what they do!*

CS9 felt that there might be a role for the government to offer a service that would provide a ‘completely unbiased’ view of what could be done. CS8 however, felt that:

> *CS8: It’s always someone trying to sell you something… even the government because they have their own agenda*

These comments suggest that informational barriers are not only about being able to access relevant information but also about the source of that information needing to be seen as trustworthy or ‘disinterested’.

A connected issue was the availability of suitably skilled tradespeople (CS2, CS8, CS9, CS11, CS14). Participants felt that finding skilled tradespeople who understood how to work sympathetically with older buildings was a challenge. CS9 for example, was very disappointed by the upstairs front windows which they had had replaced, because of the poor-quality workmanship and because the tradesperson could not understand why they were so insistent on retaining the original, coloured window lights (Figure 5.11). In contrast CS14 had been very concerned about the need for some replastering work and were delighted to find an excellent plasterer who did a job that was ‘*respectful* of the character of the building’ (CS14, original emphasis). CS8 meanwhile was enthusiastic about internal shutters but was unsure where to find a good carpenter to construct them and CS11 did not want to let anyone work on their home who would not be very careful because of their connection to the building.

Figure 5.11: CS14 and CS9's contrasting experience with tradespeople

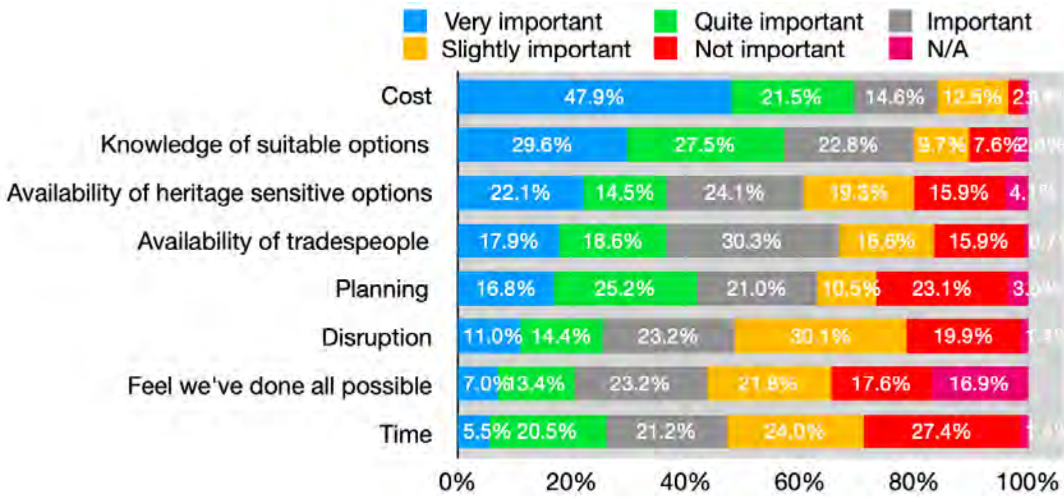
Several participants felt that a key challenge was helping their building to function as efficiently as it could (CS3, CS6, CS10, CS11) which required regular and expensive maintenance, and in several cases, a need to remove previous maladaptions (CS6, CS11, CS14) which was often very costly.

> *CS6: In an ideal world, if money was no object whatsoever, the first thing I would do is get the cement render off and get a proper clay/a breathable render on it… but that would be a very expensive exercise.*

Additional but less common barriers included CS7's feeling that, because they found their house very comfortable, they lacked the personal drivers to 'get around to making changes'. This sense of 'just getting around to it' was something that other participants mentioned, especially when related to maintenance issues or smaller measures that 'just need sorting' (CS3, CS5, CS9, CS11, CS13) but CS7 were the only ones to identify this as the main barrier to taking action.

Impact on heritage values, knowledge of appropriate options, disruption, planning constraints, practicality, and cost as well as 'just getting around to it' were therefore found to be key barriers perceived and experienced by the case study participants. Many of these barriers were also found to be important for the survey respondents (Figure 5.12). Cost was the most important barrier for most respondents, followed by knowledge of suitable options and the availability of heritage sensitive measures.

Figure 5.12: Importance of barriers for carbon reduction in their buildings to survey respondents (N = 147)



Free text comments from the survey respondents identified similar themes to the case study participants, particularly in terms of heritage sensitive options, trustworthy information, and appropriate solutions.

Keeping the feel of the building even on the parts which are not listed

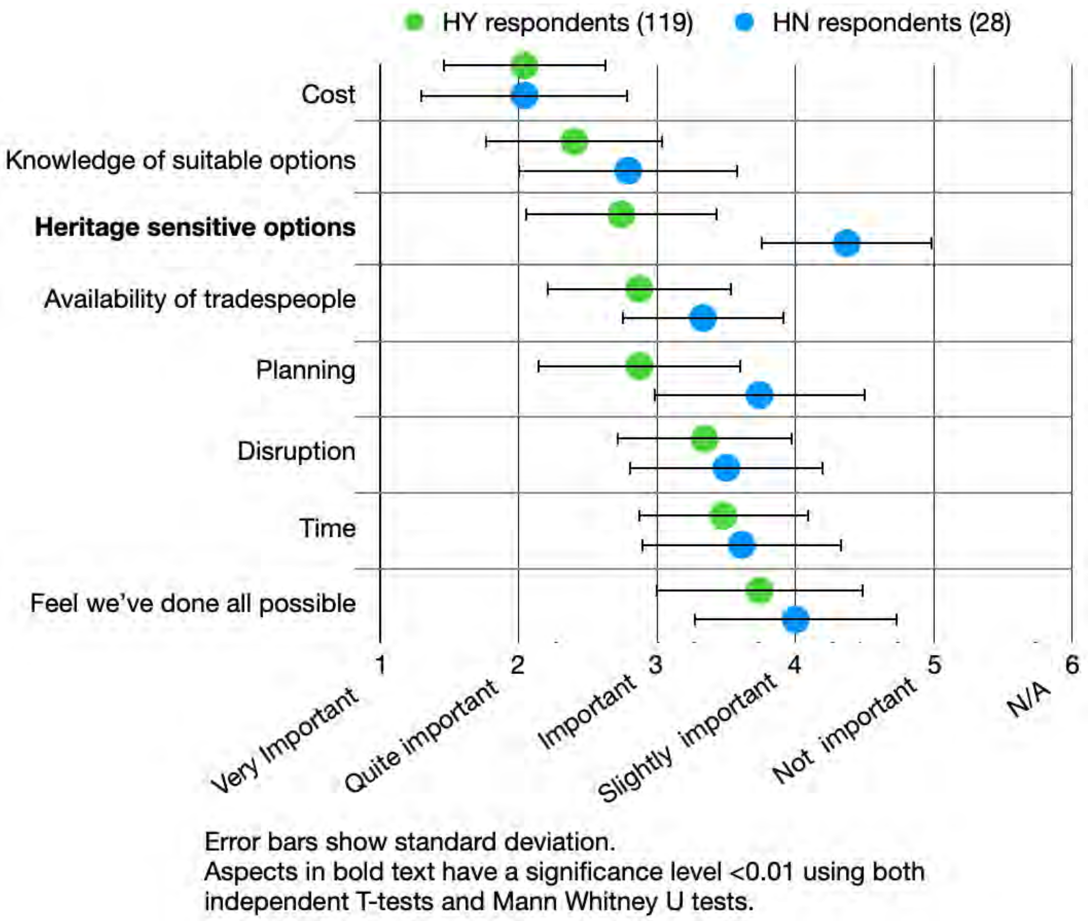
Can't find tradespeople qualified in sympathetic alterations

Cost, disruption and impact on living space major issues - based on insulation work done to date it would cost well in excess of £30K to insulate the walls and floors. Not affordable.

Greenwash con artists

Comparing the survey respondents who perceived their buildings to have heritage values (HY) and those who did not (HN) showed that although the overall order of the barriers did not change, the HY group felt that heritage sensitive options, planning and the availability of tradespeople were more important than the HN group if mean values are compared. The only statistically significant difference was for heritage sensitive options, which would logically be expected (Figure 5.13).

Figure 5.13: Comparison of mean importance of barriers to retrofit survey groups

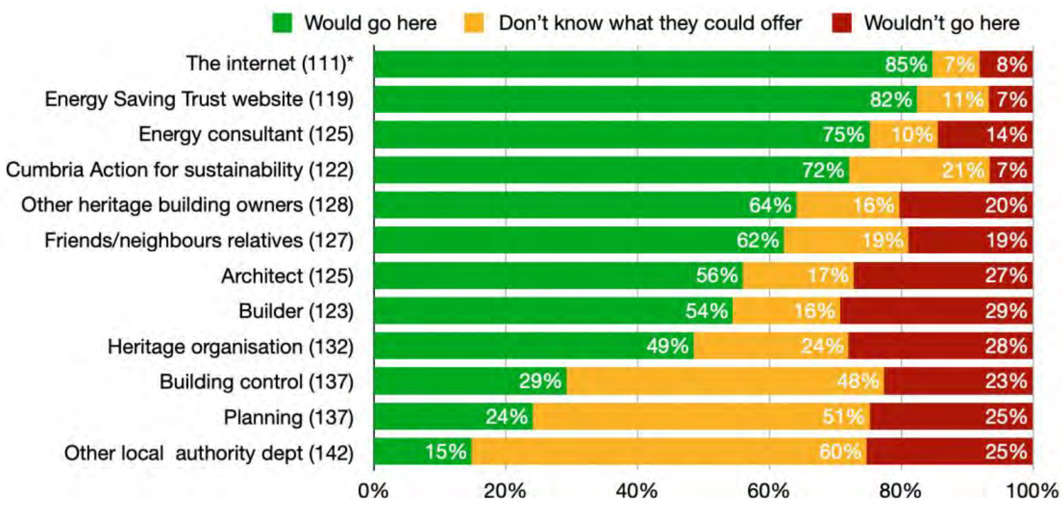


Barriers relating to cost and to identifying measures acceptable to residents' heritage values and the tradespeople able to carry them out therefore appeared to be important to both case study participants and survey respondents.

5.6 Information sources

Survey respondents were also asked where they would go for information on ways to reduce carbon from their buildings (Figure 5.14). The top sources are online (with The Energy Saving Trust having website offering generic carbon reduction advice). Five of the six most popular information sources, with the exception of 'Energy consultant,' are free, suggesting that respondents may be more likely to investigate these sources first. The popularity of sources such as other heritage building owners and social networks (friends/neighbours/relatives) confirm other findings that point to the importance of informal information networks (Hrovatin and Zorić, 2018; Bartiaux et al., 2014). Cumbria Action for Sustainability (CAfS) is an active charity which provides sustainability information, events, and initiatives across Cumbria, although because one of the survey distribution channels was through their newsletter respondents may be more familiar with their resources than average.

Figure 5.14: Information sources which survey respondents would or would not access

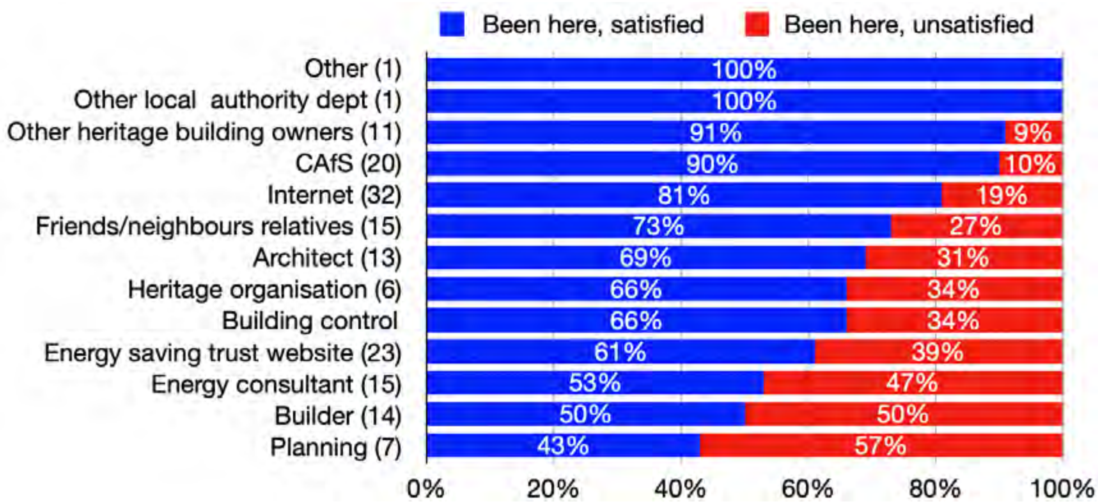


*Number of respondents

Statutory information sources such as planning departments and building control are the least likely to be accessed by respondents and significant numbers appear to be unclear on the resources that these departments could offer. Less than half of respondents would seek information from heritage organisations, despite these groups providing significant and relevant resources. This could be linked to confusion on the remit of heritage organisations and a perception that they only cover significant, or at most, listed buildings, with residents not recognising their wider historic environment remit. In could also be linked to the distinction identified in Chapter Four around how participants in undesignated building often did not consider them to be heritage buildings despite their investment of significant heritage value.

Some of the respondents had already accessed some of these information sources and were asked how satisfactory they found the information provided (Figure 5.15). ‘Other Local authority department’ and ‘other’ had only been accessed by one respondent who was satisfied. Other heritage building owners, CAfS, the internet and personal networks provided satisfactory information for the majority of respondents. This may link to the importance of sources being trustworthy and disinterested in selling solutions which was identified by the case study participants. The internet meanwhile may be preferred because of the ease of quickly accessing a range of knowledge. Information from planning departments, builders and energy consultants was unsatisfactory to approximately half of the respondents who had accessed it.

Figure 5.15: Satisfaction with information sources for survey respondents



Comments from respondents also identified interest in learning from other heritage residents and in receiving recommendations for professionals. Other comments included books and personal professional knowledge for some participants, as well as the Centre for Alternative Technology (CAT) in Wales.

You ask about other building owners, I WOULD go there but I don't know any

Other heritage users – satisfied but confirmed unaffordable cost estimates

Talking to those in historic houses to find the right advisor

Respondents therefore appeared to access a range of sources but local networks, organisations, and other heritage residents as well as the internet all appeared to be popular sources of information which were also generally satisfactory.

5.7 Discussion

It is clear that the heritage values that residents invest in their buildings affect both the changes that they have already made and the measures that they would consider acceptable in the future. The impact of measures on heritage values was a key influence for the case study participants and several of the barriers that both participants and respondents identified were related to their heritage values, including appropriate information sources, suitable tradespeople and concern about material and system compatibility.

Some residents had used natural and traditional materials, such as lime and wood fibre and sheep's wool insulation in their previous retrofits, which are more likely to be compatible with the construction of vernacular buildings. Many residents also displayed a clear understanding of how their buildings functioned and the importance of managing moisture and maintaining ventilation, as well as a desire to remove maladaptions where possible. The detailed understanding that some residents have of their buildings may contribute to their wariness about the trustworthiness of information on measures to improve their building's performance and their concern about finding suitable tradespeople to enact these measures. This supports and builds on Mallaband et al's (2013) findings that residents are often frustrated by tradespeople who lack the residents' expertise in their own buildings.

The potential benefits of a range of retrofit measures that can be termed 'soft' were identified as being used in some of the cases. These measures are unlikely to be considered by professionals in retrofit projects because they are generally deemed to fall within the remit of occupant choice. However, they clearly have effects that are considered valuable by their users, and which may have produced either carbon savings, or led to potential embodied emissions being avoided. Indeed, as this chapter highlights, all retrofit measures fall within the remit of residents' choice because if measures are not acceptable to residents, they will not be enacted. While some of the specific soft retrofits identified may not be suitable or acceptable for all residents, there are likely to be at least some changes of this type that are appropriate for most individuals. Increased consideration of these types of measures in retrofit projects would therefore be beneficial. These types of less material changes may also have advantages in terms of their adaptability to changing conditions and building use, as well as easier reversibility, which is important for heritage retention. They are also likely to be less susceptible to maladaption than more substantial physical changes, particularly with regard to moisture challenges. Finally, they are likely to have a reduced financial cost and be less disruptive to install, suggesting that there may be opportunities to roll out these types of measures quickly and on a large scale, as part of wider efforts to reduce carbon from buildings.

Some participants also showed an awareness of embodied carbon in their retrofit decisions such as CS7 not wanting to 'waste' their current, still working boiler or CS16's awareness that their substantial retrofit had 'used up' their carbon budget. This awareness is positive, although participants felt that they would benefit from more information about opportunities and challenges. CS1 for example, had looked into a biomass boiler but found that it would have to be shipped from Canada and were uncomfortable with the embodied carbon this represented. However, in contrast to continuing to use their 40-year-old, very inefficient, oil boiler, the embodied carbon of the new boiler might in this case be rapidly recouped through operational savings.

This highlights the need for information to be more readily available to help inform these types of decisions.

The external visibility of retrofit measures was an important consideration for residents. Solid wall insulation and window replacement are commonly recommended retrofit options for vernacular buildings, but they appear unacceptable to many residents, limiting their potential for carbon reduction. This lack of acceptability is likely to relate to the values that residents were found to invest in the connection of their building to its wider landscape, its specific materials and construction and to the craftsmanship of original features such as windows. Residents' dislike of exterior shutters also showed a concern with the cultural appropriateness of changes, highlighting the importance of taking local context into account when considering retrofit acceptability. Retrofit measures unacceptable to the majority of residents in this research appear comparable to the changes that might be considered unacceptable in planning to a listed building, although this was the case for residents in all buildings, designated and undesignated. The only exception is that residents appear more accepting of visible renewables, and indeed planning constraints were identified as a barrier by several participants who would otherwise consider solar panels.

The increased acceptability of visible renewables such as solar panels may be because they are more 'additions' to the building, rather than fundamental alterations of its character such as might be the case with external wall insulation on buildings with stone facades. Solar panels can also provide visible evidence of residents' 'green credentials' which may be something that some residents consider attractive. The greater acceptability of solar PV compared with solar thermal was partly attributed to their heritage impact but may also be due to greater familiarity with solar PV due to government and industry initiatives and therefore greater publicity. A further issue may be scepticism about the effectiveness of solar thermal panels in a Cumbrian climate.

Constraints other than those directly related to heritage values included practicalities, costs, planning restrictions, and disruption, which were important to participants in a variety of ways. Case specific issues included participants' ages, space constraints, and even pets. These disparate barriers highlight the need to consider residents' specific circumstances when identifying the support that they may need to develop retrofit projects, and the likelihood of them actually enacting retrofits. The majority of the participants appeared willing to pay more for heritage sensitive measures and were unwilling to compromise their heritage values for lower costs. They were however aware that 'doing the right thing' came at a financial premium and this sometimes affected their ability to undertake retrofitting.

Cost was a particularly important barrier for the uptake of renewable technologies, especially relating to heat pumps which were considered unaffordable by many participants as well as challenging to install effectively. Another issue specifically identified with air source heat pumps was a lack of detailed understanding about how they function, leading to scepticism about their effectiveness. Because many participants had a good understanding of their buildings, they wanted to be clear about the details of how any new technologies would work so that they could assess their potential for themselves. After discussions on the function of heat pumps with those who were uncertain of the technology, the majority of participants felt that the alterations required to make heat pumps work effectively in their homes were challenging and might not be compatible with their heritage values. A number of participants were interested in the potential of installing underfloor heating which would enable the heat pumps operate more efficiently, although disruption, and in some cases the heritage nature of floors, were a barrier for many. As heat pumps are a core part of the UK government's decarbonisation strategies ways may need to be found to make heat pumps, and the associated changes that they require, more acceptable to heritage residents.

Support may be required to help residents negotiate barriers, especially those related to cost and knowledge of suitable and heritage sensitive solutions, which needs to come from trustworthy sources if greater take up of retrofit measures is to be realised. Access to trustworthy and independent advice is an area that planning departments could be able to assist with, although currently very few residents would consider seeking advice from this source. This suggests that if planning departments are to fulfil this role, significant improvements in the consistency and accessibility of their services appear to be required.

The range of factors that residents must negotiate when considering retrofit solutions were shown to be many and varied, highlighting the fact that there is unlikely to be any 'one-size-fits-all' solution that is universally acceptable.

5.8 Conclusion

This chapter has investigated the acceptability of retrofit measures to residents (RsQ1d) and identified and examined a range of barriers and constraints (RsQ1e).

Most residents have already installed many common retrofit measures, as well as making use of a variety of soft retrofits which may have promise for heritage sensitive carbon reduction. Visible external changes and common measures such as wall insulation and window replacement are generally unacceptable to residents, although visible renewables are more likely to be enacted. The measures that were the most acceptable to residents were also those that are the most likely to have already been enacted, suggesting that there may not be that much potential for further significant savings from them at a larger scale. This means that additional acceptable measures must be found to help reduce carbon from vernacular buildings. The effect of retrofit measures on aspects that residents value was identified as a key determinant of retrofit acceptability, although residents also had to negotiate a variety of other factors such as building compatibility, and practical and planning constraints in their decision making.

A number of the case study participants were actively planning or considering a variety of retrofit measures to their buildings, although some of these changes were felt to be currently untenable due to cost barriers. Key general barriers identified by participants and respondents were the cost of measures and the knowledge of both heritage appropriate solutions and of suitable tradespeople to undertake the work. The trustworthiness of knowledge sources was important to residents, and the survey respondents appeared interested in learning from other heritage residents. The importance of considering residents' individual situations to understand their particular barriers and drivers was identified, and the likely need for support to help residents overcome retrofit barriers was highlighted.

Residents' heritage values therefore clearly determine the retrofits that they consider acceptable/unacceptable and strongly influence the barriers that they identify to carbon reduction from their homes. These values and the knowledge that residents have of how their buildings function are also likely to affect their comfort perceptions and behaviours within their buildings.

Some material in this chapter has been previously published in (Wise, Moncaster, Jones, et al., 2022; Wise, Jones, et al., 2021)

Figure 5.16: CS5 and CS6

Chapter 6. Energy Behaviours and perceptions of comfort

6.1 Introduction

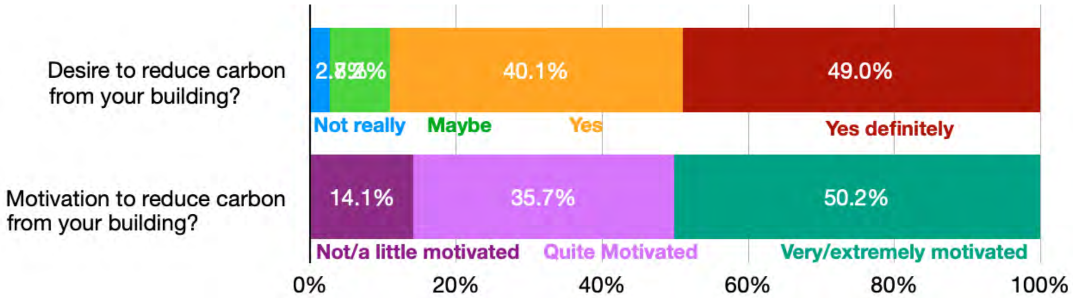
The clear heritage values that residents invest in their buildings have now been shown to significantly affect their retrofit decisions. This chapter investigates residents’ comfort perceptions (RsQ1b) and energy behaviours (RsQ1c) within their buildings, by examining the survey responses, case study interviews, building tours and energy diaries.

Residents’ attitudes to carbon reduction are identified, along with general actions that they have taken to reduce their household carbon emissions. Residents’ heating patterns and temperatures are examined, along with their attitudes to thermal comfort. The spaces that residents heat and do not heat within their buildings and their behaviours and attitudes with regard to ventilation are investigated. A range of challenges that residents may have with comfort in their buildings are identified and the effect of residents’ heritage values on their comfort perceptions are considered. Finally, residents’ perception of their buildings’ performance in summer is examined.

6.2 Residents’ environmental attitudes and behaviours

The vast majority of survey respondents indicated that they wanted to reduce carbon emissions from their buildings (89%) and that they were quite motivated to do so (86%) (Figure 6.1). One of these questions was near the start of the survey and one near the end.

Figure 6.1: Survey respondents’ desire to reduce carbon from their buildings (N = 147)



The case study participants meanwhile were all concerned about the impact of climate change and wanted to reduce their carbon emissions. Some participants felt that the effects were already noticeable in their local environments (CS1, CS6, CS9, CS11, CS12, CS14, CS16), highlighting shifting seasons, changing weather and increased flooding, something which was of personal concern to several participants (CS10, CS12, CS16).

CS5: It's not only ourselves but our responsibility for others that share our life, birds, and invertebrates and…

CS6: I do have a great concern for 'man's impact on the environment', and we're noticing here that the seasons have completely changed and that we're regularly getting flooding on the river now that didn't used to happen.

The majority of participants already engage in a variety of environmentally conscious behaviours to reduce their own carbon impact; recycling, considering sustainable transport options and diets, and, in some cases reducing consumption and attempting to shift to more sustainable practices.

CS3: I've taken up the vegan thing this year at the urging of one daughter, but I've been vegetarian forever

CS5: We try to use public transport, and cycle and walk… we don't fly much, we do our best… so we buy less stuff, clothes, or furniture, or new cars or whatever it might be.

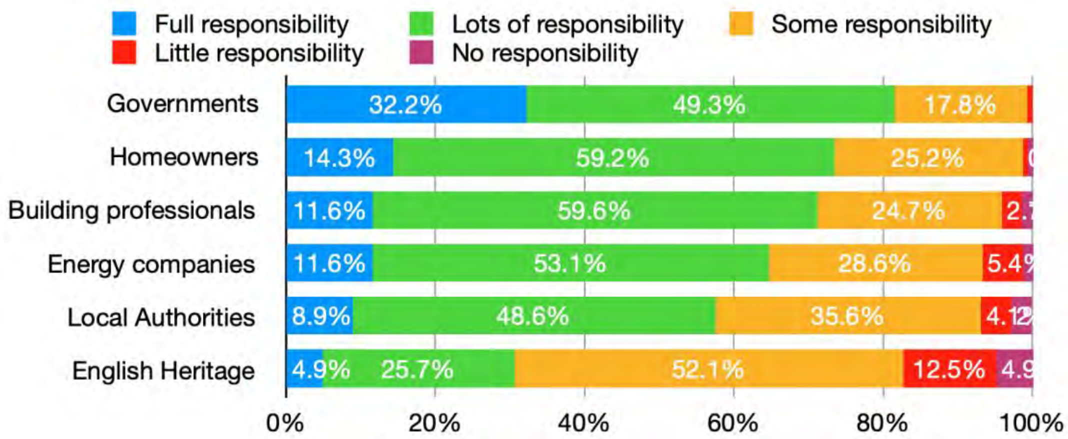
Some participants had taken more action than others, CS7 for example is concerned about the impact of climate change but acknowledges their lack of personal behaviour change in response to this.

CS7: One could be accused of being, not hypocritical but almost a philistine really, for being aware of it [climate change] but not reacting to it, but it will come to us I'm sure, by either legislation or personal responsibility, that we've got to be part of the solution.

CS11's lifestyle meanwhile is defined by their environmental principles. They feel that their annual carbon emissions are about a tenth of the UK average and they think other people could similarly reduce their emissions 'quite easily', although whether many people would be willing to be as committed as CS11 is debatable, as will be seen below.

The case study participants generally identified that individuals and businesses have significant responsibility to reduce carbon emissions more generally but that this needs to be led and either enabled or enforced by government to have the level of effect required to mitigate the climate crisis. The survey respondents (Figure 6.2) also identified that governments and residents had the greatest responsibility to reduce emissions from buildings, and that a range of other groups also had a role to play, suggesting collective action is needed. Historic England was the only organisation that respondents identified as having much lower responsibility, perhaps because they are unaware of their broader remit for older buildings (section 5.6).

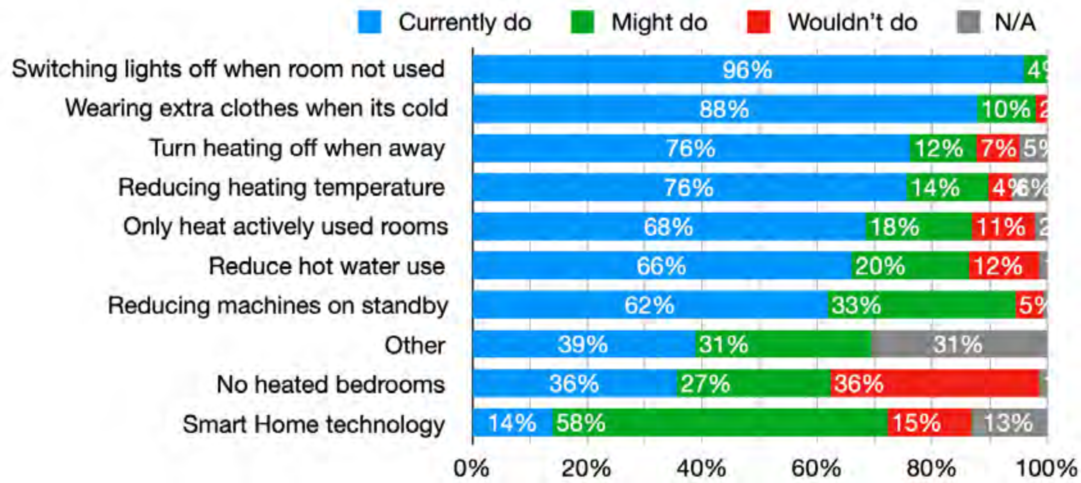
Figure 6.2: Responsibility of different groups to reduce carbon from older buildings from survey (N = 147)



6.3 General building energy practices

The survey respondents were asked to identify the behaviours that they already did or might be willing to do from a list of common household energy behaviours (Figure 6.3). Most respondents reported already engaging in many common, energy conscious behaviours, such as switching off lights, choosing energy efficient devices, and reducing hot water use. Seven of the nine behaviours listed were already practiced by the majority of respondents, although smart home technology had a poor take up and some comments suggested that limited broadband access in rural areas might be a barrier to this technology.

Figure 6.3: Survey respondents' reported energy behaviours (N = 147)



Comments elucidating the 'other' category also included a variety of behaviours around energy conservation and heating practices (Table 6.1).

Table 6.1: 'Other' energy behaviours reported by survey respondents.

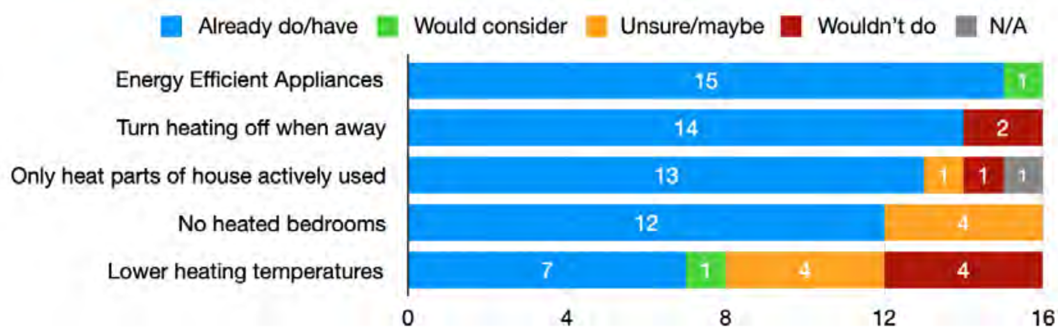
'Other' energy behaviours
Drying laundry outdoors and only using the dishwasher when it's full.
Unplugging the fridge and freezer when away
Central heating zoned – ground floor and first floor
Try and make full use of oven when on
Thick curtains kept closed during day when out
We only heat the house when the children are in and not in bed! After they're in bed the heating goes off, adults are smarter at wearing jumpers

One comment illustrated the effect of household characteristics and individual circumstances on the energy behaviours that residents may be willing and able to engage in:

We are conscious of our energy use at all times and try to be as environmentally friendly as possible. Some suggestions (not heating bedrooms) are however unrealistic at our age.

The majority of respondents turned their heating off when they were away and considered their heating temperatures to be low (both 76%). The case study participants showed similar behaviours as can be seen in Figure 6.4, with 14 out of 16 turning their heating off when they were away and 7 feeling that they already had low heating temperatures.

Figure 6.4: Case study energy behaviours (N = 16)



Case study participants had the opportunity to detail more nuance in their behaviours. Of the 14 participants who turned heating off when away three set it to a 'frost' or 'away' setting for insurance purposes, and to prevent burst pipes, while CS13 kept their heating on slightly when they were away to keep the house comfortable for their cats. The two cases who did not turn their heating off when they were away, CS1 and CS2, cited the amount of time it took for the building to warm up on their return as a barrier. CS2 is dissatisfied with their current heating system while CS1's heating system is very old and inefficient, which may be related to the ability of these systems to rapidly warm their buildings.

CS1a: The house becomes really cold and it… CS1b: 'It takes days' CS1a: 'Yes or even weeks to get back up to temperature'

Behaviours around hot water use are also an important influence on building energy demand. Most participants were asked about their shower and bath use in the interviews and the energy diaries asked all participants to note details in their diaries (Table 6.2). 14 out of the 16 participants regularly made use of showers, while baths were only used regularly in three households, two of which have young children. All participants in seven cases showered every day (CS1, CS2, CS3, CS5, CS8, CS11), as did some participants in other cases (CS9, CS14, CS16). Other participants showered several times a week (CS5, CS10, CS12, CS13). The two case studies with the oldest participants, CS4 and CS15 did not report use of showers or baths in either of the energy diary periods, although both reported basin washing each day.

Table 6.2: Case study shower versus bath frequency as an indicator of hot water use

Case study	Frequency of showers and baths
CS1 (2) *	Showers: Both shower every day
CS2 (2)	Showers: Both shower every day, would like baths but not enough hot water
CS3 (1-5)	Showers: main participant showers each day (other household members unclear)
CS4 (2)	Washed every day. No showers or baths listed in energy diary periods
CS5 (2)	Showers and baths: Both shower every other day, each baths every 2 weeks
CS6 (2)	Showers: Both showered every day in energy diary periods
CS7 (2)	Showers: Both shower every other day
CS8 (2)	Showers: Both showered every day in energy diary periods
CS9 (2)	Showers: In winter 1 showers every day, 1 every 3 days, in summer both shower every day. Baths 2-3 times a year
CS10 (4)	Shower: Both adults shower every 2 days. Both children shower twice a week. Everyone has a bath every 2 weeks
CS11 (1)	Shower: Showers once a day
CS12 (3)	Shower: 2-3 showers a week between the 3 household members
CS13 (2)	Shower: Both shower every 2 days
CS14 (4)	Showers: 1 showers every day, 3 shower every 3 days. Everyone has a bath every 2 weeks.
CS15 (1)	Washed every day, no showers or bath in energy diary period
CS16 (4)	Showers: 2-3 showers a day between four household members in energy diary period

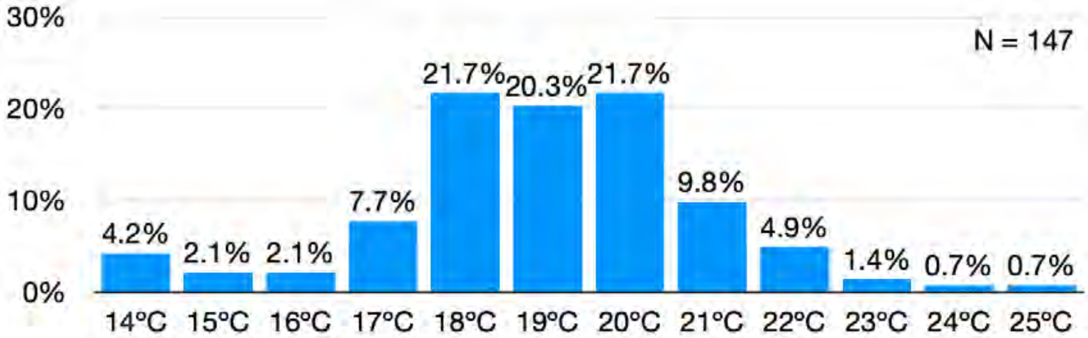
*Number of occupants

Residents therefore engage in a range of energy behaviours which are influenced by their specific circumstances. The behaviours which they report are however generally consistent with common energy saving behaviours.

6.4 Heating temperatures and timings

The mean thermostat setting which the survey respondents reported for their main living space was 19ºC (Figure 6.5). 64% of respondents reported temperatures between 18° and 20ºC, and very similar proportions reported temperatures higher and lower than this range.

Figure 6.5: Distribution of reported thermostat settings from survey



For the case study participants meanwhile, seven felt that they already heated their buildings to lower-than-average temperatures (CS3, CS4, CS6, CS11, CS12, CS14, CS16). They identified that although they were comfortable with their household temperatures, visitors and guests often found them cool. CS6 meanwhile was informed by their smart Hive heating system that their temperatures were two degrees lower than similar households, although how this comparison was undertaken was unclear.

CS5: Our visitors complain but we find it fine.

CS6: The heating would not usually be on at this time. It's when we realised that the decorators were starting to wear overcoats! That it might be a bit cold for them!

CS10 was willing to experiment with reducing their heating temperatures but they were awaiting an engineer to fix their thermostat and timer, which had been defunct for some months. At the time of the virtual visit, they were using their wood burning stove as their main heating device, occasionally boosted by the central heating. CS16 meanwhile usually had their heating on for limited periods morning and evening, despite normally having one person working from home. As a result of the pandemic however, all household members were working or studying from home and at the time of the virtual visit in January 2021 they were:

CS16: Trying to work out what works… the heating has been pretty much on all day but our thermostat… for the daytime it's set between 15.5ºC and 16.5ºC

Four case study participants would not want their heating any lower as they were comfortable with current temperatures (CS2, CS7, CS8, CS15). Another four were unsure and could potentially be convinced to try lower temperatures (CS1, CS5, CS9, CS13), CS1 for example felt that if they could improve the efficiency of their heating system, they might be able to reduce temperatures. CS9 meanwhile felt that it might be something that they would consider if they were convinced that it would make a significant difference to their carbon emissions. They did however note that they would not be willing to reduce temperatures in their bathroom which is in a modern rear extension that they had built in 2011 and which they described their: 'one concession to luxury, and that stays warm all day… nobody is taking my bathroom away from me!' (Figure 6.6).

Figure 6.6: CS9's luxurious bathroom

These comments highlight the variation in residents' circumstances that shape their behaviours, with CS16 trying to strike a balance between reducing energy use and maintaining comfort and CS9 identifying their personal red lines for maintaining comfort in certain areas.

Analysis of the energy diaries provided detailed snapshots of case study heating use in winter (Figure 6.7 and Table 6.3) and in summer (Figure 6.8). The majority of the participants use standard wet central heating systems with radiators, although CS1 and CS12 have partial underfloor heating, CS2 has storage heaters and CS4 has blown air heating. CS11 meanwhile only heats their living room, using a wood burning stove in the evenings as part of their low carbon lifestyle. Participants have a wide range of heating patterns and temperatures. CS2 and CS7 have the highest temperature set points at 21°C. CS7 identified that this is one of the behaviours that they could improve and said rather guiltily that they heat their house:

CS7a: To be comfortable, so that we can walk around in a t-shirt, rather than not heat the house, and wear a fleece.

CS15 and CS16 have the lowest heating temperatures despite CS15 being one of the oldest participants, they do however heat their house 24hrs a day, as do CS1, CS7 and CS13.

It would be expected that participants who spend more time in their buildings because they are retired or work from home would heat their buildings for longer; however this does not appear to the be case. The majority of the cases are either retired or have at least one member of the household who works from home, which as noted in Chapter Two is representative for Cumbria. However, seven of the cases only heat their homes for limited periods (CS3, CS5, CS6, CS10, CS11, CS12, CS14), although several of them (CS3, CS5, CS10) use spot heating in office spaces.

Figure 6.7: Case study winter heating patterns and set temperatures from energy diary

<table>
<tr><th>Case study</th><th colspan="2">12 am</th><th colspan="2">1 am</th><th colspan="2">2 am</th><th colspan="2">3 am</th><th colspan="2">4 am</th><th colspan="2">5 am</th><th colspan="2">6 am</th><th colspan="2">7 am</th><th colspan="2">8 am</th><th colspan="2">9 am</th><th colspan="2">10 am</th><th colspan="2">11 am</th><th colspan="2">12 pm</th><th colspan="2">1 pm</th><th colspan="2">2 pm</th><th colspan="2">3 pm</th><th colspan="2">4 pm</th><th colspan="2">5 pm</th><th colspan="2">6 pm</th><th colspan="2">7 pm</th><th colspan="2">8 pm</th><th colspan="2">9 pm</th><th colspan="2">10 pm</th><th colspan="2">11 pm</th><th>total heat hrs</th></tr>
<tr><td>CS1 (Mar)</td><td colspan="48">24hrs a day 18°C, Rayburn on constantly, Excess heat pumped around radiators/underfloor heating whenever control tank reaches 65°C, random sequencing</td><td>24</td></tr>
<tr><td>CS2 (Feb)</td><td colspan="14"></td><td colspan="22">21°C downstairs 18°C upstairs, 4 storage heaters kitchen, living and bed 2</td><td colspan="12"></td><td>11</td></tr>
<tr><td>CS3 (Dec)</td><td colspan="12"></td><td colspan="4">20°C</td><td colspan="8"></td><td colspan="4">20°C</td><td colspan="8"></td><td colspan="6">20°C</td><td colspan="6"></td><td>5</td></tr>
<tr><td>CS4 (Dec)</td><td colspan="18"></td><td colspan="19">18°C blown warm air heating, only small amount to bedrooms</td><td colspan="11">Thermostat increased to 20°C</td><td>15</td></tr>
<tr><td>CS5 (Mar)</td><td colspan="14"></td><td colspan="6">19°C</td><td colspan="14"></td><td colspan="10">19°C</td><td colspan="4"></td><td>8</td></tr>
<tr><td>CS6 (Mar)</td><td colspan="14"></td><td colspan="4">18°C</td><td colspan="16"></td><td colspan="12">18°C</td><td colspan="2"></td><td>8</td></tr>
<tr><td>CS7 (Mar)</td><td colspan="13">10°C setback</td><td colspan="7">21°C</td><td colspan="13">10°C setback</td><td colspan="13">21°C (wk/nd 5pm-11pm)</td><td colspan="2"></td><td>24</td></tr>
<tr><td>CS8 (Mar)</td><td colspan="1"></td><td colspan="10"></td><td colspan="23">18°C</td><td colspan="14">19°C-19.5°C</td><td>18</td></tr>
<tr><td>CS9 (Mar)</td><td colspan="14"></td><td colspan="31">Variable temperature, 19°C-21°C, higher in morning and evening</td><td colspan="3"></td><td>15.5</td></tr>
<tr><td>CS10 (Jan)</td><td colspan="12"></td><td colspan="6">20°C manual</td><td colspan="30"></td><td>3</td></tr>
<tr><td>CS11 (Mar)</td><td colspan="40"></td><td colspan="8">Woodburning stove</td><td>4</td></tr>
<tr><td>CS12 (Nov)</td><td colspan="12"></td><td colspan="4">19°C</td><td colspan="10"></td><td colspan="2"></td><td colspan="5"></td><td colspan="5">19°C</td><td colspan="10"></td><td>4.5</td></tr>
<tr><td>CS13 (Mar)</td><td colspan="16">17.5°C</td><td colspan="20">18.5°C</td><td colspan="10">19.5°C</td><td colspan="2"></td><td>24</td></tr>
<tr><td>CS14 (Mar)</td><td colspan="15"></td><td colspan="1"></td><td colspan="19"></td><td colspan="5">19°C</td><td colspan="8"></td><td>3</td></tr>
<tr><td>CS15 (Mar)</td><td colspan="13">12°C</td><td colspan="6">17°C</td><td colspan="27">16°C (when out placed on 7°C set back setting)</td><td colspan="2"></td><td>24</td></tr>
<tr><td>CS16 (Jan)</td><td colspan="16"></td><td colspan="26">14-15.5°C rising to 16.6°C in evening</td><td colspan="6"></td><td>12</td></tr>
<tr><td>Average</td><td colspan="48">Average temperature for central heating 18°C, average timing 12hrs and 45 minutes</td><td></td></tr>
</table>

Table 6.3: Winter case study occupancy and auxiliary heating from energy diaries

Case study	Central heating changes	Wood burning stove	Other Aux heating	Occupancy
CS1 (Mar)	None	4-5hrs in evening on two days	3-4hrs wood fire in evening on two days	(2) mostly in, retired
CS2 (Feb)	None	In evenings four out of five days	2-3 portable heater in living room and all day in main bedroom	(2) mostly in WFH (work from home)
CS3 (Dec)	None	N/A	Electric radiator in office all day and early evening	(5) 3 at university, 2 WFH but often away
CS4 (Dec)	None	N/A	None	(2) mostly in, retired
CS5 (Mar)	None	3hrs per day in evening	Gas fire one morning, Electric heating in separate studio, 3hrs per day	(2) mostly in, retired
CS6 (Mar)	Extra 1.5hrs one day	N/A	None	(2) mostly out, semi-retired
CS7 (Mar)	Extra 1hr one afternoon and 3 hrs one night	Not used	None	(2) mostly in, semi-retired
CS8 (Mar)	Off for 5hrs on three days as sunny	7hrs one afternoon	Electric fire for 1hr two mornings	(2) mostly in, retired
CS9 (Mar)	Boost at lunchtime one day	3.5hrs per evening	Electric heater in office one afternoon	(2) 1 WFH, 1 out at work
CS10 (Jan)	None	In evenings four out of five days	Electric heater 1-2hrs, two days, two electric blankets 30mins, two days	(4) School and WFH
CS11 (Mar)	N/A	N/A	Electric blanket 30mins one evening	(1) mix of WFH and out

Case study	Central heating changes	Wood burning stove	Other Aux heating	Occupancy
CS12 (Nov)	None	Two afternoons and every evening	None	(3) 1 school, 1 WFH, 1 out
CS13 (Mar)	None	N/A	None	(2) 1 WFH, 1 out at work
CS14 (Mar)	On all day on two days	One morning and afternoon, one evening	None	(4) 2 school, 2 mix of WHF and out
CS15 (Mar)	None	N/A	None	(1) mostly in, retired
CS16 (Jan)	None	2-3hrs on two evenings	Heating in annex on two days at 20°C	(4) 2 school, 2 mix of WHF and away

Figure 6.8: Summer case study heating patterns, set temperatures and auxiliary heating from energy diaries

Case study	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	total heat hrs
CS1 (Jul)	24hrs a day 18°C, Rayburn on constantly as in winter, stove not used																								24
CS2 (Aug)	Storage heaters off, portable oil filled heaters used 2-3 hours in evening if day was wet or cool. Stove used 1-2 hours 1 evening																								0
CS3 (Apr)	Central heating off, no other heating used																								0
CS4 (Jul)	Central heating mainly off, used for 2hrs one morning and 4hrs one evening, no other heating used.																								0
CS5 (Jul)	Central heating mainly off, used for 2hrs on one evening. Stove used 4hrs on two evenings, study electric heating 6hrs on one day																								0
CS6 (Jul	Central heating off, no other heating used																								0
CS7 (Jul)	Central heating off, stove used for 2-3hrs on two days																								0
CS8 (Aug)	Central heating off, electric heating in sitting room used for 1-2hrs on one evening																								0
CS9 (Aug)									20°C									20°							3.5
CS10 (Jul)	Central heating off, stove used in evening on two days																								0
CS11 (Jul)	No heating used																								0
CS12 (Sep)	Central heating mainly off, used for 2.5hrs on two mornings and one evening, stove used in evening on one day																								0
CS13	No diary returned																								0
CS14 (Aug)																				18°C					3
CS15 (Aug)															16-17°C, no stove use										17
CS16 (Sep)	Central heating mainly off, used for 1hr on one morning, no other heating used																								0
Average	Off for most cases, CS4, CS5 and CS12 all had heating on for a few hours on one or two mornings in diary period																								

CS2 uses portable, oil filled, electric radiators, in addition to their storage heaters, to maintain comfort in their living room which also acts as their office. They also heat the main bedroom with portable heaters in preference to using the two storage heaters as they find that the portable heaters are more effective and more responsive while using less energy. CS2, and, to a lesser extent, CS10, were the only participants who were dissatisfied with their overall comfort, all other participants felt that their homes were comfortable. CS2 is dissatisfied because they feel that their heating system is not suitable for their needs, while CS10 needs to get their controls fixed but also find the bottled calor gas, which fuels their central heating, to be very expensive and are actively considering alternatives. Both CS2 and CS10 had recently moved to their houses, and it may be that they have not yet been able to adjust their homes to their specific needs.

Several participants (CS3, CS5, CS7, CS10) used electric heaters to heat office spaces during the day, and CS16 had an annex, where one household member worked, which could be heated separately to the main central heating. Eight participants (CS1, CS2, CS5, CS9, CS10, CS12, CS14, CS16) also used other spot heating, generally woodburning stoves and mainly in the evenings, to supplement central heating in their main living spaces. They found that this enabled them to be comfortable with lower central heating temperatures. Participants also highlighted that their stoves could have a positive psychological impact, with some (CS5, CS7, CS12) suggesting that they would sometimes light a stove because they enjoyed its visual effect rather than specifically for heat because: ‘it’s a nice focal point’ (CS5).

The use of this spot heating can be seen in the thermometer data that participants recorded in their energy diaries (Table 6.4). The inside thermometer was positioned in participants’ main living spaces and the average maximum temperatures recorded across the case studies were higher than the main heating system temperature set points. The average temperature of 19°C was close to the average heating system set point of 18°C. Cases that did not use wood burning stoves generally had lower maximum temperatures (CS3, CS6, CS15). Graphical results for each case study can be found in Appendix O, Page- 124 -.

Table 6.4: Average of winter thermometer readings over five days over all cases

Average recorded temperature across cases	Inside thermometer	Outside thermometer	Difference in °C
Maximum (°C)	22.5	12	10.5
Minimum (°C)	15.5	2	13.5
Average (°C)	19	7	12
Thermometers were accurate to within +/-1°C, values are therefore indicative and have been rounded to nearest half degree			

In addition to spot heating, some participants (CS10, CS12, CS13, CS14, CS16) also made use of throws, blankets, and similar, as part of their evening comfort strategies. The cases who mentioned blankets were, apart from CS13, those with young families, perhaps suggesting that 'snuggling' (as described by CS14) is more acceptable to those with children.

> *CS3: It's not worth heating the house up, but that top room [office], if I'm sitting there all day it has to be warm, so there's a geriatric electric radiator*

> *CS12. If we don't put the stove on, we have sat on the sofa- and we're quite happy with this- and we'll go and get a blanket… it's lovely.*

> *CS14: We would usually be in the living room [in the evening], that usually means that either the fire is on, or a blanket is on, sometimes both for the snuggle, we like a blanket. [Figure 6.9]*

Figure 6.9: CS14's living room, with blankets, stove, and even a furry cat bed

In addition to spot heating and blankets, participants also generally made use of high levels of personal insulation, such as slippers and jumpers. The energy diaries requested clothing levels three times a day and this information was summarised for each case in each season. In winter (Figure 6.10) slippers and jumpers were the norm, and in summer (Figure 6.11) participants in eight of the cases still tended to wear jumpers and most wore slippers. Participant comments, and observation of participants during site visits, also support this view. All participants were wearing jumpers and slippers or similar during site visits, although not all mentioned footwear in the energy diaries. Several participants highlighted that outdoor conditions had the greatest influence on their clothing levels (CS1, CS5, CS6, CS12).

CS6: We dress according to the weather, it's not one of those houses where people are wandering around in short sleeves.

CS13: Something on your feet, so slippers or woolly socks… if my feet are warm the rest of me is ok.

Figure 6.10: Case study participants' average clothing levels from winter energy diaries

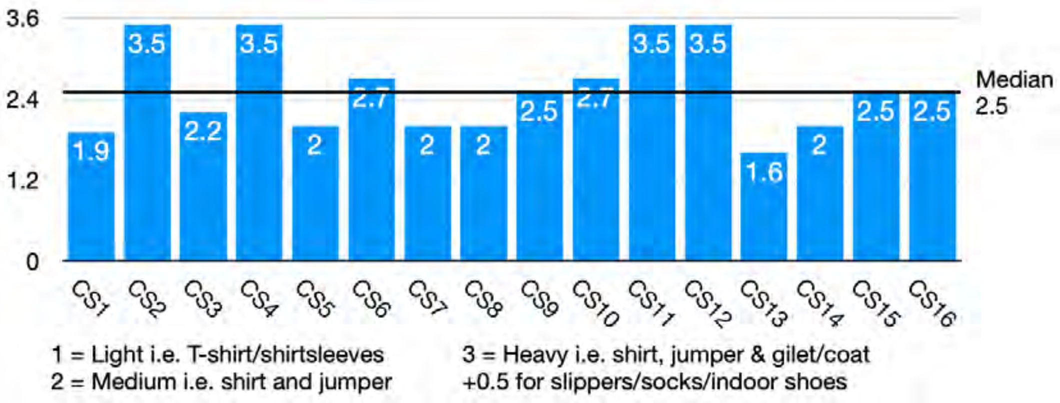
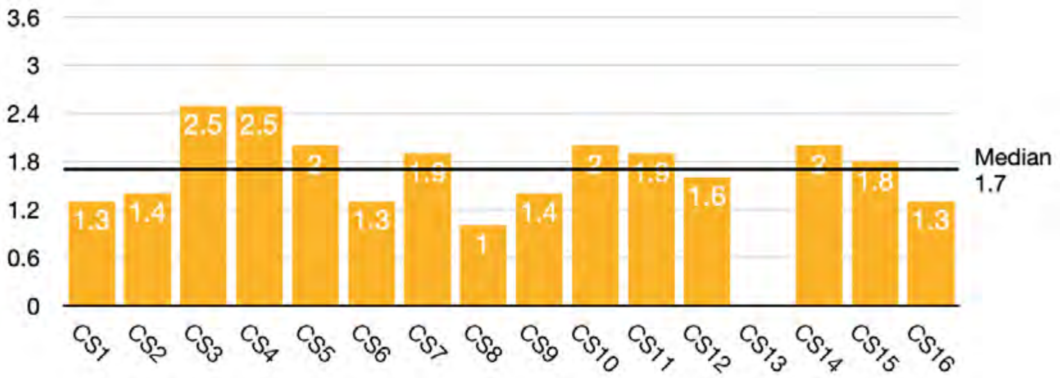


Figure 6.11: Case study participants' average clothing levels from summer energy diaries



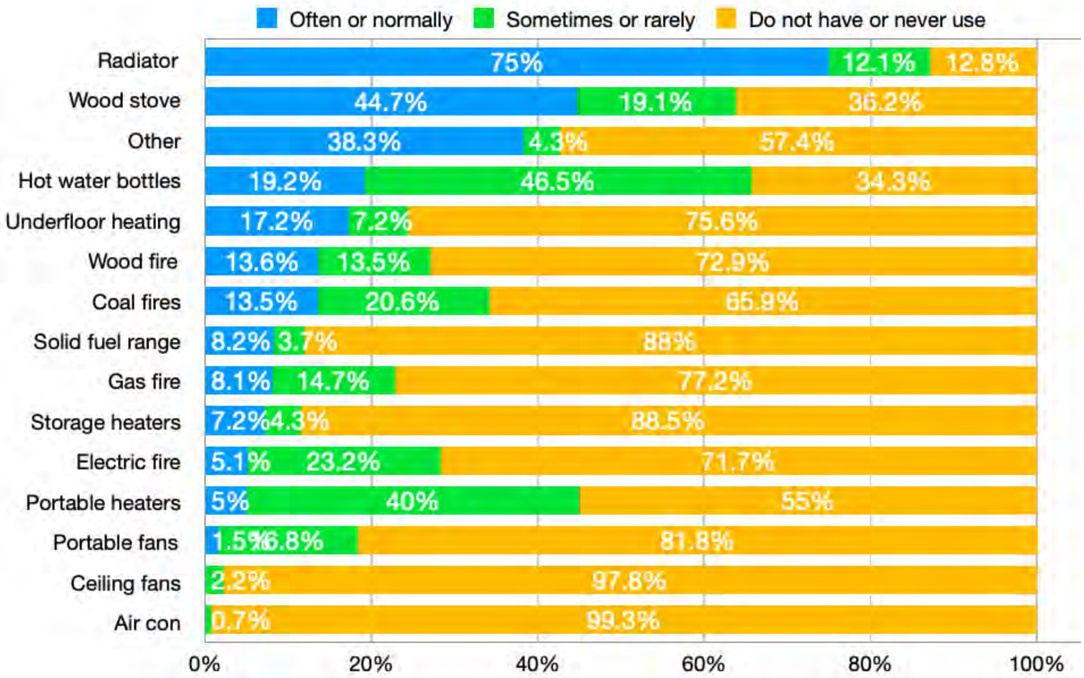
Findings from the survey also support the use of personal insulation with 88% reporting wearing extra layers in cold weather (Figure 6.3).

Case study heating practices are also supported by the survey results on the use of different heating and cooling emitters (Figure 6.12). Radiators were the most common form of heating (75% normally or often) however in addition there also significant and regular use of wood stoves (45%) and other spot heating such as open fires. Many respondents also made use of 'personal' heat sources, with the majority making regular use of hot water bottles, while portable heaters also showed considerable, although less regular usage. The 'other' comments showed that 11% of respondents made use of electric blankets which were also mentioned by several case study participants. Some also mentioned extra layers while one respondent identified that their husband and cat provide a useful heat source. Comments emphasised that spot heating was used to reduce reliance on central heating systems, confirming case study findings.

We use the log stove frequently and the central heating less often.

Wood stove is used to reduce reliance on oil central heating – if main room is heated by stove the rest of the house can be cooler.

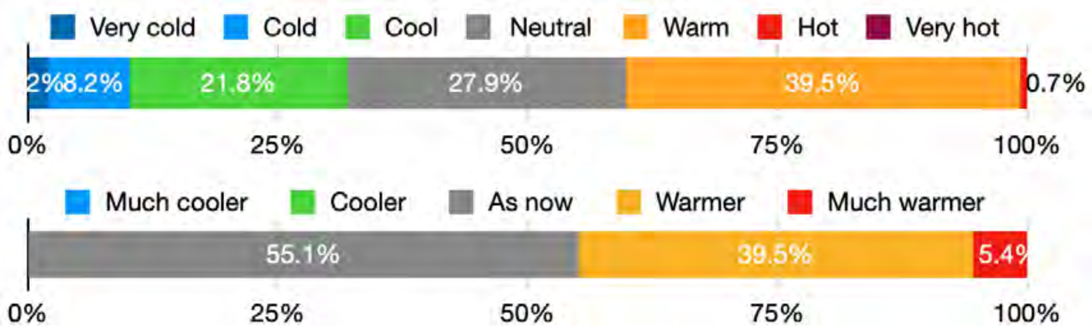
Figure 6.12: Survey respondents reported use and frequency of different heating sources (N = 147)



Note: Respondents were able to select more than one heating emitter per category so those that report often using wood stoves may also often use radiators etcetera.

In winter 28% of survey respondents considered their homes to be a neutral temperature, while slightly more perceived them to be warm or hot (40%) rather than cool or cold (32%). Respondents were also asked what temperature they would like their homes to be, and over half were content with current conditions (55%), although 40% would like it warmer and 5% much warmer. Some comments suggested that while respondents found their homes cool some preferred having cooler conditions rather than increasing their heating use because of their environmental principles.

Figure 6.13: Survey respondents' perception of thermal comfort and desired thermal comfort in winter (N = 147)



Am concerned that our main method of heating is oil but see no way of changing this. We tend to put on extra clothes rather than turn the heat up, in spite of being in our seventies.

I have to compromise between too hot or rather cool in spring and autumn… but I prefer that to emitting more CO_2.

Residents therefore have a range of temperature settings and heating patterns which they have tailored to their needs. A significant number feel that they have lower than average temperatures, and the majority make use of personal and spot heating to reduce reliance on their central heating systems. Most residents also use personal insulation such as blankets, jumpers, and slippers. 14 of the 16 case study participants were satisfied with comfort in their homes and just over half the survey respondents were content with current conditions in winter although around 45% would prefer warmer temperatures.

6.5 Space heating and ventilation

In addition to the varied heating patterns and temperatures, the survey respondents and case study participants also had different heating strategies for different spaces. 68% of respondents and 13 out of 16 of case study participants reported only heating actively used spaces, while 36% of respondents do not currently heat bedrooms and a further 27% might be willing to consider it (Figure 6.3). 12 of the case study participants do not, or only very minimally, heat their bedrooms (CS1, CS4, CS6, CS7, CS8, CS9, CS10, CS11, CS12, CS13 CS14, CS16). Many of the participants with unheated bedrooms (CS7, CS9, CS10, CS11, CS12, CS14, CS16) highlighted their enjoyment of a cool room to sleep in, although they sometimes utilised limited personal heating, such as electric blankets, to improve their comfort (CS7, CS9, CS11, CS10).

> *CS9: We don't heat the bedrooms, ever. I have an electric blanket on my side of the bed and B likes it colder anyway… we don't need the bedroom to be warm, we like a cold bedroom.*

CS14 and CS16 chose to have unheated main bedrooms but ensured that the heating was on in their children's bedrooms. The bedroom of the child in CS12's household did not have a radiator but was directly over the wood burning stove in the living room and their main complaint was that they were often too hot when they went to bed. At the time of the virtual visit in November 2020 this was leading the household to try to avoid using the stove as much in the evenings to reduce this overheating discomfort.

The use of spot heating in office spaces or living rooms, as identified above, also enabled several participants to turn their central heating off or down and just heat the spaces that they were occupying. CS5 for example deliberately undersized the radiator in their living room: 'because we knew we had the stove, so why duplicate?' One of CS7's occupants meanwhile, has an electric heater in their office and will turn off the central heating if they are the only one at home.

Ventilation is another important aspect of energy behaviour and comfort in buildings. The majority of the case study residents reported having windows open in summer and a significant proportion also have at least some windows open in winter. The open winter windows are often in unheated bedrooms and therefore are unlikely to cause significant energy loss. Participants emphasised their enjoyment of fresh air, and birdsong. Several noted that even if they did not generally have windows open, they would open them for limited periods to air rooms. This particularly applied to bedroom windows in mornings and bathroom windows after showers or baths to remove condensation. Some participants (CS4, CS8, CS9) open bedroom and or bathroom windows every morning for a few hours to air the room and remove condensation.

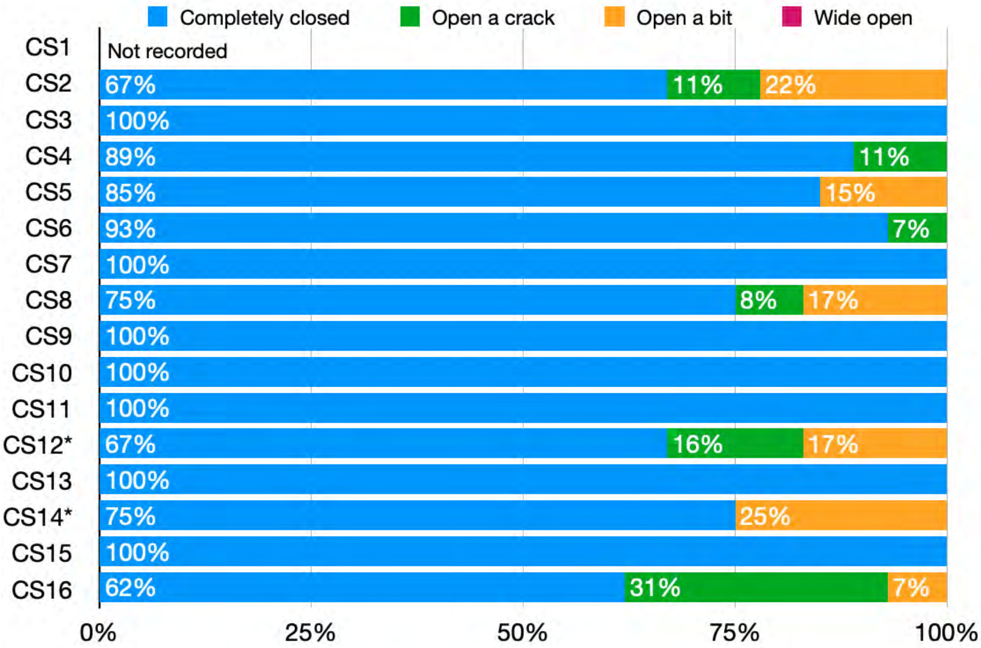
CS8: Yes, for ventilation in the bathrooms… what we do is just open up the windows as we use the bathroom in the morning, when the water vapour has gone out, we just close the window again.

CS10: Even if they're not open all the time, we'll open them for a bit and have them wide open.

CS12b: We're obsessed with fresh air, CS12a: We like to hear the birds sing

The energy diaries support participants' comments. The percentage of windows that each case study recorded as open at the beginning of the winter diary can be seen in Figure 6.14, and window opening and ventilation activities during both summer and winter periods can be seen in Figure 6.15. The percentage of windows each case had open at the beginning of the summer diary are shown in Figure 6.16 and a connection can be seen between those respondents who had windows open in winter and those who have the most windows open in summer (CS2, CS5, CS12, CS14, CS16). In summer several participants also opened doors to create cross ventilation. Nine participants used extraction fans when cooking and showering but seven reported no extraction fan use in the diary periods. CS11 however was considering installing a mechanical extraction fan with heat recovery in his kitchen as a more efficient way of ventilating the space.

Figure 6.14: Percentage of open windows in case studies at start of winter energy diary



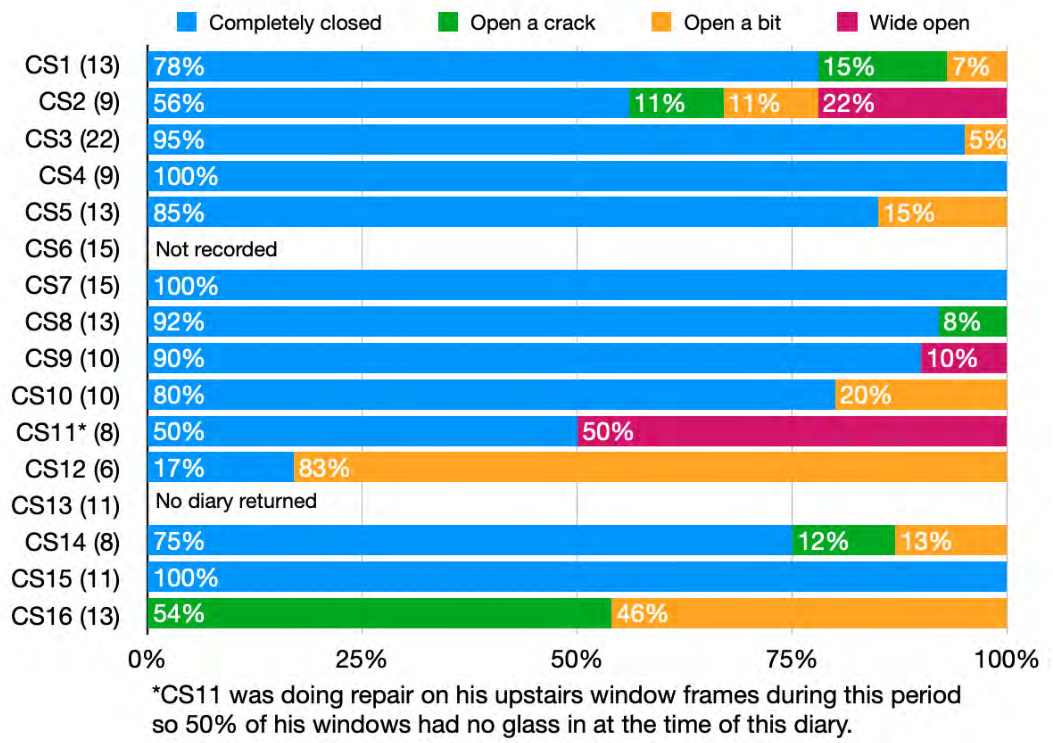
*50% of CS12 and CS14's windows are skylights they are included as some of them are open during the summer period.

Figure 6.15: Heatmap of case study window opening and mechanical ventilation activity during energy diaries. Darker colours represent higher activity levels.

Case study	Windows winter	Windows summer	Mechanical ventilation
CS1	Occasional upstairs windows for a few hours in afternoons	Bed and bathroom windows always slightly open. Pantry window open all day. Back door opened in evenings	Bathroom extractor for showers each day
CS2	All windows opened for short periods occasionally	Bed and bathroom windows open. Door (into lounge) open most of day. downstairs windows often open	Bathroom extractor in mornings. Kitchen extractor while cooking.
CS3	Office window occasionally opened for 1/2hr	Bedroom, kitchen, and office windows open most of each day. Back door open most of each day.	None used
CS4	Bed window cracked open each morning, closed later	Veranda or back door open for a few hours most evenings.	Kitchen extractor fan seldom used
CS5	Bathroom window opened some mornings. Bed windows cracked open sometimes.	No changes from baseline	Kitchen extractor used for 30min-1hr every evening

Case study	Windows winter	Windows summer	Mechanical ventilation
CS6	No changes from baseline	1 bedroom window occasionally opened in mornings	Bathroom extractor used for 30mins each morning
CS7	No changes from baseline	Bedroom window open overnight and closed each morning	None used
CS8	1 bedroom window and windows in both bathrooms are opened a bit each morning	Bathroom windows open each morning. Sitting and bedroom windows mostly open. Kitchen window open occasionally	Kitchen extractor used occasionally
CS9	Bedroom window opened each morning to air room	Office window occasionally opened in afternoons	Bathroom extractor is light controlled. Kitchen extractor occasionally
CS10	Velux windows opened when having showers	Master bedroom window opened occasionally	None used
CS11	Bedroom windows open overnight. Bathroom window opened regularly during day.	Bedroom and bathroom windows without glass during frame repair	None used
CS12	Bedroom windows open overnight. Attic skylight opened occasionally.	Bedroom windows and attic skylight open overnight and part of day. Kitchen door open for at 1-2hrs each evening	None used
CS13	Patio doors briefly open each morning when feeding birds	No diary returned for this period.	None used
CS14	Master bed window always open a bit. Slipped panes in other windows give ventilation	No changes from baseline	Bathroom extractor fan used for showers
CS15	No changes from baseline	Back door opened occasionally	None used
CS16	Bed windows open in morning for a few hours. Ensuite and master bed windows on catch.	Some doors and windows open in mornings. Increasing in afternoon and then to latch in evenings	Extractor fan for showers

Figure 6.16: Case study open windows at start of summer energy diary (the number in brackets is total windows)



Similar findings were made for the survey respondents. In summer 31% of respondents always had a least a few windows open, while 86% often had windows open and only 2% never had open windows (Figure 6.17). In winter the number and proportion of open windows is unsurprisingly much lower. However, 24% of respondents still regularly had a few or some windows open and those who never opened any windows in winter still only made up 18% (Figure 6.18). Some of the respondents highlighted issues with traffic noise which may be a reason for reduced window opening. In the case studies traffic noise was an issue for CS5, CS12 and CS15, who were all situated next to well used roads, CS12 had decided they preferred traffic noise to a lack of air in their bedroom so still opened windows, while CS5 had installed fixed secondary glazing on downstairs, road facing windows and CS15 was considering installing secondary glazing on their current UPVC double glazing to reduce noise levels at the front of their building.

Figure 6.17: Proportion and frequency of windows open in summer reported in survey (N = 147)

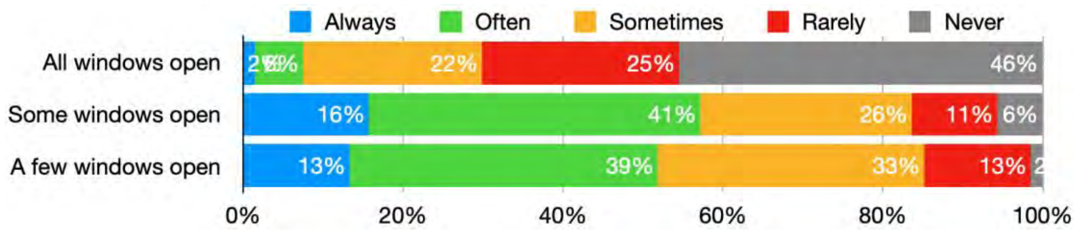
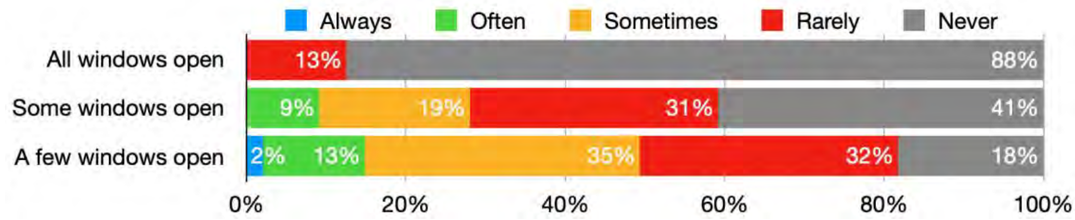


Figure 6.18: Proportion and frequency of windows open in winter reported in survey (N =147)



It would therefore appear that the residents in this research actively use their windows for ventilation to avoid moisture, for comfort in hot weather, and because they enjoy fresh air.

54% of survey respondents felt that their buildings were draughty in winter (Figure 6.19). However, surprising, only 21% would prefer less draughts in winter and 7% would like to increase their ventilation levels (Figure 6.20). In summer meanwhile the vast majority of respondents were comfortable with their current ventilation conditions.

Figure 6.19: Respondents' perception of ventilation levels (N = 147)

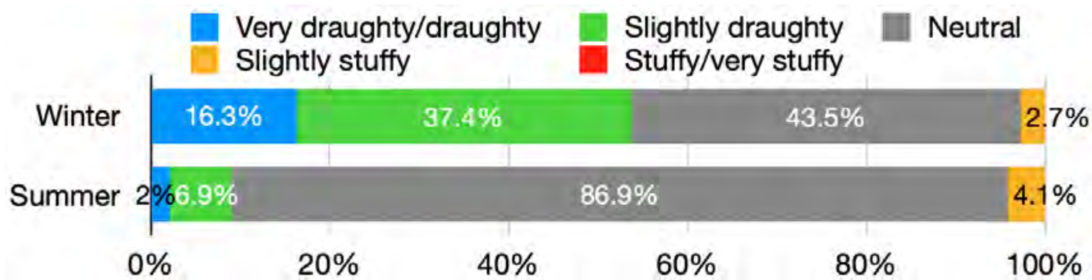
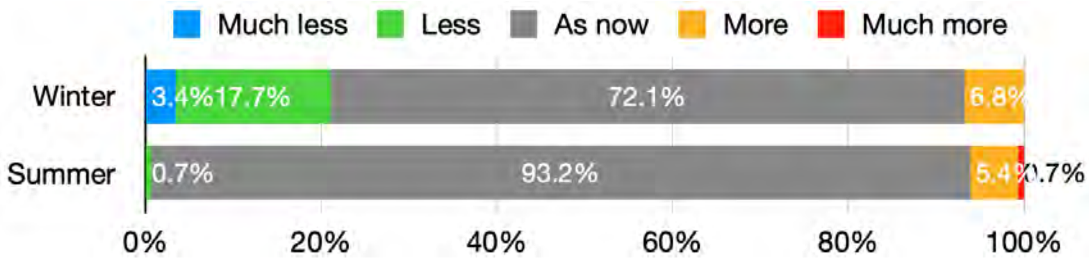


Figure 6.20: Respondents' preference for levels of ventilation (N = 147)



Overall, it would appear that the majority of residents appear to make active use of their windows for ventilation and enjoy access to fresh air during much of the year. Many residents only heated spaces that they were actively using, often utilising spot heating. A significant number of residents also did not heat bedrooms which they preferred to keep cool and well ventilated.

6.6 Heritage values and comfort challenges

Nearly all the case study participants were comfortable with conditions in their buildings but there were still aspects that some participants found unsatisfactory. Those with more than one age of construction often identified comfort challenges with more recent extensions (CS6, CS12, CS13, CS16). This did not appear to apply to very recent extensions which participants themselves had commissioned. CS9's extension was built in 2011 and CS12's in 2012 and both were very pleased with their performance. CS12 also took action to improve a 1960s, brick master bedroom extension which they said was previously an 'icebox' and they feel that their alterations have improved the feel of the whole house. CS6, CS13 and CS16 however all noted challenges with draughts, poor insulation, and greater temperature fluctuations in their 20th century extensions, comparing these parts of their homes with older sections which they perceived to perform better. Issues were also noted where modern services had been poorly installed (CS5, CS8, CS10, CS16), such as a large hole for a tumble dryer pipe in CS8's kitchen which created a substantial draught.

> *CS6: The most annoying draughts are sadly in the most recent structure… [c1995] even though it's meant to be well insulated in the*

roof space, I don't think it's particularly efficient, you can feel draughts around lamps.

CS13: Even in the middle of winter… it stays a reasonable temperature as well. The back less so, as it's a more modern building… [c1999] so that's the one room that can be colder,

CS16: The office cum spare bedroom… was a fairly modern extension around forty years ago [c1980] so it's brick rather than the stone walls, and the temperature fluctuates a lot more.

CS13's comment, in particular, suggests that they expect the rear extension to be colder because it is more modern. This may suggest that, in addition to physical performance challenges, the heritage values that they invest in the older part of their building may be influencing their expectations. This strong sense of heritage value also appeared to affect the tolerance of several participants for inconvenient aspects of their buildings (CS8, CS11, CS12, CS14). CS11 acknowledged that their house was cold because of their heating choices but they felt that because of its heritage aspects: 'You can get a bit of warmth from the character in a way'. CS12 felt that their living room was very dark because of its deep plan but that this contributed to its 'cosiness,' and CS14 identified that they could manage the moisture challenges of their home but that these would not be acceptable to everyone.

CS14: You get used to it, and it's part of the character of the house in the end, but anyone who lives in a modern house and doesn't like this kind of thing would think you were insane!

Figure 6.21: CS12 find their living room rather dark

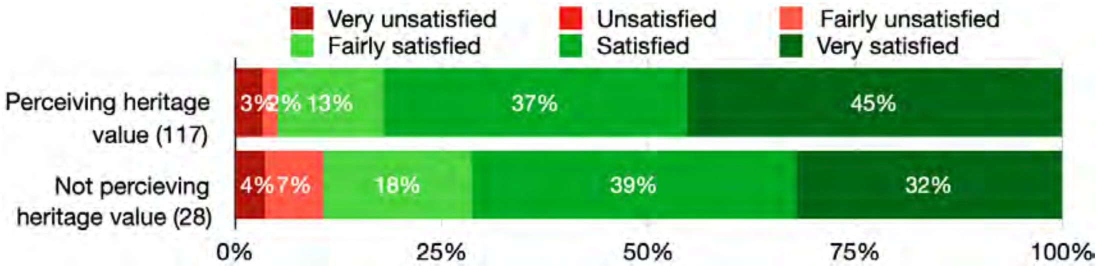
A survey respondent also highlighted this theme when asked to comment on any issues which affected their comfort.

> *My house has relatively small windows and is rather dark, but I tolerate this because it is part of the architecture to be expected in a traditional Cumbrian farmhouse.*

The vast majority of the survey respondents (94%) were satisfied or very satisfied with overall comfort in their buildings (Figure 6.22). It would also appear that those who perceived heritage value in their buildings (HY) were slightly more satisfied with their overall comfort than those who did not (HN) (Figure 6.23). This difference was not statistically significant (see Appendix L.2) but only 5% of the HY group were dissatisfied compared with 11% of HN group and 13% more of the HY were very satisfied with their comfort.

Figure 6.22: Survey responses to the question: overall what is you level of satisfaction with comfort in your building? (N = 147)

Figure 6.23: Comparison in overall comfort between respondents perceiving heritage in their buildings and respondents who do not.



It therefore appears that residents' values may affect their comfort tolerances, potentially making them more likely to accept inconveniences with the parts of their building in which they invest heritage value. They may conversely be more likely to view modern building extensions more critically, although quality of workmanship in more modern sections appears to be an actual as well as a perceived issue.

A number of residents identified various levels of challenges with moisture, from slight discolouration of walls to serious damp issues and flooding. CS16's cellar and CS12's ground floor were both flooded in storm Desmond in 2015, which caused major flooding across Cumbria. CS10 meanwhile is a former mill located at a bend in a river and their ground floor floods regularly. They therefore live on the first and second floor and use the ground floor as a cellar space for items that can be easily moved. With the exception of flooding, CS14 is the only case study with very severe moisture challenges which have a number of contributory causes. Maladaption is one issue as their lime and sandstone walls are coated externally with impermeable paint. They also had an open chimney stack that had become filled with water, although this has now been fixed it was wet for decades and the drying out of the wall is likely to take several years. They also have challenges with ground water and rising damp.

CS14: We literally have water running through our cellar, you know, that's the reality of life, and therefore ventilation is really, really important. Moisture has to move through this house, I can't prevent it getting in, but it has to move [Figure 6.24].

Figure 6.24: CS14's cellar stream

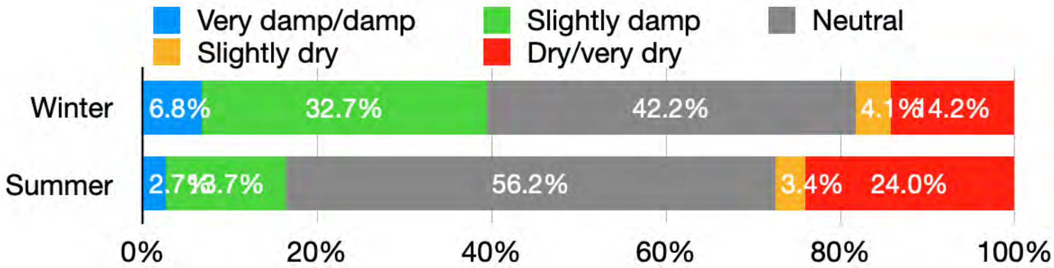
Note: The water in the centre of the photo has a current and flows from right to left through the cellar, it is 2-3cm deep.

Moisture is therefore still an issue for CS14 which they manage with ventilation and limited periods of daily heating all year round. CS1 and CS9 also have some damp challenges, and both maintain some level of heating all year to help manage this. CS1 is on a site with hydrostatic head causing rising damp and CS9 report legacy damp issues in their living room which was previously a derelict basement. Other participants also identified minor damp issues in some parts of their building, but these did not require significant management strategies.

A third of the survey respondents indicated that their homes were slightly damp while 7% have more substantial damp challenges (Figure 6.25).

Comments again revealed issues with maladaption and a need for increased heating and ventilation to keep damp challenges under control.

Figure 6.25: Survey respondents' perception of dampness (N = 147)



6.7 Buildings in summer

All of the case study participants identified that their buildings had positive performance and comfort in summer. Most felt that their homes stayed comfortably cool, even in very hot weather conditions and several again contrasted this performance with more modern buildings which they had experienced (CS1, CS9, CS12, CS16). One of the participants in CS1 for example, had worked in a state-of-the-art sustainable building constructed within the last five years which had a highly glazed atrium. This building could not be kept comfortably cool in even slightly warm weather and fire doors had to propped open to try to improve comfort. Participants' vernacular buildings in contrast, remained cool because of their thermal mass and nearly all benefited from cross ventilation.

CS1b: This building is great in summer, it's never too hot, it's comfortable inside, we can keep it warm enough for us… it's lovely

CS12b: You really notice it, when it's baking hot outside, it's lovely and cool inside

CS16: It is, the house is brilliant actually yeah, so when it was really, really hot in the summer you could close the shutters or pull the blinds… the temperature never gets very, very cold and it never gets very hot either, so you can stay inside and be fairly comfortable.

Residents' perceptions of their buildings' performance were corroborated by the summer energy diary thermometer readings. The maximum average outside temperature was around 3°C higher than the maximum inside temperature across the case studies (Table 6.5). Meanwhile the average outside temperature was 3°C lower than inside temperatures, suggesting that the buildings were reducing temperature peaks and troughs. Values for each case can be seen in Appendix O, Page - 124 -.

Table 6.5: Average of summer thermometer readings over five days over all cases

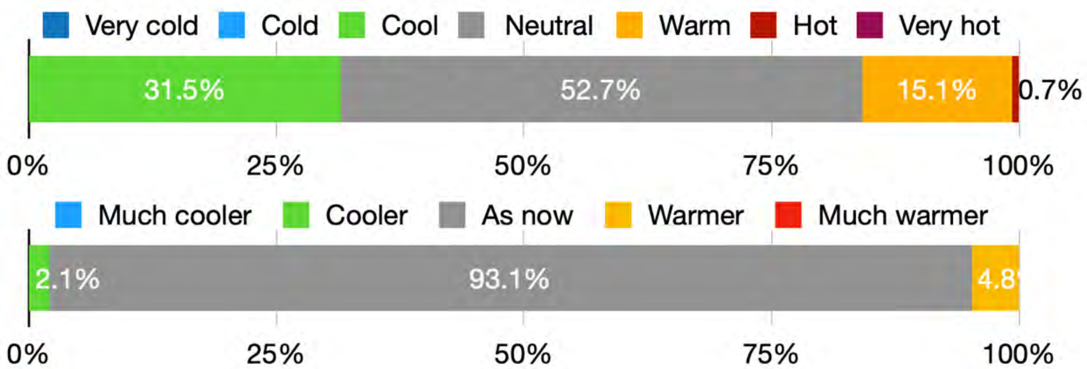
Average temperature across cases	Inside thermometer	Outside thermometer	Difference in °C
Maximum (°C)	22.5	25.5	3
Minimum (°C)	18	11	7
Average (°C)	20.5	17.5	3
Thermometers were accurate to within +/-1°C, values are therefore indicative and have been rounded to nearest half degree			

The only case who found their building slightly too hot in summer was CS14, who attributed this to a lack of insulation in part of their roof, which forms a sloped ceiling to their upstairs landing, and to several skylights which made the upper floor warm in hot weather. Their property was also the only one without cross ventilation as they only had functioning windows on the east façade of their property (Figure 6.26). In very hot weather this sometimes led to the children sleeping downstairs in the living room, which generally stayed cool.

Figure 6.26: L: CS14's rear, west facing wall, R: Close up of non-functioning window in west wall

The survey provided additional support for the positive summer performance that nearly all case study participants identified for their homes (Figure 6.27). All but one respondent perceived conditions to be within the range of cool, neutral and warm that is generally considered acceptable (Hong et al., 2009). The overwhelming majority (93%) of respondents wanted summer conditions to remain as they were now. Only 5% wanted warmer conditions and 2% cooler.

Figure 6.27: Survey respondents' perceptions of and desired thermal conditions in summer



The vast majority of residents therefore consider their homes to have positive summer comfort performance.

6.8 Discussion

Residents were found to have a range of energy behaviours and comfort practices within their buildings. These behaviours appear to be active and positive choices by residents. They are also indicative of adaptive thermal comforts strategies (Nicol et al., 2020). Residents make use of personal and spot heating and personal insulation, which is consistent with the principle of keeping occupants rather than buildings warm (Brager et al., 2015; Humphreys et al., 2011). It is possible that residents in heritage buildings may make greater use of spot heating and adaptive thermal comfort strategies than non-heritage residents. Residents also appeared to become acclimatised to conditions within their buildings, with participants stating that they find conditions comfortable but that visitors may not.

The behaviours that residents will and will not engage in are affected by their circumstances. Older residents for example may require warmer conditions and longer heating spans than younger, more active residents, although this did not hold true for all participants. Children and those with some health conditions may also require specific environments. These variations will lead to differing energy demand and may also require tailored retrofit approaches so that measures are enacted which are the most appropriate to residents' needs, and therefore the most effective. Residents' drivers for retrofit were also found to be varied, with some residents for instance, interested in secondary glazing to reduce traffic noise rather than because of its heat loss reduction properties.

In contrast to general assumptions about poor comfort in heritage buildings, the vast majority of residents were found to be satisfied with overall comfort. The majority of residents were content with current winter conditions, although a significant minority of the survey respondents would prefer conditions to be slightly warmer. The two case study participants who were dissatisfied with their comfort had both been in their homes for the shortest length of time. It may therefore be that these participants have not yet had time to become accustomed to their homes and, conversely, to tune their buildings to their own needs. This finding is also consistent with adaptive comfort principles.

Participants appeared to actively manage ventilation within their buildings for comfort, and while many of the survey respondents identified their homes as draughty, they were mainly content with these conditions. The residents in this research were therefore satisfied with their ventilation opportunities and many appeared to enjoy the fresh air provided by high ventilation levels.

In summer both the survey and case study results strongly indicate that residents perceive their vernacular buildings to be very comfortable in hot weather, keeping comfortably cool. This perception also appears to be supported by energy diary thermometer data which indicate actual performance. This is something that may be of particular relevance given the predictions of future temperature increases and heat wave events. These findings are supported by other research identifying the positive performance of vernacular buildings in warm conditions (Cardinale et al., 2013; Li et al., 2013). They also clearly contrast with concerns that have been identified for more modern buildings around overheating (Adekunle and Nikolopoulou, 2014; Lomas and Kane, 2013).

Residents' general dislike of modern construction (section 4.6) could also be seen in their identification that their 20th century extensions had the greatest comfort challenges compared with older sections. Residents' appreciation of their buildings' heritage values may mean that they are more likely to view the performance of older building elements more positively. Residents appeared to have more tolerance of some of the inconveniences of their homes because of their heritage aspects, in some case identifying these as adding to the character of the building. This finding builds on other research which has suggested that residents' heritage values may affect their comfort tolerance in timber framed UK buildings (Whitman et al., 2019). It could also be synonymous with findings that occupants of 'green' naturally ventilated offices have more tolerance for temperature variation than the same occupants would have in 'normal' air conditioned offices because their values effect their expectations (Martínez-Molina et al., 2016; Rupp et al., 2015). If residents did not invest the same values in their buildings, they might be less willing to accept some of these irritations.

A significant number of residents report challenges with damp in their buildings, although most seem to have strategies to manage moisture through ventilation. Previous maladaptions were a contributing factor for some residents. This highlights the need to address current building conditions and undertake any necessary repairs or maintenance prior to any retrofit activity. It also emphasises the need to ensure that retrofits are appropriate to specific buildings and that they do not create new problems or contribute to existing ones.

The varied behaviours that residents were found to engage in, and their generally positive comfort perceptions, will have implications for the energy demand and also for the level of retrofit they may be willing to engage in. As will be identified in the next Chapter, these behaviours are very different to the assumptions made in policy and standard energy models. It is therefore critical that behaviours and comfort perceptions are understood if effective retrofits are to be enacted at scale.

6.9 Conclusions

This chapter has investigated residents' energy behaviours (RsQ1c) and perceptions of comfort (RsQ1d).

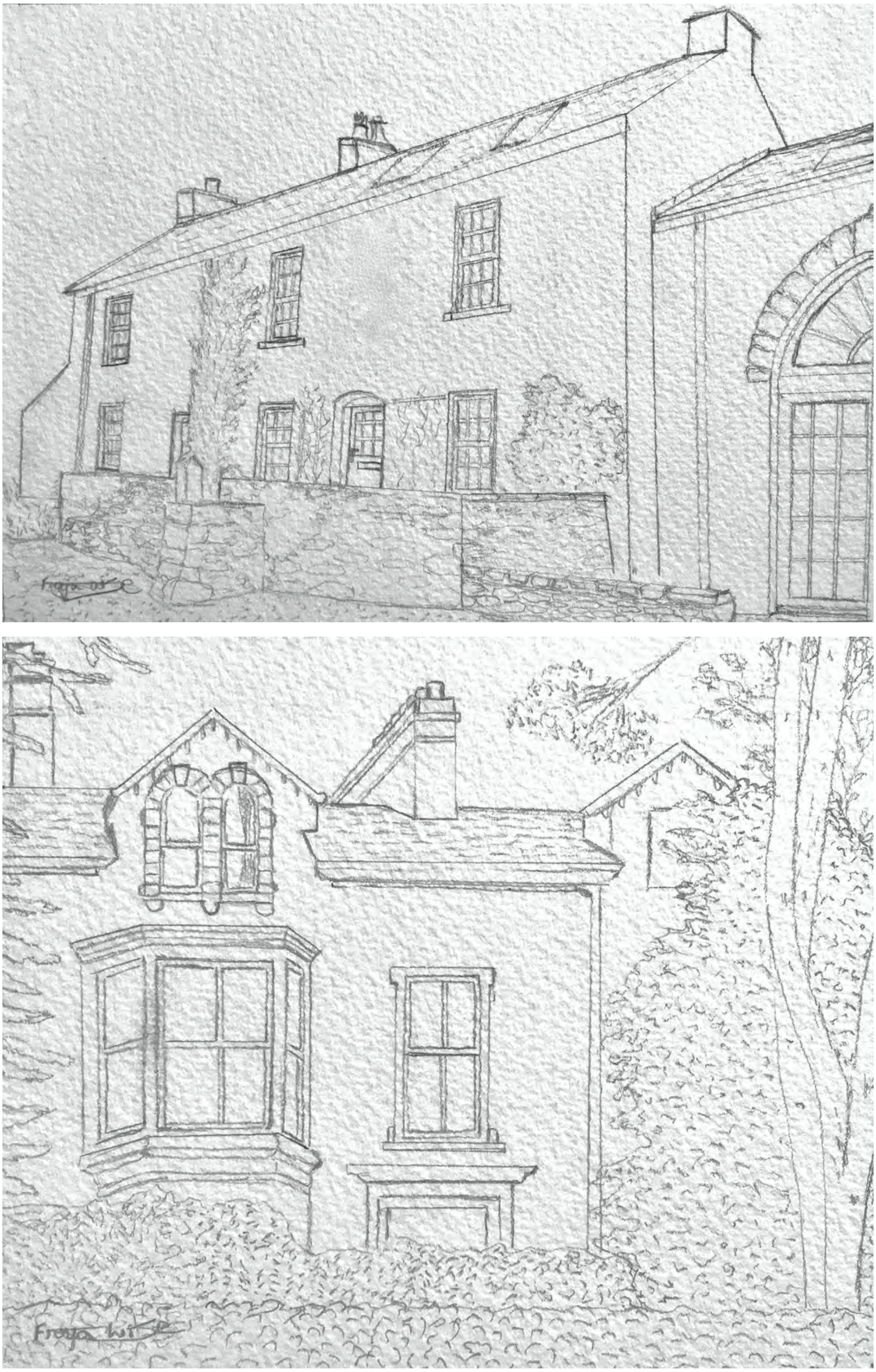
The vast majority of residents are concerned about their environmental impact and this likely fed into the common low energy behaviours that they engaged in and their perception that their household temperatures were lower than average. Residents engaged in a varied range of behaviours, such as heating residents rather than buildings to maintain comfort, and these behaviours were consistent with adaptive thermal comfort principles. Most residents also engaged in active behaviours around managing ventilation for comfort and moisture removal.

While some residents would prefer warmer conditions, and a number have moisture challenges which need addressing, the vast majority were content with overall performance and ventilation levels. These comfort perceptions were potentially influenced by their heritage values, meaning that they were more tolerant of some inconveniences. Residents identified that their vernacular buildings had excellent performance in warm weather.

Residents' comfort perceptions are generally positive and influence energy behaviours, which are varied. These perceptions and behaviours are important to understand as they will have a significant effect on the energy demand and carbon emissions from these buildings.

Some material in this chapter has been previously published in (Wise, Jones, et al., 2021; Wise, Moncaster, et al., 2021)

Figure 6.28: CS7 and CS8



Chapter 7. Real and modelled case study energy and carbon

7.1 Introduction

The case study participants invest heritage values in their buildings which influence the retrofits that they are willing to make, and their perceptions of thermal comfort. These in turn effect their energy behaviours which help to shape building energy demand. This chapter identifies the actual energy and carbon demand from the case studies (RsQ2a) and compares this with the results of standard energy simulation models (RsQ2b). It uses the data from the case study building tours, building surveys and energy meter and utility bill data.

The actual energy and carbon demand for the case studies is identified, including fuel sources, energy use and carbon emissions and the context of UK average energy demand is considered. This actual data is also compared with modelled energy and carbon results from RdSAP and the EPC ratings that it produces for these buildings. Some of the assumptions made by the model around construction and behaviours are also examined.

7.2 Actual case study performance

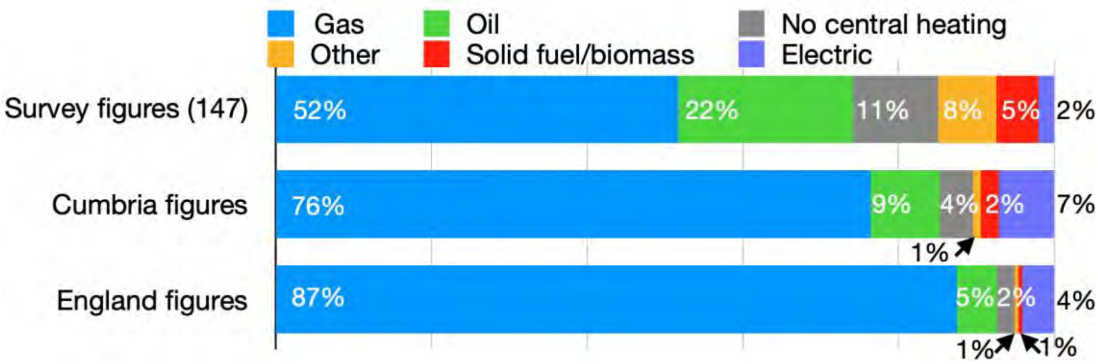
The case studies use a range of main heating fuels which will affect their carbon emissions (Table 7.1). All cases also use electricity for lighting and household equipment.

Table 7.1: Case study main fuel types

Main fuel type	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10	CS11	CS12	CS13	CS14	CS15	CS16
Mains gas			x	x	x	x		x	x			x	x	x	x	x
Oil	x						x									
Electricity		x														
Wood											x					
LPG										x						

This range of fuel types is also reflected in the broader survey responses, which can be compared with Cumbria wide (Cumbria Intelligence Observatory, 2020a) and English national (Slater and Garrett, 2019) figures (Figure 7.1). A significantly lower percentage of the survey respondents use gas as their main fuel compared with Cumbria as a whole, which itself has lower gas use than national figures. A higher percentage of the survey respondents use oil, no central heating, other fuel types and biomass, compared with broader figures, although the percentage of those with electric heating is lower.

Figure 7.1: Percentage of main fuel types for survey respondents compared with Cumbria and England.

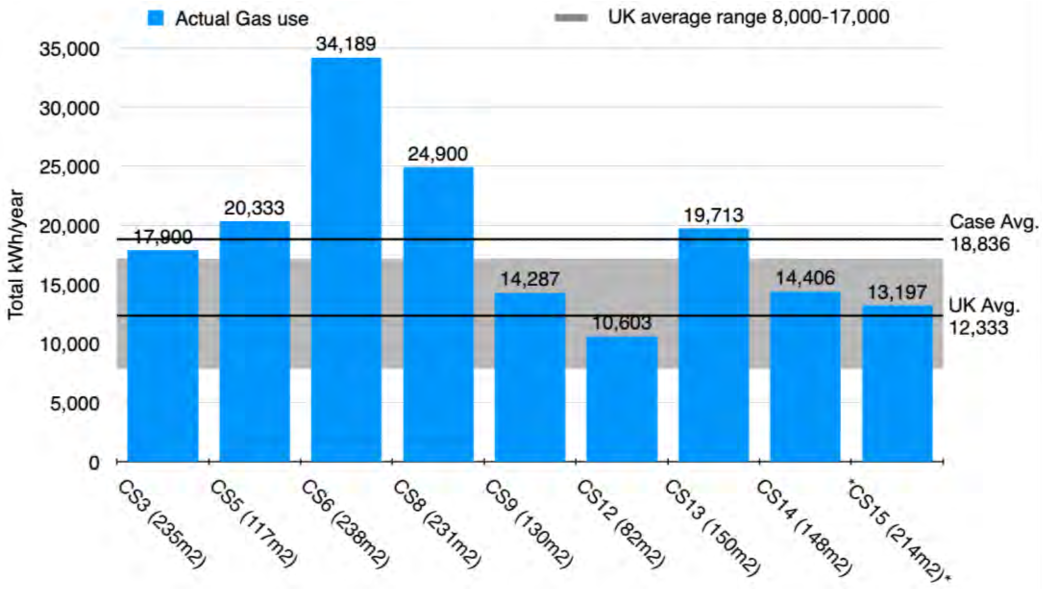


This lower gas use is likely to be a result, firstly of Cumbria itself being a rural area where many properties lack access to the gas grid and need to make use of alternative fuels (ACT, 2014), and secondly, because the evolution of planning regulations means that older buildings, whose residents were targeted by the survey, are also likely to be those that are more rural and therefore less likely to have access to the gas grid. CS7 for example take part in a village oil buying collective because there is no access to gas in the local area while CS4, CS5 and CS14 had all had gas installed in their properties during their occupancy when the opportunity arose.

Energy data was gathered for the 13 case studies for which it was possible to undertake a physical site visit and conduct the building survey. No energy data was therefore collected or CS4, CS10 or CS16. Participants provided energy data in various forms (see Chapter Three and Appendix H.2). Most provided data over several years which enabled a weather independent average to be calculated. The data was collected by fuel type and could not be disaggregated into different end uses. The main heating fuel included domestic hot water (DHW) for all cases except CS11 who has electric hot water. For cases using gas, this also generally included energy used for cooking as most participants had gas hobs. Electricity use included both fixed building services such as lighting and extractor fans, as well as the energy used by appliances and household devices (known as plug loads). Seven cases (CS1, CS2, CS5, CS7, CS9, CS12, CS14) regularly used wood burning stoves as secondary heating but were generally unable to provide estimates of their wood use. Wood burning stove fuel use has therefore not been included in either the actual figures or the energy modelling.

Natural gas from the national grid is the most common UK heating fuel and national UK consumption figures often only include gas use. The case studies which use gas are therefore considered first and compared with national figures. A typical gas consumption range for UK households is predicted by Ofgem each year, based on national energy bill data. Gas consumption for the cases that use this fuel are compared with typical consumption figures predicted for 2020 by Ofgem based on data from 2019 (Ofgem, 2020) (Figure 7.2). The Ofgem values range from 8,000kWh/y to 17,000kWh/y and it can be seen that four of the nine cases (CS5, C6, CS8, CS13) have higher values than this range while only one of the case studies is below the average Ofgem value of 12,333kWh.

Figure 7.2: Case study natural gas usage compared with average UK domestic gas use



Note: Cases with * * have some uncertainty in their energy calculation as described in Appendix H.2. Case study floor area is shown in brackets

This comparison suggests that the case studies may have higher than average gas use. However the average floor area of a UK dwelling is 95m^2 (Piddington et al., 2020), while the average size of the case study buildings which use gas is 45% larger at 172m^2. An alternative source of data to Ofgem is the UK National Energy Efficiency Data Framework (NEED) (BEIS and National Statistics, 2021). This data is climate adjusted to reduce the bias from colder or warmer than average winters and provides median data for floor area and number of occupants for England and Wales. The NEED data for 2019 for gas and electricity is shown in Figure 7.3.

Figure 7.3: Median annual gas and electricity consumption by floor area and occupancy England and Wales, 2019.

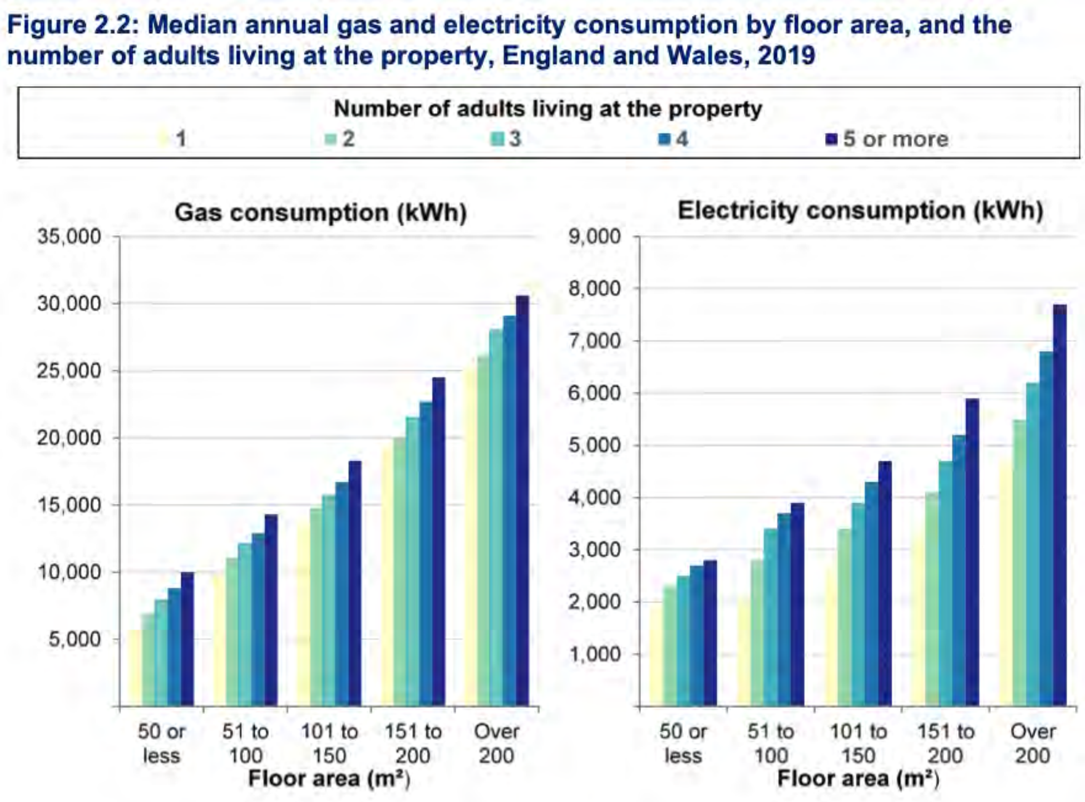
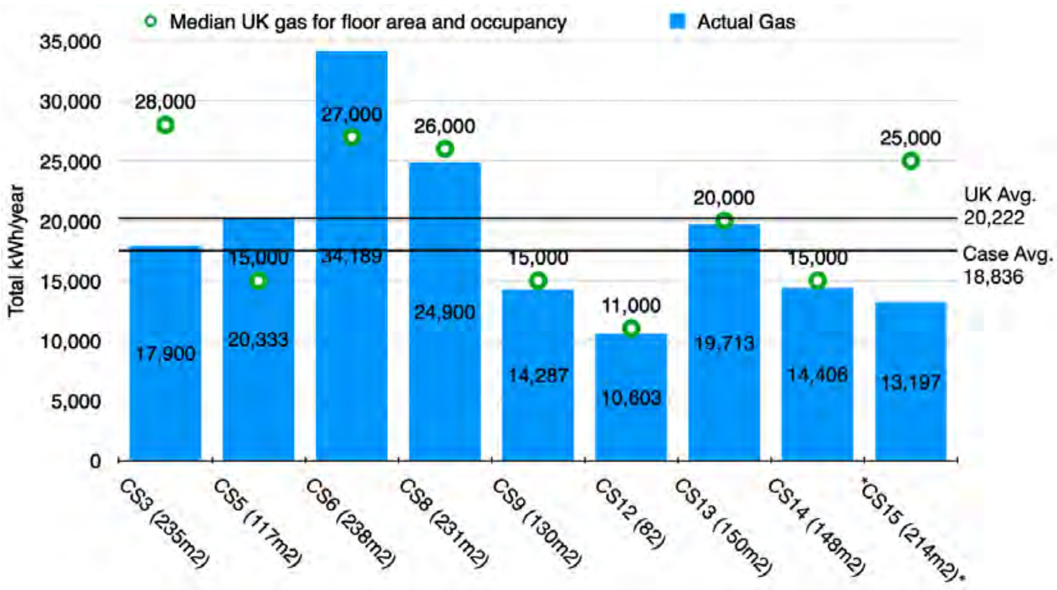


Figure reproduced from (BEIS and National Statistics 2021, p. 9) under the terms of The Open Government Licence (The National Archives, n.d.).

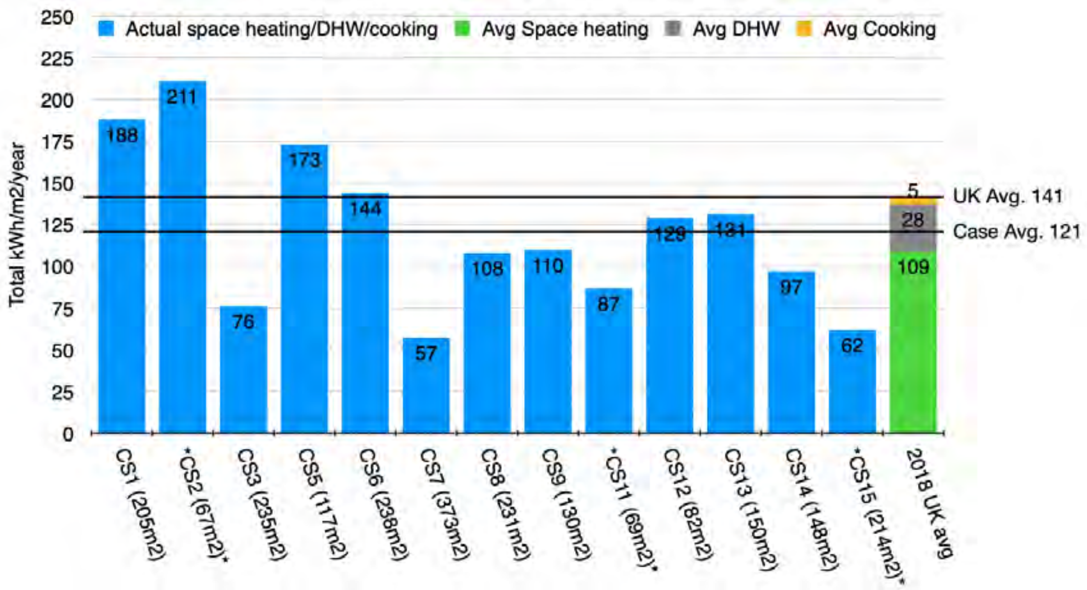
The appropriate national values for the floor area and occupancy for each case can therefore be compared with the actual values (Figure 7.4). Using this measure, it can be seen that, while two of the nine cases (CS5 and CS6) have higher energy use than the national figures, the other seven cases are around or below the median for their size and occupancy. The average case study figure is 7.4% lower than the national average figure, suggesting that, when floor area is considered, the majority of the case studies in fact have lower than average gas use. This finding is consistent with the energy behaviours explored in Chapter Six.

Figure 7.4: Case study gas use compared with UK median gas use by floor area and occupancy



A average figure for UK residential consumption per square meter of floor area is also available from the European ODYSSEE-MURE database and includes all heating fuels, not only gas (ODYSSEE-MURE, 2021b). This data is also climate adjusted and can be compared with main fuel use for all 13 of the case studies, which is divided by measured floor area (Figure 7.5). The ODYSEE-MURE data is divided into energy for space heating, DHW and cooking energy while the case study data cannot be disaggregated but includes the same elements. CS1 uses a separate fuel, propane, for cooking which has been added to their main fuel use; this equates to 3kWh/m^2/y for cooking which is similar to the UK average of 5kWh/m^2/y. 1,008kWh has been subtracted from the value for CS2, who only use electricity, as this is the estimated proportion for lighting and plug loads which is provided by the detailed energy modelling. CS11's DHW and cooking uses electricity and the proportion calculated by the detailed energy modelling has been added to their main fuel use; this equates to 4kWh/m^2/y.

Figure 7.5: Space heating, domestic hot water, and cooking energy per m² of floor space for all case studies, compared with UK average data



When this metric is considered, four of the case studies (CS1, CS2, CS5, CS6), have higher than average energy. CS1 and CS2 both feel that their heating systems are inefficient, CS2's small floor area also increases their energy use per m². CS6 was using more heating than normal as a result of an older relative staying with them during the time in which they provided energy data. Their building also has a poor form factor, which is a measure of the external surface area and the internal floor area. Simpler shapes and non-detached buildings such as terraces have improved efficiency as they have a lower heat loss area, while detached and more complex buildings such as CS6 have a higher proportion of external surface to internal space and are therefore subject to higher heat loss for the same floor area (Figure 7.6). It is unclear why CS5's energy use is so high; however they also have a detached property with fairly poor form factor and a large proportion of north facing glazing which may contribute to their higher usage.

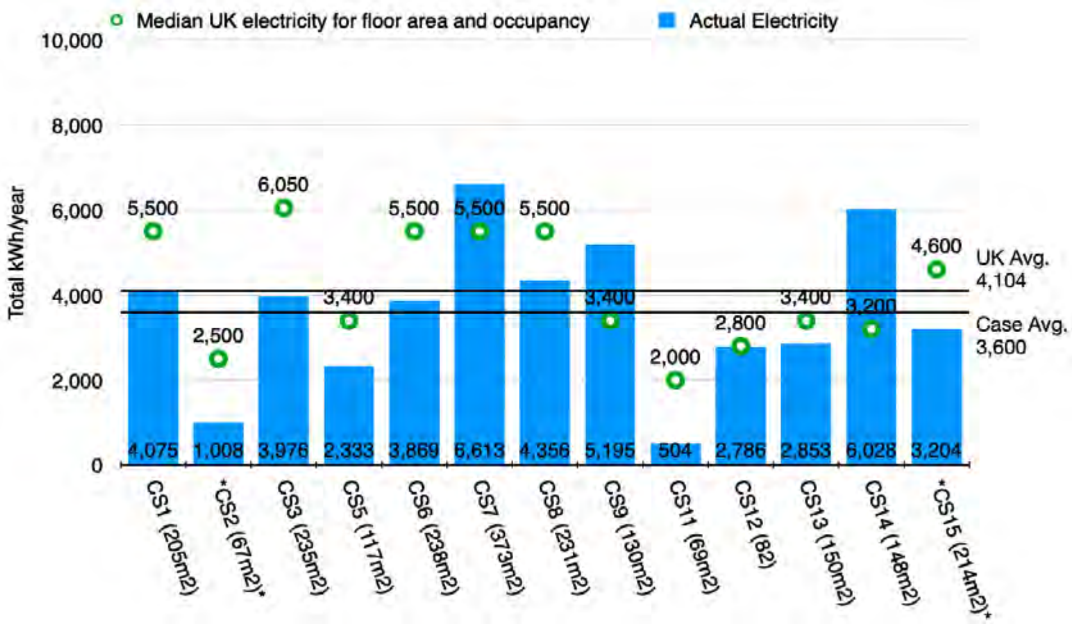
Nine of the case studies meanwhile have lower than average energy demand (CS3, CS7, CS8, CS9, CS11, CS13, CS13, CS14, CS15). The case study average demand is 16.5% less that the UK average. It would therefore appear that the case study vernacular buildings do not have higher than average demand for their main fuel use when the size of property is taken into account.

Figure 7.6: CS6, poor form factor with several complex elements

Electricity demand for the case studies can also be compared with NEED data for median floor area and occupancy (BEIS and NS, 2021) (Figure 7.7). Electricity use for the case studies includes lighting, extractor fans and plug loads. CS1's electricity also includes an electric shower in the downstairs bathroom which participants described as a 'back up' shower in case there is insufficient hot water in the main system. CS11 uses only 767kWh of electricity each year, 34% of this was estimated to be used on cooking and DHW by the detailed energy modelling and was included in Figure 7.5. This 263kWh was subtracted from the electricity demand displayed in Figure 7.7. CS11's extremely limited energy demand is attributable to their very frugal and environmentally principled lifestyle. Similarly, the electricity demand for CS2 is only that estimated to be used for lighting, fans and plug loads.

Overall, the electricity used by the case study participants is 14% lower than the UK average and the majority of the participants feel that they have lower than average recreational device use, which may be a factor in their reduced electricity demand. Nine of the case studies have lower than average demand, three (CS7, CS9, CS14) have higher and one (CS12) has a similar demand to the median figure. The cases with higher electricity demand are different to those with higher-than-average main fuel demands.

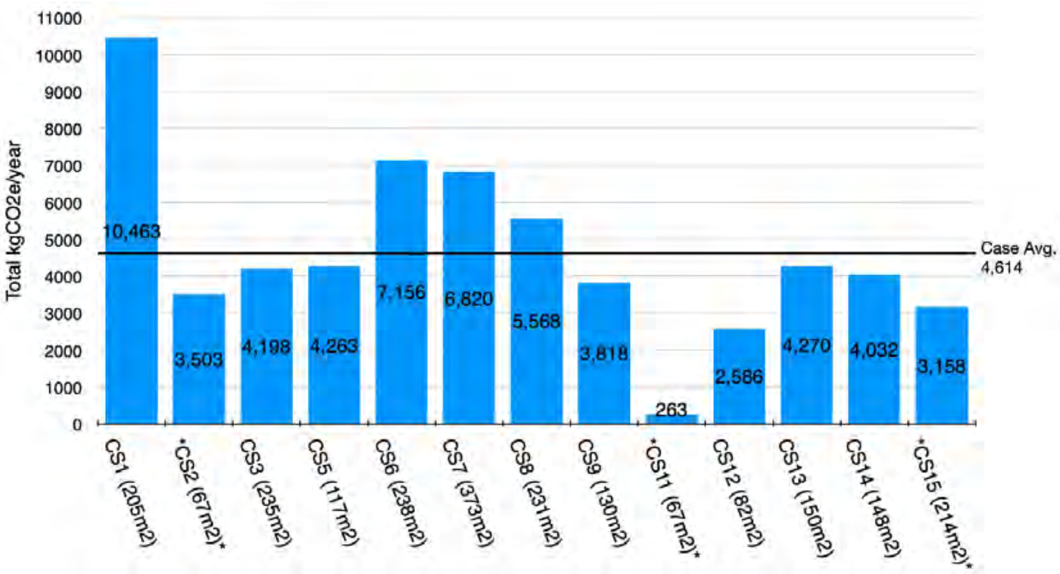
Figure 7.7: Case study electricity use for lighting, ventilation and plug loads, compared with NEED electricity data by floor area and occupancy.



The participants of CS7 both have permanent home offices and are quite technologically active, with one of the participants for example, having radio broadcasting equipment. One of CS9's household works from home full time with significant office equipment and both participants state that they enjoy cooking and have many electrical appliances for this purpose- including a micro-brewery -professing themselves to be 'Complete gadget freak[s]' which is likely to explain their substantial electricity use. CS12 and CS14 meanwhile, both have young children, and both also have participants working at least partially from home. The whole of CS14's household engages in substantial amounts of recreational video gaming as a family activity. CS12 feel that they use limited devices for recreation, however their home lacks natural light (Figure 6.21, Chapter Four), and they feel that they therefore use a comparatively large amount of electricity for lighting.

Carbon equivalent emissions, which include other greenhouse gases as well as CO_2 were calculated from the energy demand for each fuel type using the UK Government's carbon factors for 2021 (BEIS, 2021b). Significant variation can be seen amongst the different cases (Figure 7.8). At one end of the scale, CS1 has by far the highest carbon emissions, despite reporting engaging in a range of positive environmental behaviours. However, they have oil fuelled central heating and a system with two boilers both over 40 years old which are estimated to be only around 65% efficient. They are actively planning to upgrade their heating system and are currently investigating low carbon heating options. CS7 also uses oil central heating but, in contrast to CS1, have a much more modern boiler, listed as 80% efficient in the UK Product Characteristics Database (BRE, 2020b). At the other end of the scale, CS11 uses very little energy and also uses a wood burning stove, which has much lower emissions, as their only heat source. The average carbon emissions across the case studies are 4,614kgCO_2e or 4.6tCO_2e per year.

Figure 7.8: Overall case study carbon equivalent emissions



CS1, CS2, CS5, CS7, CS9, CS12 and CS14 also make regular use of wood burning stoves as secondary heating and the emissions from these are not included in these carbon figures. However, because these participants use wood, the additional emissions are likely to have a limited effect, CS7's wood use is known for example and leads to an additional 3,998kWh/y of energy but only 62kgCO_2e/y. The omission of this fuel source is therefore unlikely to significantly affect the total carbon emissions.

Normal grid electricity carbon factors (BEIS, 2021b) are assumed for these carbon calculations. Over half of all the case studies and seven of the 13 modelled have a green electricity tariff, where energy companies promise to offset their energy use by investing low carbon energy generation, and CS9 also has a green gas tariff. While the energy that the cases receive is still the standard UK grid mix, residents on green tariffs are investing in renewable energy generation and therefore contributing to wider grid decarbonisation. In addition, CS2 has onsite hydroelectricity generation, which will account for a proportion of their all-electric demand. This means that actual emissions will be lower than those listed here (exact figures for hydroelectricity used on site were not available, see Appendix H.2). None of the other case studies for whom energy data was analysed had renewable generation. The pilot case study has a biomass boiler and solar PV and CS16 has solar thermal panels, but energy surveys were not undertaken for either of these cases, so energy data was not provided.

In summary, the case studies use a variety of different fuels and have a range of annual energy demand and carbon emissions. The average case study energy demand is lower than national energy demand for all fuel uses when floor area is accounted for.

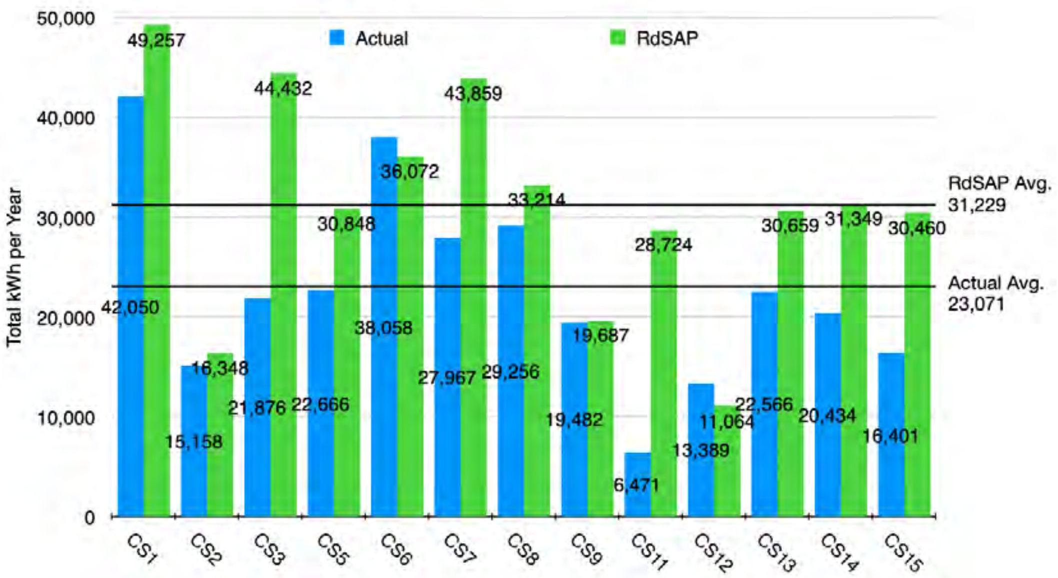
7.3 Standard energy models and actual performance

RdSAP is the tool used to produce EPCs (Energy Performance Certificates) for existing residential buildings in the UK. RdSAP models consistent with the official conventions (Chapter Three) were created for each of the 13 case studies that were physically visited. As noted above, secondary wood fuel use data was not available for most of the case studies and has therefore been omitted from the energy modelling. This secondary heating may reduce the demand on the main heating system if they are used concurrently (i.e., wood burning stove and radiators both on together in a living room), thus leading to overestimated main fuel use if the secondary heating is omitted. This has been controlled for by including a secondary heating source in the model for applicable cases and then subtracting predicted energy demand for this secondary heating from the RdSAP totals so that these can be appropriately compared with the actual measured data.

The results of the RdSAP models were compared with the actual case study energy demand and RdSAP was found to generally overpredict the actual demand (Figure 7.9), with an overestimation of 35% on average for total energy use.

Only for CS6 and CS12 is the actual energy use slightly higher than that modelled, and CS9 has actual and modelled use that is similar. These cases differ from the others in that they have large modern extensions. Research from other European countries has shown that energy use is often *underestimated* in modern construction by EPC models (Majcen et al., 2013; Sunikka-Blank and Galvin, 2012). This may therefore contribute to a modelled value closer to reality for these three properties. CS13 is the other case which has a modern extension, but this forms a much smaller proportion of the overall building than the extensions for the other three cases.

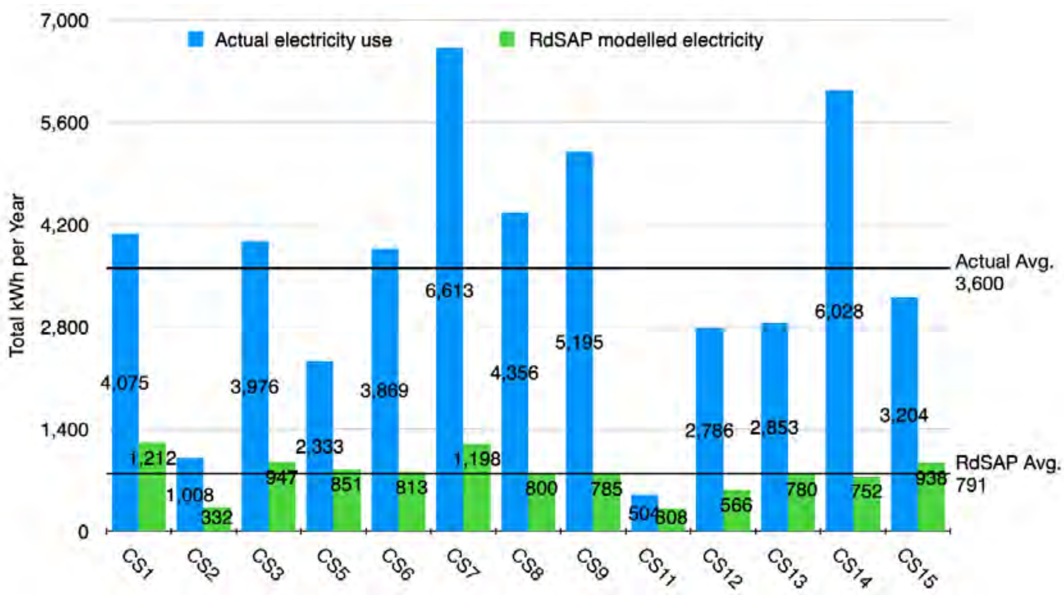
Figure 7.9: Case study total energy use compared with RdSAP predictions



It would therefore appear that RdSAP is overestimating energy demand for most of these case study buildings. One omission from the RdSAP model is that plug loads, which make up 14% of an average households' total energy use (Palmer and Cooper, 2014), are not included. RdSAP only includes fixed electrical demands such as extractions fans, system pumps and fixed lighting. To assess the impact of this omission, the results were disambiguated into the disparate fuel types from the RdSAP model outputs (Figure 7.10 and Figure 7.11). The actual energy data was divided into main fuel use for heating, DHW and cooking, and electricity as described above, with estimated proportions once again used for CS2 and CS11.

In contrast to the total energy use, electricity demand is underestimated in RdSAP by an average of 78% (2,809kWh) across the cases because of the omission of plug loads. CS11 with their very low electricity demand is the only case whose actual electricity is close to that predicted by RdSAP. Meanwhile the cases identified as having high electricity demand (CS7, CS9, CS14) are substantially underestimated.

Figure 7.10: Case study electricity demand compared with RdSAP predicted demand



RdSAP assumes standard heating patterns and temperatures to enable comparison between different properties (DCLG, 2017) (Table 7.2). These assumptions do not reflect the behaviours of the case study participants or survey respondents which were identified in Chapter Six. Survey respondents' average temperature set point for their main living space was 2°C less than that assumed by RdSAP (Figure 6.5) while the case study participants heated their homes to 18°C on average (3°C less than assumed) (Figure 6.7). The case studies' average heating time was longer than that assumed by RdSAP at 12hrs and 45minutes but only varied at weekends for one of the 16 cases. Most importantly, the vast majority of residents in this research only heat actively used parts of their buildings and most also do not heat bedrooms. This is very different to the uniform heating assumptions made by RdSAP. The prevalence of spot heating usage by the residents in this research may also contribute to their lower main heating settings in comparison with SAP/RdSAP assumptions. It must be noted however that RdSAP also assumes the use of secondary heating in the main living space as part of its calculation process.

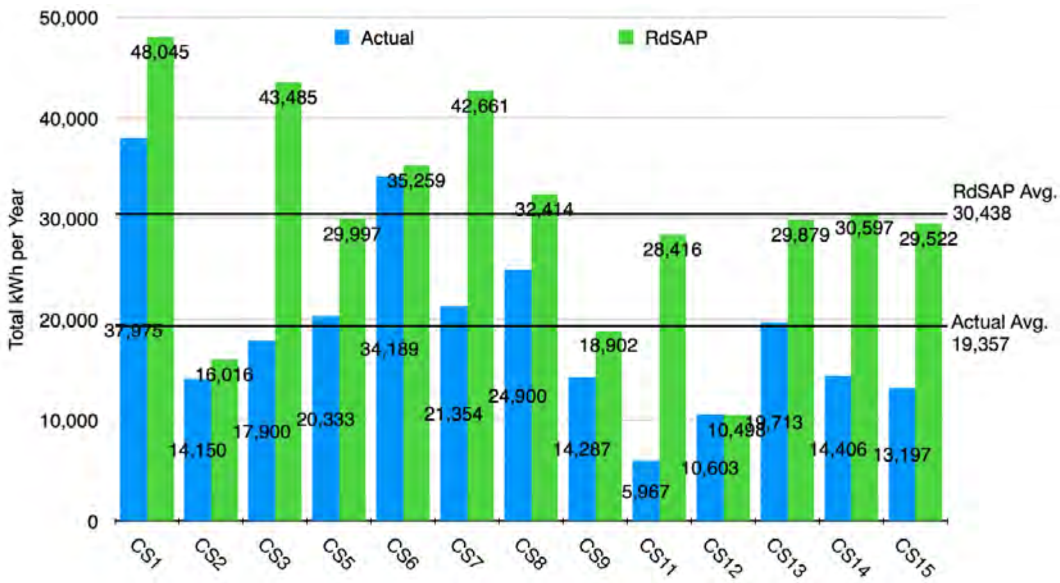
Table 7.2: SAP/RdSAP assumed heating patterns and temperatures

Day	**SAP/RdSAP Heating pattern**
Weekdays	2hrs on, 7hrs off, 7hrs on, 8hrs off (9hrs in total)
Weekends	16hrs on, 8hrs off (16hrs total)
Temperature settings	
Main living space heated to 21°C **The rest of the building uniformly heated to 18°C**	

Values from (BRE and DECC, 2014).

This significant difference between actual and assumed heating behaviours is likely to be one of the causes of the large gap between modelled and actual energy for heating, DHW and cooking energy (Figure 7.11). The average overestimation for this main fuel demand is 57% (11,081kWh). This is despite the fact that RdSAP does not include an estimate of the energy used for cooking, while this is included for the figures for the majority of the case studies.

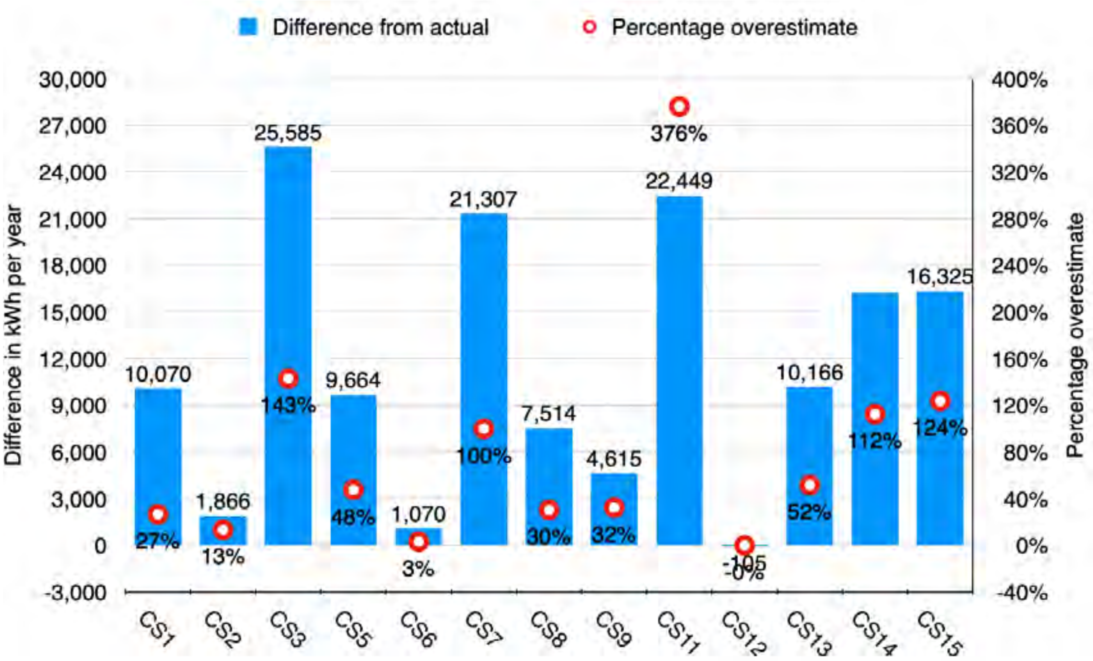
Figure 7.11: Case study heating, DHW, and cooking energy compared with RdSAP results



The energy demand for CS6 and CS9 is now overestimated by the model. CS12 is now only underestimated by 105kWh while the difference for CS14, which has one of the highest electricity demands, has increased by over 5,000kWh, to an overestimation of 16,191kWh. The modelled energy use is twice the actual energy use for four of the case studies (CS3, CS7, CS14, CS15) and nearly five times more than the actual use for CS11. The occupants of CS3 are often away for work and education so will have lower occupancy than predicted by RdSAP. CS7 heat their home to warmer temperatures for longer than many of the other cases (Chapter Six); however, their home is large, and they only heat a comparatively small proportion of it. RdSAP in contrast bases its calculations on number of rooms and floor area and will be assuming that a much larger area is heated. CS11 has extremely low energy behaviours, very different to the standard assumptions made in RdSAP, and CS14 also has very limited heating patterns, making use of adaptive comfort strategies to maintain comfort.

The difference for the main fuel used for heating, DHW and cooking, in kWh and in percentage terms was calculated for each case study (Figure 7.12). The average overestimation for this energy demand across the case studies is 11,306kWh or 81.5%.

Figure 7.12: Overestimation in kWh and percentage by RdSAP compared with actual values



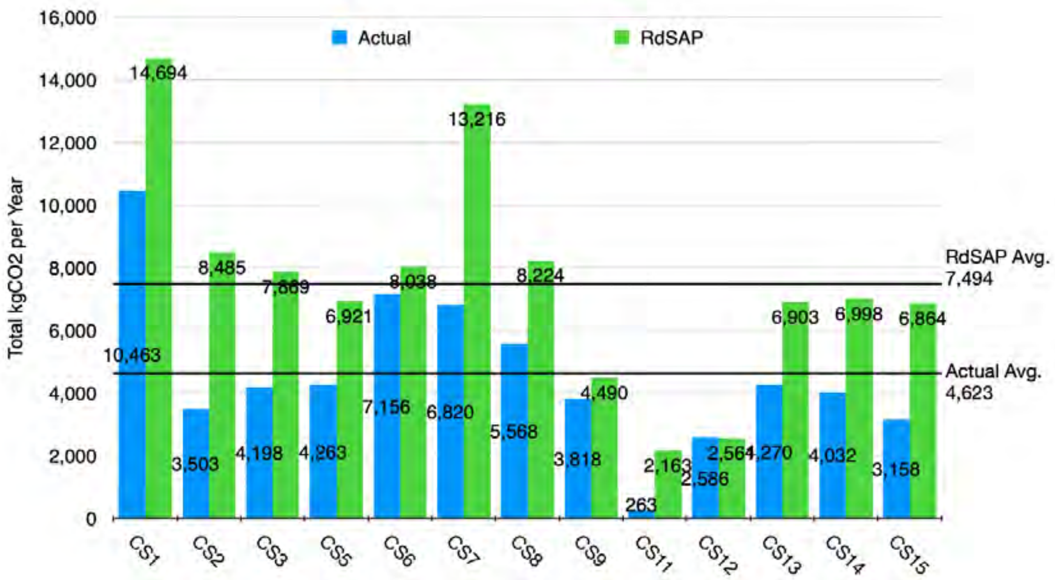
The discrepancy between actual and modelled figures can also be seen in the carbon emissions produced by RdSAP and those calculated from the actual energy figures (Figure 7.13). This discrepancy is exacerbated because the amount of CO_2 per kWh, known as the conversion factor, for different fuels is not up to date in RdSAP (Table 7.3). This is particularly evident for electricity which has decarbonised rapidly in recent years and for 2021 was 0.231kgCO_2e/kWh (BEIS, 2021b), or less than half the 0.519kgCO_2/kWh used for RdSAP (BRE and DECC, 2014).

Table 7.3: RdSAP and current UK carbon factors for different fuels

Fuels	RdSAP carbon factors (kgCO2/kWh)	2021 government carbon factors (kgCO2e/kWh)
Electricity	0.519	0.231
Gas	0.216	0.183
Oil	0.298	0.248
Wood	0.019	0.015

RdSAP overestimates the total carbon emissions for the case studies by 62%, which equates to slightly less than three tons (2,871kgCO_2) of carbon per case study per year. This is despite the underestimation of electricity demand. Note that the actual figures are calculated using CO_2 equivalent factors, while the RdSAP figures only consider CO_2. This should mean that the actual values would be slightly higher than those produced by RdSAP. It was not possible to model micro hydroelectricity as a source of renewable generation in RdSAP.

Figure 7.13: Case study total carbon emissions for RdSAP and actual emissions

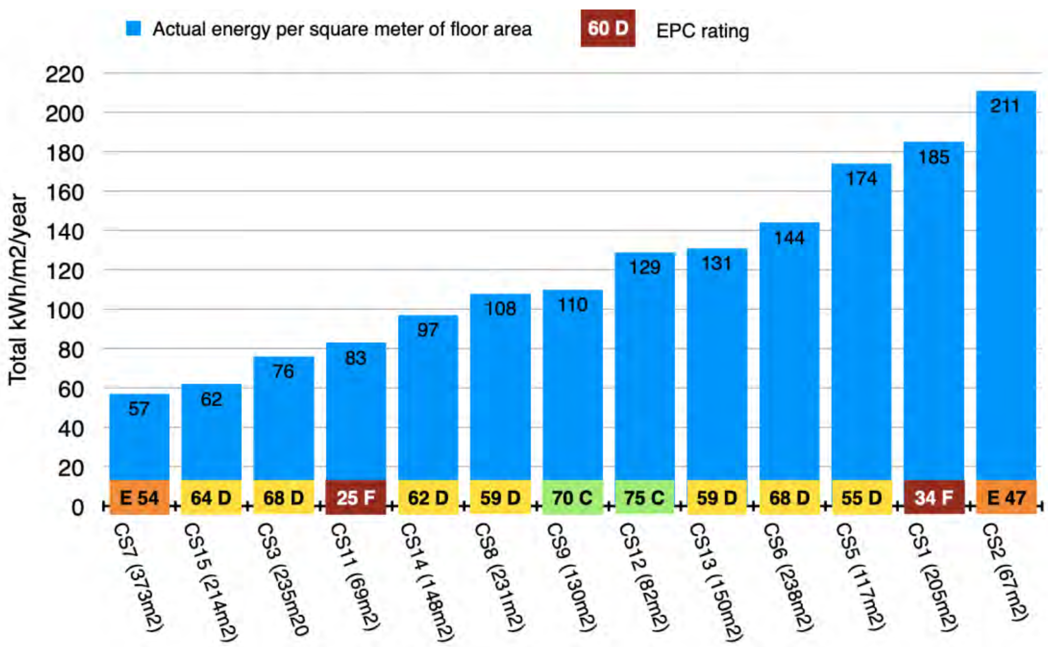


RdSAP produces energy efficiency ratings for EPCs which run from the worst performing band G (0-20) to the best performing band A (92+). These ratings are not based solely on energy use but also relate to the predicted fabric performance and to the cost of different fuels, although the exact calculation method is opaque (BRE and DECC, 2014) A relationship however would still be expected between energy demand and energy efficiency rating.

The EPC rating was compared with actual main fuel use by floor area (Figure 7.14). Electricity use was disregarded due to the absence of plug loads in RdSAP. The case study energy use has been arranged from least to most, left to right. If the EPC ratings reflected actual energy use it would be expected that the highest ratings would be to the left and the lowest to the right. However, it can be seen that this is not the case, with low ratings at both ends of the scale and the highest ratings in the middle. CS1 and CS7 which both use oil, and CS2 and CS11, on electricity and wood respectively, have lower ratings than the cases which use mains gas, because RdSAP considers other fuels to be more expensive.

To test the apparently weak relationship between EPC rating and actual energy demand for heating, DHW and cooking observed in Figure 7.14, a Pearson moment correlation was run. This confirmed that the relationship was not statistically significant at ($p < .01$ or $p < .05$) and the results had a low negative correlation $r(11) = -.224$, $p = .463$. EPC energy efficiency bands and actual energy demand therefore do appear to have a weak relationship based on this small sample.

Figure 7.14: Actual main fuel use by floor area compared with energy efficiency rating from EPCs based on RdSAP



7.4 Discussion

The majority of the case studies have lower than national average demand for both their main heating, DWH and cooking fuel, and for electricity. Average demand across the case studies is also lower than the average UK household when floor area is taken into account. This finding is contrary to general assumptions identified in the literature (Chapter Two) around vernacular buildings having high energy demand. It also reflects the low energy, adaptive heating practices identified for both the case study participants and survey respondents in Chapter Six. Energy data was not collected for the survey respondents, but the case studies appear representative of the wider survey in terms of building characteristics and energy behaviours, so the energy demand from these buildings could be inferred as likely to be similar. The vernacular buildings in this research therefore do not appear to have high energy demand.

The importance of considering a range of metrics when assessing energy performance is also highlighted. There are benefits and challenges with considering both absolute energy and energy by floor area. CS7 for instance has 4th highest absolute main fuel demand but when demand is compared by floor area, because they have such a large house, they have the lowest energy intensity per m^2. There is a relationship between building floor area and energy use, although this is only one of many complex factors that affect energy demand. The use of comparative metrics such as floor area is nonetheless considered useful to enable the normalisation of data and the comparison of energy across differently sized buildings, and is commonly used in policy and research (LETI, 2021; Fawcett and Topouzi, 2020; Gram-Hanssen, Georg, et al., 2018). In the context of climate change and the critical need to reduce carbon, is it however important to consider absolute as well as relative measures (Gram-Hanssen, Georg, et al., 2018), and it is generally acknowledged that more than one metric is required to gain a full picture of building performance (Fawcett and Topouzi, 2020).

EPCs have an important policy role and RdSAP, as the tool to produce them, is also often used for retrofit design in the UK (Chapter Two). Since the modelling results are often used to inform retrofitting decisions in this manner it is important that those results provide a reasonably accurate reflection of the actual energy originally consumed in the building, otherwise retrofitting activities may not achieve predicted energy and carbon savings. RdSAP was found to significantly overestimate energy and carbon in the case study buildings. If retrofit decisions were informed by this modelling they would not be based on accurate information. As such, they would most probably lead to significantly lower than predicted actual energy and carbon savings; contributing to the performance gap and failing to achieve carbon goals. From a lifecycle carbon perspective, retrofits based on overestimated baselines may in fact lead to increased carbon emissions, because if operational savings are lower than expected they may not outweigh the embodied carbon investment required for the retrofit. On a national perspective, UK policy is also being driven by a tool that appears to systematically overestimate energy demand and resultant carbon emissions from the historic built environment. This may lead to inappropriate policy development and poor-quality policy approaches to carbon reduction from heritage buildings.

Total energy demand figures for RdSAP may appear more accurate than they actually are, because the omission of electric plug loads mean that electricity demand is underestimated. This obscured the significant overestimations found for space heating which makes up the largest percentage of main fuel use. Reducing space heating demand is the main focus of most retrofit projects, reinforcing the findings that RdSAP would not provide accurate results to inform retrofitting.

These models do not take individual behaviours into account because they try to ensure that buildings with residents with different behaviours can be compared and because it simplifies the use of the tool (Jain et al., 2020). The energy behaviours of the case study participants are very different to the standard behavioural assumptions around heating practices however. This discrepancy is likely to be one of the key factors in the overestimation of energy use in RdSAP.

Several authors have also identified that RdSAP poorly reflects the performance of traditional materials (Pickles and Cattini, 2015), in particular assuming higher, and therefore poorer, u-values than in situ measurements indicate (Baker, 2011). This is partly attributed to an underestimation of the percentage of mortar in many traditional solid walls, which may make up around 40% of the wall composition (Li et al., 2015). As non-uniform and individual structures, accurately calculating the u-values of solid walls without in-situ measurements is challenging. However, there is sufficient data to suggest that the averages assumed by RdSAP may be poorer than the reality and that this is another critical factor in RdSAP's overestimation of predicted energy use.

For illustrative purposes the main wall u-values from the Design Builder modelling (see Chapter Three and Appendix H.1), which are still assumptions but are based on data from international materials databases and a more detailed wall build up, were compared with the RdSAP values. The average difference across the traditional materials (excluding modern walls in extensions) was 0.23W/m^{2}K and the RdSAP values suggested a 23.3% poorer performance on average. Some of the assumptions around the poor performance of vernacular buildings may therefore be influenced by their poor reflection in standard models

The substantial discrepancies in the carbon factors used for RdSAP will have implications for the retrofits measures that this tool recommends. The particularly large discrepancy for electricity, for instance, will affect the apparent viability of heat pumps for decarbonising heating if modelled in RdSAP. The installation of heat pumps in existing buildings is a key part of the UK Government's recent Heat and Buildings Strategy and their installation is being financially incentivised (BEIS, 2021a). Currently however, different policy tools are providing mixed drivers because of the inaccuracy of EPC modelling tools.

The energy ratings produced by RdSAP are a poor reflection of energy demand in the case study buildings and do not reflect the trends in actual energy performance. This is particularly concerning given the increased use of EPCs as a policy tool across the UK and Europe to encourage retrofitting by mandating that buildings meet certain energy efficiency ratings though the use of Minimum Energy Efficiency Standards (MEES) (BEIS, 2020a). If energy efficiency standards are being measured by tools such as RdSAP then they are very likely to poorly reflect actual building performance and energy demand and may not lead to actual performance improvements, thus jeopardising climate goals. The use of these ratings may also incorrectly penalise heritage buildings because of their poor representation in standard tools rather than accounting for their actual performance. The principle of mandating energy standards may be reasonable. However ratings must reflect actual energy performance if policies are to be effective and real savings are to be made.

7.5 Conclusion

This chapter identified and examined the actual energy demand of the case study buildings (RsQ2a) and compared these findings with UK averages using absolute and relative metrics. It also assessed the ability of the UK's standard energy simulation tool for existing buildings, RdSAP, to accurately reflect the energy demand of the case studies (RsQ2b). The majority of the case studies use gas as their main fuel type. A variety of other fuels were also used, and the proportion of mains gas was less than that for national figures. This was reflected in the wider survey data and influenced by the rural nature of Cumbria. Most of the case studies were found to have lower energy use than UK averages if floor area is taken into account, challenging general assumptions around the poor performance of vernacular buildings.

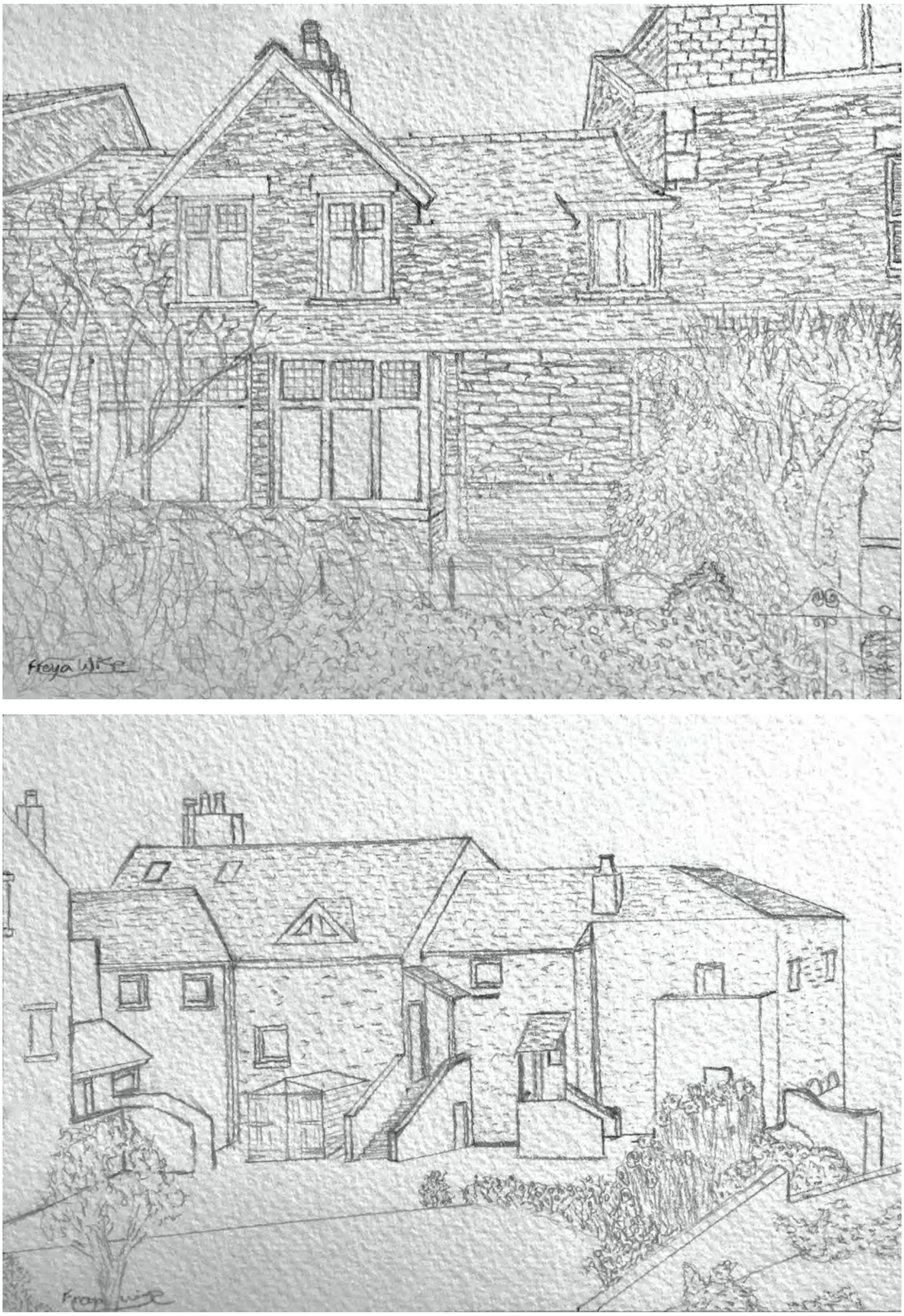
RdSAP was shown to significantly overestimate the main fuel use for heating, DHW and cooking, and the overall carbon emissions. Inaccurate assumptions about residents' behaviours and the performance of traditional materials are likely to be important contributors to the significant overestimations of energy use by RdSAP for the case study buildings. The use of out-of-date carbon factors is also a contributory factor.

It is not possible to save energy that is not actually being used and retrofit decisions based on these models would therefore lead to significantly lower than predicted actual energy and carbon savings for these cases. The relationship between EPC ratings and actual energy demand was also found to be weak, with significant implications for policy tools based on these ratings. It was therefore concluded that, in its current form, RdSAP is unfit for purpose when it comes to assessing vernacular buildings and that retrofit decisions should not be informed by this model.

The current energy demand of the buildings studied in this research is around or below average for domestic UK buildings however it is still critical to reduce carbon from these types of buildings, and indeed all buildings, to help mitigate climate change and meet global and national carbon goals. Ways must be found of retrofitting vernacular buildings that are compatible with their vernacular construction, and residents' heritage values and energy behaviours. A model that better reflects the actual energy demand of these buildings is required to assess the energy and carbon impact of a range of retrofit measures.

Some material in this chapter has been previously published in (Wise, Moncaster, et al., 2021)

Figure 7.15: CS9 and CS10



Chapter 8. Carbon reduction potential of retrofit

8.1 Introduction

Residents' views, values and behaviours have been found to play a critical role in determining the energy demand of their buildings. The UK's standard energy model for existing buildings has been found to poorly represent the current energy and carbon performance of vernacular construction or the complex interrelationship of residents with their buildings. More accurate baseline models are required if they are to help to develop an understanding of the operational energy and carbon effects of retrofit. For a full picture of the potential for retrofit to reduce carbon from buildings, the embodied carbon of retrofit measures must also be calculated as part of a lifecycle approach.

This chapter examines the opportunities to create reasonably representative baseline models of the case study buildings, which take account of their traditional construction and their residents' behaviours (RsQ2c). Using these baseline models and lifecycle assessment, the operational, embodied, and overall lifecycle carbon impact of a range of individual retrofit measures is calculated (RsQ3a). The data collected during the case study site visits is used to inform the development and calibration of the energy models. The LCA then uses data from Environmental Product Declarations (EPDs) and LCA databases to calculate the embodied and lifecycle impact of measures.

8.2 Baseline models

Three energy modelling tools were assessed as part of this research, RdSAP, SBEM and Design Builder (see Chapter Three). The functionality, flexibility, and level of input data for these tools was compared and summarised (Table 8.1).

RdSAP is the least detailed of the models, it uses standard behavioural assumptions for the whole building (Chapter Seven). It has limited options for choosing construction materials, and choices generally apply at a whole building level with little opportunity for variation. It does not use detailed dimensions or specific location data. These features mean that limited data is required, and models are quick and easy to produce but that accuracy is poor, as found in Chapter Seven. RdSAP is a steady state model where the calculation is based on monthly, averaged, data simulations (Godefroy et al., 2021; BRE and DECC, 2014).

SBEM is more detailed. Standard behavioural (activity) templates can be selected at an individual zone/room level, although these templates cannot be altered. More detailed data on constructions can be used from a library within the software or by entering u-values. Materials and heating systems can also be defined for each zone and each envelope within that zone. SBEM uses detailed dimensions, and location data can be selected from 14 regions across the UK. A greater amount of data is required than for RdSAP and the data input process is slow. Models still lack flexibility in the definition of materials, complex shapes, and the ability to model specific behaviours. SBEM, like RdSAP is a steady state model using monthly average data, meaning that accuracy is reduced. Details of the SBEM modelling can be seen in Appendix G.

Design Builder (based on the EnergyPlus simulation engine) is the most detailed of the three models, providing much greater flexibility around data entry and tailoring models to specific buildings. Standard behavioural templates can be used for each zone. These templates can be altered to reflect actual behaviours and/or new, user defined, templates and schedules can be created. The individual materials that make up construction assemblies can be selected from a large database and new materials can be defined. Specific location and hourly weather data is used and can be uploaded from other sources. Design Builder requires detailed data, the modelling interface is user friendly but modelling is complex, increasing the opportunities for user error. Data entry takes a similar time to SBEM but produces more detailed models. Design Builder uses a dynamic simulation calculation which for this research was set to six timesteps per hour, meaning calculations updated at ten-minute intervals. This means that results are much more responsive to small changes and are therefore more representative of reality, although simulation times are slow and require significant computing power. Details of the Design Builder modelling can be seen in Appendix H.1.

Table 8.1: Overview comparison of RdSAP, SBEM and Design Builder

Data/function	RdSAP	SBEM	Design Builder
Climatic location	Based on an average UK location in the Pennines	14 regional locations across UK (Manchester closest to Cumbria)	Location specific hourly weather data can be used. 7 locations within Cumbria
Dimensions	Age band of building pre-1919. Overall floor area, ceiling height and length of party walls. Detachment and storeys. Number of habitable rooms (reception, kitchen-diner, bedrooms, studies). Number of heated habitable rooms.	Define 'zones' which can be synonymous with rooms. Manually define each envelope element's area, orientation, and connection (i.e., another zone, outside, other property).	Define zones through 3D modelling. Floor areas and room heights for each zone. Envelope areas, orientation and connection calculated automatically from 3D model.
Ground definitions	Heated basements are included as a room. Otherwise, floor connection defined as 'above unheated basement' or above ground.	Connection of envelope elements can be defined as 'ground' for underground spaces	Several options for modelling ground. Can include half submerged or fully submerged spaces and specific ground temperatures, or defaults based on location
Materials	For whole building, wall, floor, and roof materials selected from limited drop-down list, and thickness of any insulation above 50mm specified. System calculates u-values based on building age band. Four 'extensions' can be used to define different construction ages and materials.	Individual constructions for each envelope in each zone can be defined from a library of common constructions or specific u-values can be entered. Thermal bridges can be input or left as defaults.	Individual constructions can be defined in material layer build ups rather than as a single entity. Substantial library of materials, new materials can be easily defined. Includes thermal mass data. Provision to input specific linear thermal bridging values and to calculate repeat thermal bridging.

Data/function	RdSAP	SBEM	Design Builder
Windows	For whole building proportion of glazed surface is based on age band. User can define less than typical, typical, or more than typical, single, double, or triple glazing, and frame material for whole building. Input percentage of double glazing, otherwise deemed to be single glazed	Area, window u-value, frame to glass factor and shading of any glazing in each envelope	Windows drawn in 3D model. Define material layers or u-values and solar values for glass in each window. Large glazing library. Define frame materials and thickness, including number of window dividers. Can define blinds and operation. Dynamic shading calculated automatically. Internal glazing also definable.
Heating systems	One heating system for building. Input fuel source, emitter type, boiler type and boiler efficiency from national database. Option for a second main heating system based on percentage of load. Option for one secondary heater with fuel type and emitter.	Define as many heating systems as required and apply them to individual zones. Secondary heating can be applied to any zone. Details of system efficiency, fuel source and emitters. Wood burning stoves and open fires can be defined	Schematically define as many heating systems as required and apply to individual zones, including combinations of different systems. Emitter types, efficiency, fuel sources, water temperatures/fan speeds, performance parameters, booster systems. Output power or auto size function. Only electricity can be used as fuel for direct room heaters. Wood burning stoves and open fires cannot be defined
Hot water	Source (from boiler or direct). Size category of tank if applicable. Tank insulation. Physical number of showers and baths in property	Source, tank size, tank insulation. Number of showers. Waste-water recovery for any showers.	Define schematically as part of detailed HVAC. Connection to boiler and/or internal heater. Size of hot water tank or auto size, can define auxiliary tanks. Water temperature and zones served.
Lighting	Percentage of fixed lighting with LED bulbs	Define lighting type and control for each zone	Define lighting type, power, and control for each zone. Add specific ‘task lighting’ if needed

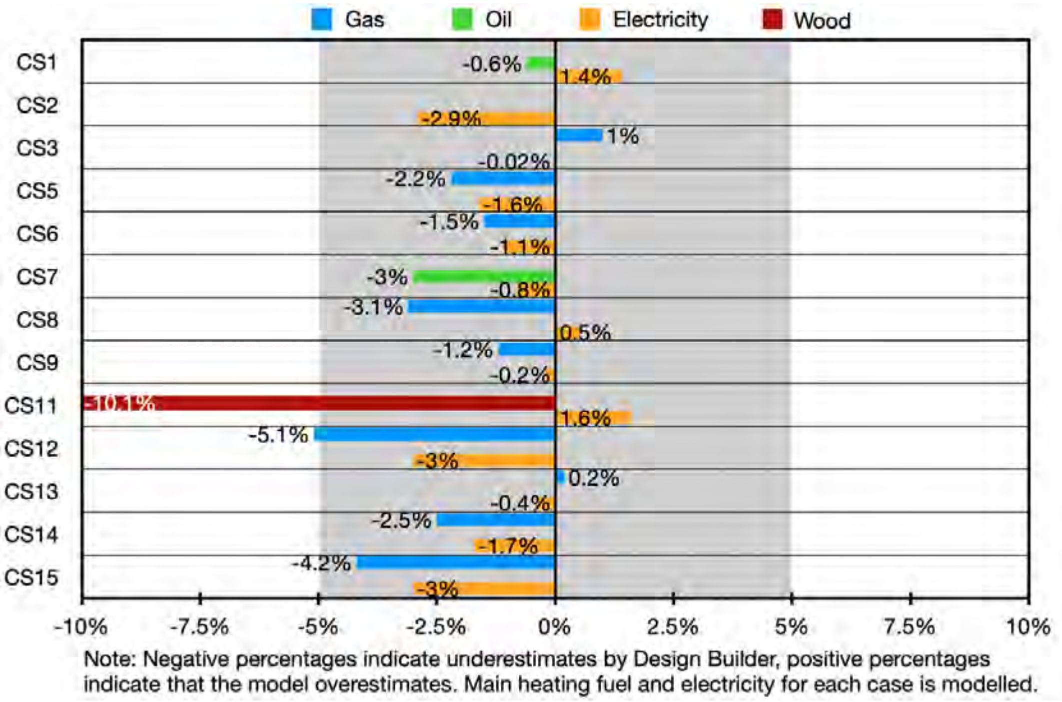
Data/function	RdSAP	SBEM	Design Builder
Ventilation /Infiltration	Natural or mechanical ventilation	Select ventilation type for each zone from list. Overall infiltration	Natural ventilation details and rates can be defined as can mechanical ventilation for each zone (extract fans or larger systems). Overall infiltration or more detailed calculations.
Renewable technologies	Limited details of renewables.	Details of renewables	Details of renewables, specific location of collectors for solar panels. Integration with HVAC systems (i.e., solar hot water and back up boiler).
Behaviours	Standardised assumptions for whole building	'Activity' of each zone can be defined from database (bedroom, kitchen etc) and determines heating temperature and pattern and zone occupancy	Activity of each zone can be defined from database or individual heating patterns, temperatures, occupancy, lighting, electrical equipment, and hot water use can all be defined individually or adjusted from templates
Simulation options	One option, produces EPC certificate and data sheet which summarises some outputs over an annual period	One option, produces EPC certificate and data sheet which summarises some outputs over an annual period	Simulations can be run at various levels of detail for periods ranging from individual days to multiple years. Detail and length of simulation affects simulation time. Can run system sizing calculations. Significant flexibility in outputs and details are available. Options to conduct sensitivity and uncertainty analysis

Design Builder (DB) was therefore chosen as the tool to undertake the retrofit modelling. Baseline models were created for each of the case study buildings.

There were a range of uncertainties in the DB baseline modelling because of the limited input data available (as discussed in Chapter Three). It was not possible to undertake in-situ u-value testing, air tightness testing, or detailed internal and external temperature measurements. The fabric performance and rate of infiltration for each case study building was developed from the site visits through a detailed visual inspection and information provided by residents on construction build-ups and infiltration levels. The performance data for the materials used in the construction build-ups data was sourced from Design Builder's large library of materials from authoritative sources, and from manufacturer data for specific products where applicable. Infiltration levels were chosen within a range of values based on the literature and checked with a Cumbrian air tightness expert. Specific values for each case study were estimated within this range based on residents' feedback and site visit observations. Details of occupant behaviours and internal temperatures from the energy diaries, interviews, and site visits, informed the behavioural aspects of the model. Meanwhile, because site specific weather data was not available, values from the nearest weather station with hourly data were used, taking local topographic and climatic variations into account when choosing which data set to utilise. The material u-values and construction build ups, air permeability, weather data locations, and other data and assumptions for the baseline models are detailed in Appendix H.1 (weather details in Appendix H.3).

These models were calibrated with actual energy use, based on yearly, or where available, monthly, fuel totals. Calibration was undertaken in a stepwise manner, making alterations to individual parameters where there was uncertainty. For all but one of the case studies it was possible to calibrate the modelled yearly energy demand to within 5% of the actual yearly energy demand for each fuel type (Figure 8.1). Heating demand for CS11 could not be calibrated to closer than 10.1% because it was not possible to accurately model their wood burning stove. This is because only electric direct heating can be modelled in DB. The way that wood burning stoves have been treated in DB and the additional uncertainty this adds to the model is detailed in Appendix H.1. Variations between actual and modelled energy use across the year were also assessed for four of the cases where a breakdown of annual data was available (Federal Energy Management Program, 2015) and this suggested that variation was within reasonable limits (Appendix H.3).

Figure 8.1: Percentage difference between actual and modelled energy demand after calibration



The Design Builder baseline models were therefore considered likely to be reasonably representative of actual building performance (more details on the calibration process are available in Appendix H.3). The level of detailed data collection and construction build ups, more localised weather data and behavioural tailoring, as well as the calibration of the DB models, lead to a much closer approximation of reality than that produced by either the RdSAP or SBEM models, and the dynamic nature of the model means that the simulation process is more accurate.

However, it is clear that, due to the limitations and assumptions necessary for the input data, there are still significant uncertainties in the parameters of the model. If for example more detailed input data was available, it would have been possible to calibrate the outputs of the model in different categories (such as fabric heat loss) against more detailed input data. The Design Builder models, and indeed all models, are only reflections of reality and, as such, their results should be treated as indicative rather than absolute.

In modelling the potential operational savings of the retrofit measures, it is therefore important to note that the absolute values of the predicted savings will be subject to uncertainty. However, the relative savings of the different measures are still very useful in assessing the impact of these measures for carbon reduction and heritage retention in vernacular buildings, and as the operational basis for the lifecycle assessment.

Design Builder was selected as the most effective and detailed modelling tool after investigating and comparing RdSAP, SBEM and Design Builder. Detailed baseline energy models of the case studies were created which were calibrated to actual energy use, details of the assumptions and inputs for the Design Builder models can be found in Appendix H.1 and H.3.

8.3 Operational energy and carbon savings from retrofit measures

A total of 40 individual retrofit measures were modelled for each of the 13 case studies for which it was possible to conduct physical site visits. Design Builder provides the energy demand for different fuels used as well as more detailed breakdowns. From this energy demand, the carbon emissions were calculated using the appropriate government conversion factors for each fuel (BEIS, 2021b). The predicted energy and carbon effect of each retrofit measure was calculated. 19 of the 24 measures listed in the acceptability matrix for the case studies were applied individually to the baseline Design Builder models. chimney balloons, aluminium windows, exterior shutters, WSHPs and wind turbines were excluded.

Chimney balloons were excluded because it was not possible to model specific air infiltration from chimneys. They were also not applicable for the majority of the case studies who mainly had wood burning stoves with closed flues or already used chimney balloons or similar. Discussions with participants highlighted confusion around the interpretation of aluminium windows, with some considering this to mean aluminium clad wood and some full aluminium windows. Because of this confusion and their lack of acceptability, aluminium windows were not modelled. Constraints in the way that shutters had to be modelled (Appendix I), meant that there would be no difference in the results for interior or exterior shutters, so exterior shutters were excluded because of their lack of acceptability to residents. WSHPs were excluded because they were not applicable to any of the modelled case studies. Wind turbines were excluded because they were mainly not acceptable to residents, were unlikely to be acceptable in planning policy in Cumbria and were also complex to model.

Three adjustments to heating settings were also modelled: reducing heating setpoint temperatures, turning heating off while away, and not heating bedrooms. A range of natural, standard, and technical insulation materials were modelled to explore the impact that different material choices would have on energy and carbon (see Chapter Three and Appendix I for further details of each measure).

The 40 retrofit measures and main assumptions made in the modelling are displayed in Table 8.2. For insulation products, a range of thicknesses were modelled to provide practical alternatives where; for example, a change of floor height would be required, or where internal space would be an issue for IWI. Not all of the measures were applicable to all of the case studies; CS12 for example only has a warm roof which already has over 150mm of insulation, so no further insulation was modelled.

Table 8.2: Summary of operational modelling of retrofit measures

Retrofit measure	Summary details
Loft insulation: for cold roofs	
Natural material: Cosywool	Fitted between joists to top up existing insulation to 300mm thickness
Standard material: Supersoft	As above
Technical material: Ultrawool	As above
Ceiling insulation: for warm roofs	
Natural: Gutex thermoflex	150mm fitted between and below rafters, leaving a ventilation gap

Retrofit measure	Summary details
Standard: Knauf rocksilk	As above
Technical: Aerogel	20mm fitted between rafters, leaving ventilation gap
Heritage: Diathonite	50mm fitted between rafters, leaving ventilation gap
Internal wall insulation	
Natural: Gutex thermoroom	50mm installed on the internal side of external walls against the stonework where internal insulation is not already extant
Standard: Knauf omnifit	As above
Technical: Aerogel	20mm as above
Heritage: Diathonite	50mm as above
External wall insulation	
Natural: Gutex multitherm	100mm installed on the external face of external walls fitted against the stonework and considered to be covered with lime render
Standard: Knauf rocksilk	As above
Technical: Isohemp blocks	As above
Solid ground floor insulation	
Natural: Geocell foamglass	New floor build-up of 50mm gravel, 300mm foamglass and 85mm limecrete, with existing floor covering re-laid.
Standard: Kingspan Kooltherm	60mm fitted with existing floor covering re-laid
Technical: Aerogel bonded chipboard	20mm bonded to chipboard fitted with existing floor covering re-laid
Suspended ground floor insulation	
Natural: Thermofloc	140mm fitted between joists in suspended floors, leaving a ventilation gap
Standard: Knauf omnifit	As above
Technical: Aerogel bonded to chipboard	20mm bonded to chipboard fitted between joists in suspended floors, leaving a ventilation gap
Window replacement	
Low e double glazed, hardwood frames	Replaces all single glazing, secondary glazing, or poor quality (as defined by homeowner) double glazing.
Low e double glazed, UPVC frames	As above
Low e triple glazed, hardwood frames	Replaces all glazing
Low e triple glazed, UPVC frames	Replaces all glazing
Window additions	
Curtains	Added to all windows currently lacking curtains by adjusting glazing U-values as described in Appendix I

Retrofit measure	Summary details
Interior shutters	As above
Secondary glazing	Added to all single glazed windows by adjusting the U-value as described in Appendix I
Heating systems and renewable technologies	
EE boiler	High efficiency gas/oil boiler model from the UK's Product Characteristics Database (PCDB)
Biomass pellet boiler	High efficiency Austrian domestic biomass pellet boiler
Solar PV: Maxeon 3 black	21.1% efficient solar panel based on manufacturer data. Black model used as likely to be less visually intrusive.
Solar thermal: evacuated tubes	Evacuated tube solar collector sized to provide 60% of hot water demand
GSHP: flat or borehole collector with underfloor heating	Generic ground source heat pump based on Design Builder template and taking into account the peak heat load calculated by the model for each case. Underfloor heating is applied downstairs and low temperature radiators upstairs. DHW is provided separately.
ASHP: high temperature with radiators	Generic air source heat pump based on Design Builder template using the existing boiler as back up for the ASHP. Coefficient of performance (CoP) of 2.8. Heat pump provides heat to radiators at 50°C.
Other retrofit measures	
EE lighting: LED bulbs	Replacing all non-LED bulbs
Thick wall hangings	Applied to one external wall in main and secondary living spaces.
Smart heating controls: Wi-Fi controlled room thermostat	Temperature set points of individual rooms are adjusted, based on each case study's reported thermostatic radiator valve settings from the energy diaries.
Draught proofing	A 20% percentage reduction in whole house infiltration is assumed, based on the literature and expert interview with Cumbrian airtightness expert
Heating setting adjustments which do not require any additional products	
Bedroom heating	All bedrooms set to unheated areas for applicable cases
Holiday heating	Heating during holiday periods set to off for applicable cases
Reduce temperatures	Temperature set points in all rooms reduced by 2°C in 0.5°C increments
Note: Retrofit is likely to reduce infiltration rates and as a result additional ventilation strategies may be required in some instances. This has not been considered in this modelling as the cases have high initial levels of infiltration and moreover, residents appeared to be actively managing their ventilation strategies.	

The average annual operational energy and carbon saving of each measure across the case studies was calculated (Table 8.3). The predicted operational results for individual case studies can be found in Appendix M. The average results within the different categories of measures i.e., loft insulation, are colour coded to show the greatest (green) savings, second (orange) and third (light orange) greatest savings where applicable, and lowest (black) savings. If a measure fails to make savings, it is colour coded red.

In operational terms, the standard insulation materials are predicted to make the greatest average savings for all insulation types except loft insulation. However, the difference between natural, standard, and technical materials is small. For window replacement low emissive triple glazing is predicted to make significantly greater average savings than double glazing, and a hardwood frame leads to slightly larger savings than a UPVC frame. Secondary glazing appears to make comparable savings to double glazing and has the greatest predicted savings of the window additions, followed by shutters. Comparing biomass boilers with energy efficient boilers shows that energy efficient boilers make greater energy savings, while biomass boilers lead to a much greater reduction in carbon emissions because current fossil fuels are swapped for wood pellets with much lower emissions. This shows the importance of considering both the energy and carbon impact of measures.

Different measures provide the greatest carbon reduction for different case studies, depending on their form, construction, and usage. For example, most of the case studies have relatively modern and high efficiency boilers and improving the efficiency of the boiler from 89% to 91% has very limited carbon savings (around 0.8% or 20kg/CO_2e/y). CS1 however has a 40-year-old oil boiler that is only 65% efficient and replacement by a 92% efficient oil boiler is predicted to reduce carbon emissions by 42% (just under 4.4t/CO_2e/y). Loft and ceiling insulation also has a varied impact (0.2-543kg/CO_2e/y); dependant on how much insulation is already present in roof spaces. Six of the case studies (CS2, CS3, CS7, CS11, CS14, CS15) are predicted to accrue greater carbon savings from window alterations such as secondary glazing or shutters, than they do from replacement with double or triple glazing with low emissive coatings, as the latter reduce daylight and consequently increase the electricity demand for lighting.

Table 8.3: Average, maximum and minimum annual operational energy and carbon savings across case studies

Retrofit measures	Carbon savings (kgCO2e)			Energy savings (kWh)		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**
Loft insulation: for cold roofs						
Natural material: Cosywool	**86.8**	2.1	523	**396.9**	9	2,111
Standard material: Supersoft	**85.2**	2.1	516	**389.5**	9	2,081
Technical material: Ultrawool	**89.3**	2.3	543	**408.9**	10	2,190
Ceiling insulation: for warm roofs						
Natural: Gutex thermoflex	**96.4**	0.5	235	**545**	3	1,286
Standard: Knauf rocksilk	**97.3**	0.2	238	**550.6**	1	1,300
Technical: Aerogel	**75.1**	0.4	172	**422.4**	2	936
Heritage: Diathonite	**89.1**	1.1	177	**518**	70	966
Internal wall insulation						
Natural: Gutex thermoroom	**917.6**	10	2,633	**4,539**	634	10,625
Standard: Knauf omnifit	**953.4**	10	2,735	**4,718**	656	11,037
Technical: Aerogel	**933.8**	10	2,675	**4,623**	644	10,794
Heritage: Diathonite	**862**	9	2,499	**4,133**	609	10,086
External wall insulation						
Natural: Gutex multitherm	**1,100**	7.3	3,222	**5,405**	482	13,001
Standard: Knauf rocksilk	**1,127**	7.4	3,297	**5,535**	492	13,303
Technical: Isohemp blocks	**987**	6.6	2,919	**4,851**	436	11,779
Solid ground floor insulation* (see notes at end of table)						
Natural: Geocell foamglass	**300.1**	-46	2,745	**1,286**	-252	11,079

Retrofit measures	Carbon savings (kgCO2e)			Energy savings (kWh)		
	Average	Min	Max	Average	Min	Max
Standard: Kingspan Kooltherm	**301.7**	-29	2,678	**1,296**	-160	10,807
Technical: aerogel bonded chipboard	**249.7**	-27	2,420	**1,056**	-150	9,766
Suspended ground floor insulation* (see notes at end of table)						
Natural: Thermofloc	**-25.6**	-320	53	**-75.4**	-1,293	290
Standard: Knauf omnifit	**-25.6**	-322	54	**-73.7**	-1,299	297
Technical: Aerogel bonded to chipboard	**-25.4**	-236	22	**-76.1**	-854	120
Window replacement						
Low e double glazed, hardwood frames	**119.6**	-0.4	285	**639.8**	85	1,559
Low e double glazed, UPVC frames	**113.7**	-0.5	279	**608.9**	82	1,533
Low e triple glazed, hardwood frames	**141**	-20	361	**754.8**	-83	1,982
Low e triple glazed, UPVC frames	**137**	-26	355	**735.6**	-107	1,947
Window additions						
Curtains	**30**	0.1	67	**153.7**	5	368
Interior shutters	**74.1**	0.9	149	**387**	74	811
Secondary glazing	**108.4**	1.1	268	**566.9**	33	1,462
Heating systems and renewable technologies						
EE boiler	**1,213**	20	4,391	**4,925**	107	17,719
Biomass pellet boiler	**3,357**	73	9,035	**1,437**	-1,248	16,568
Solar PV: Maxeon 3 black	**159.5****	43	361	**679.5****	79	1,567
Solar thermal: evacuated tubes	**558.5**	16.2	3,195	**1,770**	94	5,502
GSHP: flat or borehole collector with underfloor heating	**2,082**	-122	7,896	**11,620**	4,259	31,437
ASHP: high temperature with radiators	**1,534**	-295	7,585	**9,609**	3,513	30,091
Other retrofit measures						
EE lighting: LED bulbs	**57.3**	1	202	**186.8**	8	679

Retrofit measures	Carbon savings (kgCO2e)			Energy savings (kWh)		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**
Thick wall hangings	**40.7**	-16	132	**208.7**	-88	719
Smart heating controls: Wi-Fi controlled room thermostat	**828.5**	105	3,335	**3,131**	573	5,760
Draught proofing	**96.1**	0.9	196	**489.1**	60	1,047
Heating setting adjustments						
Bedroom heating	**455.2**	128	1,150	**2,255**	698	4,974
Holiday heating	**60.3**	25	107	**287.3**	127	462
Heat reduction 0.5°C	**276.3**	5.5	903	**1,293**	363	3,645
Heat reduction 1°C	**514.7**	11	1,742	**2,532**	711	7,030
Heat reduction 1.5°C	**756.2**	16	2,527	**3,720**	1,057	10,197
Heat reduction 2°C	**979.2**	20	3,261	**4,821**	1,339	13,160

***Note Floor Insulation**: There were some challenges with modelling floor insulation. Solid floor insulation increased energy demand for four of the case studies (CS3, CS5, CS11, CS14). This was also the case for the suspended floor insulation for the two cases (CS1, CS5) whose suspended floors were directly over the ground rather than above an unheated cellar. This appears to be related to how the software modelled heat exchange with the ground, but it was not possible to identify the exact fault and correct it. The average savings from floor insulation are therefore very likely to be underestimated in the modelling

****Note Solar PV:** Solar PV savings assume that 25% of generated energy is used on site unless this is greater than the building's electricity demand, in which case 25% of this demand is assumed to be met. Average UK figures for onsite use of PV generation are 15-25%, with higher figures if residents, such as the case study participants, are generally at home in the day (The Energy Saving Trust, 2021).

The average annual percentage energy and carbon savings predicted to be made by each retrofit measure was also calculated (Table 8.4). The average savings for all materials for roof, floor, and internal and external wall insulation are combined to save space in this table because they make very similar savings with differences between 0.1%-2%. CS11 is excluded from this the average across the case studies because of the uncertainty in the modelling of their wood burning stove (the results for each case study can be found in Appendix M).

A biomass pellet boiler is predicted to make the largest carbon savings (72%) for the retrofit measures modelled but makes no reduction in energy demand. Ground source heat pumps in contrast make the largest average energy savings (47%) and the second highest carbon savings (35%), although these heat pumps are based on a generic template and more detailed analysis of ground temperatures would be necessary to refine the GSHP modelling. Air source heat pumps make the second highest energy saving (39%) and carbon savings (31%) and could provide greater savings if they were designed as part of a lower temperature heating system. This however would require greater changes to current heating systems, and therefore increased disruption and embodied carbon, than has been assumed for this modelling.

External wall insulation is predicted to make slightly greater savings for both energy (26%) and carbon (25%) than internal wall insulation (23% and 22% respectively). Heating system alterations and wall insulation provide the greatest average energy and carbon savings. The next most effective measures and the only others predicted to make average savings in double figures are heating system adjustments; reducing heating temperatures by 1-2ºC (12-21% carbon savings), making use of smart controls (13% carbon), and not heating bedrooms (12% carbon). Solar thermal panels have a higher level of carbon reduction (10%) than solar PV panels (4%), they will also generally have a much lower financial cost. Solar PV panels however also provide electricity to be exported, thus contributing to national grid decarbonisation.

The replacement of windows appears to make only limited reductions in energy and carbon of between 2.9-3.3%. This may be partially because many participants already make use of traditional window additions such as shutters and curtains or have secondary glazing. Window additions and replacement may have an effect on comfort, disproportionate to their energy and carbon saving potential, as they can prevent draughts and reduce heat loss from residents' bodies to the cold glass, thus improving comfort. This is also the case with wall hangings, which only have a limited 1% average saving for energy and carbon. This highlights the importance of considering retrofits holistically and not just in terms of their predicted technical impact.

Table 8.4: Average operational energy and carbon percentage savings across all case studies (excluding CS11), arranged in order of greatest average carbon savings

Retrofit measure	Average energy saving	Average carbon saving
Biomass boiler	-4.4%*	71.6%
Ground source HP	47.2%	34.9%
Air source HP	39%	31.1%
External wall insulation	25.9%	25.2%
Internal wall insulation	22.7%	22.2%
Heating reduction: 2°C	21.9%	21.2%
Heating reduction: 1.5°C	16.9%	16.5%
EE boiler	13.4%	13.5%
Smart controls	13.1%	12.9%
No heated bedrooms	12.3%	12%
Heating reduction: 1°C	11.5%	11.2%
Solar thermal	8.5%	9.6%
Heating reduction: 0.5°C	5.9%	5.7%
Solid floor insulation	4.3%	4.2%
Solar PV	3.3%	3.7%
Window replacement: Triple Wood	3.5%	3.3%
Window replacement: Triple UPVC	3.3%	3.2%
Window additions: Secondary	3.3%	3.2%
Window replacement: Double wood	3.1%	2.9%
Window Replacement: Double UPVC	3.1%	2.9%
Ceiling insulation	2.8%	2.6%
Draught proofing	2.4%	2.3%
Heating off when away	2.1%	2%
Windows additions: Shutters	2%	2%
EE lighting	1%	1.5%
Roof insulation	1.2%	1.2%
Wall hangings	0.9%	0.9%
Window additions: Curtains	0.7%	0.7%
Suspended floor insulation	0%	0%

***Note:** The negative average energy value for the biomass boiler is because it is slightly less efficient that some of the cases' current gas boilers, thus leading to slight greater energy use.

Heating system improvements therefore appear to lead to the greatest operational carbon reductions, although the effect of measures varied across cases. Further details of the operational impact of each retrofit measure over the 50-year LCA lifespan are included in section 8.5 However, before this, the embodied impact of the retrofit measures is considered.

8.4 Embodied carbon of retrofit measures

The embodied carbon of the retrofit measures was calculated using data from EPDs and the software OneClickLCA (as described in Chapter Three and Appendix J). Only embodied carbon was calculated as this data was more readily available for all retrofit measures than information on embodied energy, especially in relation to transport and end of life impacts. A total of 52 materials were analysed, consisting of the 40 retrofit measures and any additional materials required for their installation.

The initial embodied carbon (A1-A3) for each of the retrofit measures and the key supporting materials was calculated (Table 8.5). This includes the extraction of raw materials, transport and manufacture, often termed cradle to factory gate. The biogenic carbon storage potential for these measures is also shown and the final column shows the effect if biogenic storage were included in the overall A1-A3 impact. For some natural materials such as Gutex wood fibre insulation or Isohemp EWI insulation, the inclusion of biogenic carbon storage would mean that a measure would have positive initial embodied carbon. This biogenic carbon would be re-released at the end of a building's life, but the storage effect could still have a positive impact on current carbon emissions, especially if measures were long lasting. This would also have the effect of smoothing out the initial carbon emissions associated with the retrofit. The majority of the embodied emissions come from the initial manufacture, transport and installation life stages, while the operational savings are spread over the fifty-year period.

The number of replacements required for each measure over the 50-year lifespan is also shown, most of the insulation materials will last for longer than the 50-year assessment period. Manufacturer's data for lifespans has been used because data on actual lifespans is limited. This may mean that lifespans are overoptimistic for some materials compared with their real-world performance. The initial carbon for additional materials required as part of the retrofit process is also shown, such as lime render for external wall insulation or curtain poles.

While the standard insulation measures were predicted to make the greatest operational carbon savings, the natural and technical insulation generally has lower initial embodied costs, except for floor insulation where the technical aerogel has the lowest initial emissions but the embodied carbon of the chipboard that it is bonded to raises the carbon for the complete measure above that of the standard Kingspan insulation panel. If biogenic storage is considered however, the aerogel has lower emissions and most of the natural insulation materials also have significant carbon storage potential.

Window replacements with hardwood frames have initial embodied carbon 40-55% lower than window replacements with UPVC frames while they also have better operational performance. As would be expected, the double glazing also has lower embodied carbon than the triple glazing. For the GSHPs, flat collectors were modelled for cases which had sufficient outdoor space and borehole collectors were modelled for cases with less space. The flat collector (366kg/CO_2 per unit) has much lower embodied carbon than the borehole collector (1426kgCO_2 per unit). The three heating setting adjustment measures are not included in this table because they have no embodied emissions.

Table 8.5: Initial (A1-A3) embodied carbon of retrofit measures independent of case studies, the effect of biogenic carbon is also shown

Retrofit measures and supporting materials	Thickness (mm)	Initial A1-A3 embodied carbon per m2 ($kgCO_2e$)	Initial A1-A3 biogenic carbon per m2 $kgCO_2e$	Replace-ments in 50-year lifespan	Initial A1-A3 embodied including biogenic ($kgCO_2e$)
	Loft insulation: for cold roofs				
Natural material: Cosywool	Average 100[1]	2.36	2.2	0	0.16
Standard material: Supersoft	Average 100[1]	2.88	N/A	0	2.88
Technical material: Ultrawool	Average 100[1]	3.97	3.4	0	0.57

Retrofit measures and supporting materials	Thickness (mm)	Initial A1-A3 embodied carbon per m2 ($kgCO_2e$)	Initial A1-A3 biogenic carbon per m2 $kgCO_2e$	Replace-ments in 50-year lifespan	Initial A1-A3 embodied including biogenic ($kgCO_2e$)
Ceiling insulation: for warm roofs					
Natural: Gutex thermoflex	150	4.24	13.1	0	-8.68
Standard: Knauf rocksilk	150	7.72	N/A	0	7.72
Technical: Aerogel	20	0.246	N/A	0	0.246
Heritage: Diathonite	50	15.15	0.001	0	15.15
Lime plaster (also used for IWI)[2]	12.5	0.568	N/A	0	0.568
Plasterboard (also used for IWI)[2]	12.5	1.89	N/A	0	1.89
Internal wall insulation					
Natural: Gutex thermoroom	50	3.67	11.32	0	-7.65
Standard: Knauf omnifit	50	1.05	N/A	0	1.05
Technical: Aerogel	20	0.246	N/A	0	0.246
Heritage: Diathonite	50	15.15	0.001	0	15.72
Wooden studwork for plasterboard	46	2.31	2.75	0	-0.44
External wall insulation					
Natural: Gutex multitherm	100	7.91	24.38	0	-16.47
Standard: Knauf rocksilk	100	17.3	1.27	0	16.03
Technical: Isohemp blocks	120	10.66	22	0	-11.34
Lime render	16	8.97	N/A	1[3]	8.97
Solid ground floor insulation[4]					
Natural: Geocell foamglass (with 85mm lime floor screed)	300	18.46	0.096	0	18.45
Lime floor screed	85	12.71	N/A	0	12.71
Standard: Kingspan Kooltherm	60	4.07	N/A	0	4.07
Technical: aerogel bonded to chipboard	10	0.125	N/A	0	0.125
Chipboard (also used for suspended floor)	12.5	16.33	12.5	0	3.83
Suspended ground floor insulation[4]					
Natural: Thermofloc	140	0.871	0.897	0	-0.03

Retrofit measures and supporting materials	Thickness (mm)	Initial A1-A3 embodied carbon per m2 ($kgCO_2e$)	Initial A1-A3 biogenic carbon per m2 $kgCO_2e$	Replace-ments in 50-year lifespan	Initial A1-A3 embodied including biogenic ($kgCO_2e$)
Standard: Knauf omnifit	60	2.94	N/A	0	2.94
Technical: Aerogel bonded to chipboard	10	16.46	12.5	0	3.96
Window replacement					
Low e double glazed, hardwood frames	N/A	79.5	N/A	0	79.5
Low e double glazed, UPVC frames	N/A	123	N/A	0	123
Low e triple glazed, hardwood frames	N/A	114	N/A	0	114
Low e triple glazed, UPVC frames	N/A	160	N/A	0	160
Window additions					
Curtains	N/A	3	N/A	2	3
Curtain pole (20mm x 20mm also used for wall hangings & door curtains)	per m length	0.06	3.28	2	3.22
Interior shutters	22	10.22	24.4	0	-14.18
Secondary glazing	N/A	50.49	N/A	1	50.49
Heating systems and renewable technologies					
EE boiler Gas	1 unit	243.6	N/A	2	243.6
EE boiler Oil	1 unit	481.6	N/A	2	481.6
Biomass pellet boiler	1 unit	1168	N/A	2	1168
EE/Bio boiler: radiator (CS2 and CS11) (also used for ASHP)	1 unit	69.48	N/A	1	69.48
EE/Bio boiler: water pipework (CS2 and CS11)	per m2	0.59	N/A	1	0.59
Solar PV: Maxeon 3 black	N/A	109.45	N/A	1	109.45
Solar PV: Inverter	1 unit	128	N/A	1	128
Solar thermal: evacuated tubes	N/A	109.6	N/A	2	109.6
Solar thermal: hot water tank	1 unit	358.5	N/A	2	358.5
GSHP borehole collector	1 unit 10-20kW	1426.4	N/A	2	1426.4
GSHP borehole collector pipes	1 unit 10-20kW	1209.2	N/A	0	1209.2

Retrofit measures and supporting materials	Thickness (mm)	Initial A1-A3 embodied carbon per m2 ($kgCO_2e$)	Initial A1-A3 biogenic carbon per m2 $kgCO_2e$	Replace-ments in 50-year lifespan	Initial A1-A3 embodied including biogenic ($kgCO_2e$)
GSHP flat collector	1 unit 10-20kW	365.95	N/A	2	365.95
GSHP flat collector pipes	1 unit 10-20kW	545.7	N/A	0	545.7
GSHP underfloor heating	N/A	22.32	N/A	1	22.32
ASHP: high temperature with radiators	1 unit 7-14kW	575.5	N/A	2	575.5
Other retrofit measures					
EE lighting: LED bulbs	1 bulb	2.4	N/A	4	2.4
Thick wall hangings	22	20.03	N/A	1	20.03
Smart heating controls: Wi-Fi room thermostat	1 unit	30.27	N/A	4	30.27
Draught proofing: window foam sealing strips	1m in length	0.161	N/A	1	0.161
Draught proofing: base of door seals	1m in length	4.811	N/A	1	4.811
Draught proofing: airtightness tape	1m in length	8.22	N/A	1	8.22
Draught proofing: Door curtains	N/A	3.06	3.28	2	-0.22

Notes:
1 = Thickness varies depending on the case study as insulation is used to top up current levels to 300mm.
2 = Lime plaster or plasterboard was used for different cases dependent on what was already there.
3 = Although the insulation is not replaced in the 50-year period, one of the two coats of lime render applied over it is replaced once at 30 years.
4 = For both types of floor insulation the existing floor covering is reapplied after installation. A 15% wastage rate for the floor covering is assumed and new slate tiles, carpet, or timber flooring to cover this wastage is calculated as appropriate.

The full embodied carbon of each retrofit measure and any necessary supporting materials, including transport, installation, maintenance, and replacement, was then calculated for each case study over a 50-year period and the average, maximum and minimum values across the case studies were identified (Table 8.6).

The measures which were predicted to have the greatest operational carbon savings, biomass boilers, GSHPS and external wall insulation can be seen to also have some of the highest embodied carbon figures. Ground source heat pumps have the highest average embodied carbon at 10.3t/CO_2e, and ASHP at 6.5t/CO_2e, followed by solar PV panels at just under 5 tonnes, natural geocell floor insulation (4.8t/CO_2e), biomass pellet boilers (4.3t/CO_2e), triple glazed UPVC windows (4.1t/CO_2e), and technical Isohemp wall insulation (3.8t/CO_2e). The heat pumps, solar PV and biomass boilers in part have high emissions because they are all required to be replaced twice within the assessment period. The need to dispose of the old products and create, transport, and install replacements thus raises their embodied carbon significantly. For the ground and air source heat pumps, the refrigerant emissions in the heat exchanger also lead to high B1 (use) and B2 (maintenance) emissions.

For insulation, the natural materials have the lowest average embodied carbon for loft, external wall, and suspended floor insulation, while the technical material has the lowest embodied carbon for ceiling insulation and internal wall insulation and the standard material has the lowest emissions for solid floor insulation. Secondary glazing made the greatest operational savings of the window additions; however, it also has the highest embodied emissions (average of 1.3t/CO_2e). These emissions are still significantly less that the average embodied carbon of window replacement however (2.1-4.1tCO_2e). Solar PV and solar thermal panels have similar initial embodied carbon (Table 8.5). A significantly greater area of solar PV collector is required compared with solar thermal however, meaning that solar PV (5t/CO_2e) has much higher embodied carbon across the case studies than solar thermal (2.9tCO_2e).

Measures that are likely to be more compatible with vernacular construction such as natural, breathable materials, and those that are likely to have a lower impact on residents' heritage values such as window additions, wall hangings (0.5t/CO_2e), and draught proofing (0.3t/CO_2e) appear likely to have lower embodied carbon emissions than more substantial or technical measures. Some of these measures were predicted to make only limited operational savings, although some, such as secondary glazing, had a comparable impact to alternative measures (Table 8.4). The heating setting adjustment measures had no embodied impact while they had significant potential to make operational savings, highlighting the benefits of encouraging participants to make behavioural changes as these will also have no impact on heritage values. It therefore appears that measures that are more suitable for vernacular buildings may also have low embodied carbon.

Table 8.6: Average, maximum and minimum embodied carbon emissions of retrofit measures over fifty-year lifespan across the case studies

Retrofit measures	Average embodied carbon ($kgCO_2e$)	Embodied min	Embodied max	Average biogenic ($kgCO_2e$)	Biogenic min	Biogenic max
Loft insulation: for cold roofs						
Natural material: Cosywool	**168.5**	8	449	**142.9**	5	408
Standard material: Supersoft	**201.7**	9	545	**N/A**	N/A	N/A
Technical material: Ultrawool	**274.4**	12	751	**221.3**	8	632
Ceiling insulation: for warm roofs						
Natural: Gutex thermoflex	**139.6**	23	253	**201.8**	11	478
Standard: Knauf rocksilk	**175.8**	25	336	**N/A**	N/A	N/A
Technical: Aerogel	**60.8**	11	124	**23.6**	0	53
Heritage: Diathonite	**640.5**	522	759	**0.35**	0.3	0.4
Internal wall insulation						
Natural: Gutex thermoroom	**660.8**	146	1,089	**1,242**	215	2,196
Standard: Knauf omnifit	**263.9**	70.8	502.6	**5.8**	0	33
Technical: Aerogel	**210.6**	58	438	**5.8**	0	33
Heritage: Diathonite	**2,115**	424	3,958	**4.8**	35	11
External wall insulation						

Retrofit measures	Average embodied carbon ($kgCO_2e$)	Embodied min	Embodied max	Average biogenic ($kgCO_2e$)	Biogenic min	Biogenic max
Natural: Gutex multitherm	**2,788**	805	4,821	**2,751**	756	4,730
Standard: Knauf rocksilk	**3,687**	1,052	6,366	**143.2**	39	246
Technical: Isohemp blocks	**3,827**	1,092	6,668	**3,059**	843	5,298
Solid ground floor insulation						
Natural: Geocell foamglass	**4,832**	1,724	11,775	**89.1**	2.9	383
Standard: Kingspan Kooltherm	**848.4**	276	1,532	**82.8**	0	372
Technical: aerogel bonded chipboard	**1,628**	553	3,028	**835.7**	316	1,913
Suspended ground floor insulation						
Natural: Thermofloc	**455**	152	792	**139**	48	224
Standard: Knauf omnifit	**482.9**	161	840	**N/A**	N/A	N/A
Technical: Aerogel bonded to chipboard	**901.1**	307	1,512	**486.3**	170	782
Window replacement						
Low e double glazed, hardwood frames	**2,163**	887	4,460	**N/A**	N/A	N/A
Low e double glazed, UPVC frames	**2,757**	1,081	6,393	**N/A**	N/A	N/A
Low e triple glazed, hardwood frames	**3,111**	1,174	6,071	**N/A**	N/A	N/A
Low e triple glazed, UPVC frames	**4,114**	1,394	8,344	**N/A**	N/A	N/A
Window additions						
Curtains	**188.7**	67	405	**36.7**	18	64
Interior shutters	**263.7**	85	508	**566.5**	151	1,139
Secondary glazing	**1,298**	151	3,273	**N/A**	N/A	N/A
Heating systems and renewable technologies						
EE boiler	**1,435**	1,017	1,819	**N/A**	N/A	N/A
Biomass pellet boiler	**4,336**	3,795	5,889	**N/A**	N/A	N/A

Retrofit measures	Average embodied carbon ($kgCO_2e$)	Embodied min	Embodied max	Average biogenic ($kgCO_2e$)	Biogenic min	Biogenic max
Solar PV: Maxeon 3 black	**4,982**	1,007	11,954	**N/A**	N/A	N/A
Solar thermal: evacuated tubes	**2,865**	1,772	4,798	**N/A**	N/A	N/A
GSHP: flat or borehole collector with underfloor heating	**10,308**	6,178	14,654	**N/A**	N/A	N/A
ASHP: high temperature with radiators	**6,536**	4,276	11,679	**N/A**	N/A	N/A
Other retrofit measures						
EE lighting: LED bulbs	**108.5**	0	309	**N/A**	N/A	N/A
Thick wall hangings	**542.5**	173	1,035	**30.8**	12	149
Smart heating controls: Wi-Fi controlled room thermostat	**3,657**	0	7,122	**N/A**	N/A	N/A
Draught proofing	**272.4**	169	506	**20.1**	9	26

The measures with predicted high operational savings therefore also appear to be amongst those with a high embodied carbon cost. It would appear that measures that may be more heritage sensitive and compatible with vernacular construction also generally have lower embodied carbon.

8.5 Lifecycle carbon of retrofit measures

Having identified the predicted annual operational savings using the Design Builder models and the initial and overall embodied carbon costs, it was possible to calculate the lifecycle carbon of the retrofit measures over the 50-year assessment period. The embodied carbon over fifty years includes any necessary replacements during this period for measures with shorter lifespans. The future decarbonisation of the electricity grid was taken into account when calculating the operational carbon savings over fifty years, using government decarbonisation predictions (BEIS 2020c) as described in section 3.5. The embodied carbon without biogenic carbon, separate biogenic carbon, operational carbon, and lifecycle carbon of all measures for each case study are shown and discussed below (Table 8.7-8.23). The measures in each table have comparative colour coding as above. Embodied costs and biogenic storage are shown as positive numbers while operational savings and lifecycle savings are shown as negative numbers because they (nearly always) result in overall carbon reductions.

For loft insulation it can be seen that the technical material makes the greatest saving for five of the cases and the natural material for four (Table 8.7). There is only a limited difference between the different materials however. Loft insulation makes the greatest difference for CS1, who has the lowest current insulation levels and an inefficient heating system which means that any improvements save a large amount of absolute carbon. For CS2 in contrast, who already have significant loft insulation, the embodied costs outweigh the carbon savings, meaning that additional loft insulation would actually increase lifecycle carbon for this case. CS11, CS12 and CS13 do not have cold roofs so this measure is not applicable to them.

Table 8.7: Loft insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e-1											
	Cosy-wool E	Cosy-wool B	Cosy-wool O	Cosy-wool L	Super-soft E	Super-soft O	Super-soft L	Ultra-wool E	Ultra-wool B	Ultra-wool O	Ultra-wool L
CS1	449	408	-26,139	-25,690	545	-25,764	**-25,230**	751	632	-27,114	-26,363
CS2	39	16	-19.7	19	43	-19.7	23.2	51	24	-21.9	29
CS3	8	5	-432.7	-425	9	-432.7	**-424**	12	8	-442.2	-430
CS5	232	200	-2,500	-2,268	278	-2450	**-2,177**	380	310	-2600	-2,220
CS6	346	308	-8,600	-8,254	416	-8500	**-8,091**	573	478	-8950	-8,377
CS7	155	119	-700	-545	183	-550	**-370**	244*	184	-175	69
CS8	69	51	-331.7	-263	81	-322.7	**-243**	107	78	-359.2	-252
CS9	70	55	-700	-630	83	-700	**-618**	111	85	-780	-669
CS11											
CS12											
CS13	100	79	-2,050	-1,950	119	-2000	**-1,883**	159	122	-2200	-2,041
CS14	217	188	-1,760	-1,543	260	-1,671	**-1,415**	356	292	-1,804	-1,448
CS15											
Note	*This operational value for Ultrawool for CS7 is an outlier. Contrary to expectations and the input material values, the model predicted lower savings for this material than for the Cosywool or Supersoft. The modelling was re-run several times and a number of possible causes were explored but it was not possible to identify the reason for this result. This value should therefore be considered an outlier and treated with caution, thus also effecting the lifecycle value for this material for CS7. It does not meaningfully affect the broader results.										

Only five cases currently have uninsulated warm roofs where ceiling insulation is applicable, these are over kitchens (CS5, CS8), for the main house (CS11 and CS14) and for an uninsulated bay window (CS9) (Table 8.8). Ceiling insulation makes the greatest difference for CS14 over their kitchen and upstairs landing and could also have a role in reducing the overheating of the landing roof as they are the only case that identified discomfort in summer. The natural insulation is better for both CS8 and CS14 while the standard insulation makes greater savings for CS5. Insulation to CS9's bay window does not make a useful difference while insulation for CS11's main roof increases, rather than reduces lifecycle carbon. This result is likely to be influenced by the fact that they do not heat their first floor, meaning the insulation has a limited effect.

Table 8.8: Ceiling insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e															
	Gutex/ Cosy-wool E	Gutex/ Cosy-wool B	Gutex/ Cosy-wool O	Gutex/ Cosy-wool L	Knauf/ Super-soft E	Knauf/ Super-soft O	Knauf/ Super-soft L	Aerogel/ Ultra-wool E	Aerogel /Ultra-woolB	Aerogel /Ultra-wool O	Aerogel/ Ultra-wool L	Diatho-nite E	Diatho -nite B	Diatho-nite O	Diatho-nite L
CS1															
CS2															
CS3															
CS5	117	90	-1,950	**-1,833**	128	-2050	**-1,922**	11	48	-1600	**-1,489**				
CS6															
CS7															
CS8	127	105	-10,298	**-10,171**	146	-10,298	**-10,152**	124	53	-8,558	**-8,434**				
CS9	23	11	-25	**-2**	25	-10	**15**	31	17	-20	**11**				
CS11	253	478	-75	**178**	336	-75	**261**	73	0	-50	**23**	759	0.4	-55	**704**
CS12															
CS13															
CS14	178	325	-11,806	**-11,628**	244	-11,933	**-11,689**	65	0	-8,533	**-8,468**	522	0.3	-8,833	**-8,311**
CS15															
Note	Some of these roofs include both sloped and flat ceilings, for the flat ceilings the same insulation as used for lofts is utilised														

For internal wall insulation the standard mineral wool makes the greatest lifecycle savings for 11 of the 13 case studies while aerogel makes the greatest savings for CS7 and CS11 (Table 8.9). However if the biogenic carbon storage were included in the embodied carbon, then the natural wood fibre insulation would make the greatest lifecycle savings for all cases. Internal wall insulation is one of only two measures, the other being Solar PV, that make lifecycle savings for CS11. The remaining measures all increase their lifecycle emissions because their operational carbon emissions are so low to begin with that any savings do not outweigh the embodied costs. The heritage material, dithionite cork lime plaster does make lifecycle savings for all of the cases except CS11, but these are clearly lower than the other materials. However, it may be more suitable for some cases because the lime would follow the current contours of the walls better than more solid insulation materials, thus potentially retaining greater character. The aerogel insulation, meanwhile, being only 20mm thick, might be suitable for those cases concerned about space loss (CS2, CS5, CS9, CS12).

Table 8.9: Internal wall insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e																
	Gutex E	Gutex B	Gutex O	Gutex L	Knauf E	Knauf B	Knuaf O	Knauf L	Aerogel E	Aerogel B	Aerogel O	Aerogel L	Diatho-nite E	Diatho-nite B	Diatho-nite O	Diatho-nite L
CS1	764	1,533	-131,568	-130,804	268	2	-136,670	-136,402	202	2	-133,670	-133,468	2,634	3.6	-124,918	-122,284
CS2	511	980	-12,630	-12,119	200.2	0	-13,104	-12,904	158	0	-12,854	-12,696	1,800	1	-12,095	-10,295
CS3	870	1,376	-26,527	-25,657	433	31	-27,779	-27,346	375	31	-27,077	-26,702				
CS5	1,082	2,196	-68,718	-67,636	375.4	0	-72,318	-71,943	281	0	-70,668	-70,387	3,958	2.3	-65,215	-61,257
CS6	983	1,895	-75,965	-74,982	386.4	9	-79,118	-78,732	305	9	-77,265	-76,960				
CS7	1,089	2,162	-47,224	-46,135	393.6	0	-46,955	-46,561	301	0	-47,089	-46,788	3,920	2.3	-43,193	-39,273
CS8	536	1,057	-33,311	-32,775	194.2	0	-35,111	-34,917	149	0	-34,111	-33,963	1,917	1.1	-31,311	-29,394
CS9	240	441	-19,637	-19,397	93.8	0	-20,339	-20,245	75	0	-20,248	-20,173	817	0.5	-18,785	-17,968
CS11	187	346	-500	-313	72.8	0	-500	-427	58	0	-500	-442	638	0.4	-450	188
CS12	146	215	-8,002	-7,856	70.8	0	-8,202	-8,131	62	0	-8,102	-8,040	424	0.2	-7,652	-7,228
CS13	964	1,504	-47,763	-46,799	502.6	33	-49,665	-49,162	438	33	-48,663	-48,225	2,750	35	-45,313	-42,563
CS14	622	1,263	-29,222	-28,600	226.3	0	-30,383	-30,157	172	0	-29,681	-29,509	2,290	1.3	-27,826	-25,536
CS15	596	1,182	-38,011	-37,415	213.1	0	-39,613	-39,400	162	0	-38,761	-38,599				

The external wall insulation can be seen to make greater savings than the internal wall insulation, which would be expected given that the external insulation is twice as thick (100-120mm rather than 20-50mm) (Table 8.10). The standard and natural materials each make the greatest savings for six of the case studies, while all EWI materials increase the lifecycle carbon for CS11. The difference between the two materials is quite small over fifty years (300-2,000kgCO_2e) but if biogenic storage were included then the natural material would lead to the greatest savings for all cases and would even make a small carbon saving (365kgCO_2e) for CS11. The majority of the cases (CS1, CS2, CS3, CS5, CS9, CS11, CS13, CS15) have bare stone facades however and are unlikely to find EWI acceptable.

Table 8.10: External wall insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e												
	Gutex E	Gutex B	Gutex O	Gutex L	Knauf E	Knauf B	Knuaf O	Knauf L	Isohemp E	Isohemp B	Isohemp O	Isohemp L
CS1	3,331	3,316	-160,972	-157,641	4,415	173	-164,722	-160,307	4,602	3,711	-145,870	-141,268
CS2	2,156	2,121	-14,180	-12,024	2,850	110	-14,421	-11,571	2,968	2,374	-12,409	-9,441
CS3	2,908	2,902	-33,992	-31,084	3,856	151	-34,744	-30,888	4,024	3,245	-30,531	-26,507
CS5	4,717	4,730	-77,011	-72,294	6,263	246	-78,911	-72,648	6,506	5,298	-68,509	-62,003
CS6	4,821	4,730	-88,268	-83,447	6,366	246	-90,718	-84,352	6,668	5,298	-79,815	-73,147
CS7	4,735	4,657	-66,259	-61,524	6,257	243	-67,922	-61,665	6,517	5,207	-57,889	-51,372
CS8	2,293	2,292	-39,661	-37,368	3,042	119	-41,313	-38,271	2,959	2,292	-35,011	-32,052
CS9	990	975	-21,927	-20,937	1,309	51	-22,575	-21,266	1,359	1,100	-20,122	-18,763
CS11	805	756	-365	440	1,052	39	-370	682	1,092	843	-330	762
CS12	854	829	-10,952	-10,098	1,124	43	-11,272	-10,148	1,156	935	-9800	-8,644
CS13	3,253	3,170	-57,850	-54,597	4,289	165	-58,938	-54,649	4,496	3,538	-52,390	-47,894
CS14	2,811	2,731	-34,783	-31,972	3,703	142	-35,370	-31,667	3,874	3,062	-31,804	-27,930
CS15	2,567	2,560	-44,613	-42,046	3,404	133	-45,513	-42,109	3,531	2,860	-40,646	-37,115

Solid floor insulation made lifecycle carbon savings for seven of the case studies (Table 8.11), although this was influenced by the simulation errors for the operational modelling. Nonetheless the natural material had greater embodied emissions because it involved the replacement of the whole floor, while the standard and technical measures installed the insulation above the subfloor surface. Solid floor insulation made the greatest difference for CS1 and CS12 because they both have partial underfloor heating with limited insulation; improving the insulation therefore increased the efficiency of this system. The standard insulation had the greatest savings for most of the cases.

Table 8.11: Solid floor insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e												
	Geocell E	Geocell B	Geocell O	Geocell L	King-span E	King-span B	King-span O	King-span L	Aerogel E	Aerogel B	Aerogel O	Aerogel L
CS1	3,076	3.8	-137,131	-134,055	276	0	-133,781	-133,505	794	500	-120,878	-120,084
CS2	2,806	3.4	-498	2,308	1,029	0	-555	474	1,482	438	-473	1,009
CS3	7,407	307	-1,116	6,291	1,197	293	6.6	1,204	2,350	1,411	68	2,418
CS5	1,724	68	2,300	4,024	294	66	1,450	1,744	553	316	1,350	1,903
CS6	9,429	383	-14,979	-5,550	1,532	372	-13,899	-12,367	2,995	1,785	-7,852	-4,857
CS7	11,775	15	-4,985	6,790	1,047	0	-7,550	-6,503	3,028	1,913	-3,939	-911
CS8	2,352	2.9	-4,079	-1,727	859	0	-4,059	-3,200	1,247	375	-1,832	-585
CS9	3,366	4.1	-2,492	847	1,229	0	-2,369	-1,140	1,786	538	-805	981
CS11	2,671	3.3	90	2,761	976	0	95	1,071	1,416	425	55	1,471
CS12	3,001	118	-13,356	-10,355	508	115	-17,213	-16,705	961	553	-13,006	-12,045
CS13	6,567	8.1	-1,400	5,167	599	0	-900	-301	1,700	1,063	-800	900
CS14	3,815	152	-147	3,668	635	148	248	883	1,218	711	458	1,676
CS15												

Suspended floor insulation made limited savings for those cases who had suspended floors over unheated cellars (Table 8.12). Savings are much lower than those for solid floors, which generally make up a larger area of participants' homes. Challenges with the operational modelling invalidated the results for CS1 and CS5. Meanwhile the technical aerogel failed to make savings for CS9, CS14 and CS15 because the embodied carbon outweighed the operational savings. The natural and standard insulation materials made very similar lifecycle savings for this measure and also had similar embodied carbon. However the natural material is likely to be more compatible with the construction of vernacular buildings and also makes use of recycled materials, which is compatible with circular economy principles.

Table 8.12: Suspended floor insulation lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e											
	Thermo-floc E	Thermo-floc B	Thermo-floc O	Thermo-floc L	Knauf E	Knauf O	Knuaf L	Aerogel E	Aerogel B	Aerogel O	Aerogel L
CS1	424	151	16,000	16,424	453	16,100	16,553	906	527	11,800	12,706
CS2											
CS3											
CS5	387	102	1,700	2,087	406	1,700	2,106	714	357	1,150	1,864
CS6	152	48	-1,250	-1,098	161	-1,250	-1,089	307	170	-900	-593
CS7											
CS8	576	158	-2,200	-1,624	607	-2,246	-1,639	1,084	554	-1,092	-8
CS9	408	139	-1,490	-1,082	438	-1,527	-1,089	857	487	-365	492
CS11											
CS12											
CS13											
CS14	446	151	-1,065	-619	475	-1,093	-618	928	527	-732	196
CS15	792	224	-2,650	-1,858	840	-2,700	-1,860	1,512	782	-950	562

Window additions can be seen to make greater lifecycle savings than window replacements for seven of the 13 case studies (Table 8.13 and Table 8.14). In fact, from a lifecycle perspective, all four window replacement options actually increased lifecycle carbon for three of the cases (CS2, CS7, CS11), although window additions also increased lifecycle carbon for CS11. If biogenic carbon were considered then shutters would provide greater savings than secondary glazing for CS8 and CS15, as well as making a small lifecycle saving for CS11. The timber framed window replacements would also have a biogenic storage value, but this data was not available for the window replacement products.

Triple glazed timber framed windows make the greatest savings for nine of the 13 cases when only the window replacements are considered, while double glazed timber framed windows make the greatest savings for CS15. The UPVC windows have higher embodied carbon and lower operational performance across both window types leading to lower lifecycle savings than the timber framed windows. Therefore, in addition to their adverse heritage impact, UPVC windows should not be preferred for their energy or carbon lifecycle performance.

Table 8.13: Window replacement lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e												
	Double wood E	Double wood O	Double wood L	Double UPVC E	Double UPVC O	Double UPVC L	Triple wood E	Triple wood O	Triple wood L	Triple UPVC E	Triple UPVC O	Triple UPVC L
CS1	4,277	-7,271	-2,994	6,393	-6,861	-468	6,071	-12,158	-6,087	8,344	-11,763	-3,419
CS2	932	-528	404	1,092	-498	594	1,220	-432	788	1,406	-406	1,000
CS3	2,752	-10,936	-8,184	4,126	-10,726	-6,600	3,868	-12,477	-8,609	5,343	-12,282	-6,939
CS5	1,908	-4,251	-2,343	2,694	-4,169	-1,475	2,635	-5,821	-3,186	3,485	-5,701	-2,216
CS6	4,460	-7,580	-3,120				5,958	-11,097	-5,139	7,880	-10,787	-2,907
CS7							4,297	857	5,154	5,632	1,152	6,784
C08	2,995	-14,424	-11,429	4,294	-14,184	-9,890	4,138	-18,451	-14,313	5,541	-18,131	-12,590
CS9	1,424	-9,294	-7,870	1,980	-9,237	-7,257	2,516	-12,281	-9,765	3,341	-12,089	-8,748
CS11	922	-52	870	1,260	-50	1,210	1,258	-52	1,206	1,627	-47	1,580
CS12	887	-1,408	-521	1,081	-1,373	-292	1,174	-2,418	-1,244	1,394	-2,338	-944
CS13	2,243	-9,961	-7,718	3,095	-9,806	-6,711	3,039	-11,387	-8,348	3,963	-11,232	-7,269
CS14	1,289	-2,187	-898	1,763	-2,117	-354	1,761	-4,187	-2,426	2,277	-4,102	-1,825
CS15	1,870	-2,803	-933	2,550	-2,683	-133	2,508	-3,067	-559	3,245	-3,042	203

For window additions, shutters provide greater lifecycle savings for six of the cases (CS1, CS2, CS5, CS6, CS7, CS12), and secondary glazing for six cases (CS3, CS8, CS9, CS13, CS14, CS15). The level of overall savings is quite varied as it is affected by the current window types and orientations of the buildings as well as the wall to window ratio. Both CS2 and CS3 for example, have single glazed windows, but CS3 has a much higher proportion of glazing than CS2, resulting in greater lifecycle savings from window additions.

Table 8.14: Window additions lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e											
	Curt-ains E	Curt-ains B	Curt-ains O	Curt-ains L	Shutters E	Shutters B	Shutters O	Shutters L	Secondary E	Secondary O	Secondary L
CS1	405	64	-3,245	-2,840	508	1,139	-4,203	-3,695	1,371	-4,439	-3,068
CS2	109	18	-180	-71	114	207	-940	-826	928	-1,493	-565
CS3	161	40	-2,050	-1,889	357	803	-7,375	-7,018	3,273	-13,348	-10,075
CS5	92	23	-1,007	-915	244	522	-4,356	-4,112	1,353	-5,291	-3,938
CS6	323	56	-2,100	-1,777	366	808	-3,650	-3,284			
CS7	242	42	-1,142	-900	398	843	-2,224	-1,826	211	-1,050	-839
CS8	263	49	-1,050	-787	378	822	-4,600	-4,222	1,765	-6,127	-4,362
CS9	200	40	-3,362	-3,162	233	500	-6,211	-5,978	1,194	-9,867	-8,673
CS11	67	19	-4	63	116	242	-54	62	972	-95	877
CS12	106	22	-550	-444	85	151	-900	-815	151	-300	-149
CS13	164	35	-2,728	-2,564	269	572	-5,810	-5,541	911	-8,672	-7,761
CS14	135	30	-368	-233	163	339	-1,852	-1,689	1,470	-4,453	-2,983
CS15	186	39	-958	-772	197	417	-1,933	-1,736	1,973	-3,812	-1,839

Biomass boilers make much greater carbon savings than EE boiler replacement because of the difference in operational fuel emissions (Table 8.15). The level of savings for biomass are lower for CS2, who currently use electric heating, because of grid decarbonisation. Biomass boilers make slightly greater lifecycle carbon savings than air or ground source heat pumps for all cases (Table 8.16). As seen from the operational modelling however, ASHPs and GSHPs are likely to make much greater *energy* savings than biomass, which will reduce energy costs to residents and may make measures more financially viable, as well as reducing overall national energy demand. GSHPs make the greatest savings for eight of the cases (CS1, CS3, CS5, CS6, CS7, CS8, CS9, S12) while ASHPs make the greatest savings for CS2, CS13, CS14 and CS15. None of these measures make lifecycle savings for CS11 and replacing existing boilers with only slightly more efficient boilers does not make lifecycle savings for CS12 and CS14.

Table 8.15: EE and biomass boiler lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e						
	EE boiler E	EE boiler O	EE boiler L	Biomass boiler E	Biomass boiler O	Biomass boiler L
CS1	1,819	-219,550	**-217,731**	3,974	-451,750	**-447,776**
CS2				5,889	-15,888	**-9,999**
CS3				3,795	-144,500	**-140,705**
CS5				3,827	-162,350	**-158,523**
CS6	1,021	-3,350	**-2,329**	3,924	-274,500	**-270,576**
CS7	1,755	-77,850	**-76,095**	3,910	-248,300	**-244,390**
CS8				3,825	-199,050	**-195,225**
CS9				4,241	-106,800	**-102,559**
CS11				5,687	-2,514	**3,173**
CS12	1,017	-1,000	**17**	3,921	-80,550	**-76,629**
CS13				4,751	-162,950	**-158,199**
CS14	1,561	-1,400	**161**	4,465	-115,250	**-110,785**
CS15				4,164	-104,000	**-99,836**

Table 8.16: Air and ground source heat pump lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e						
	GSHP E	GSHP O	GSHP L	ASHP E	ASHP O	ASHP L
CS1	8,059	-453,178	**-445,119**	6,930	-450,920	**-443,990**
CS2	6,178	-7,122	**-944**	5,502	-10,980	**-5,478**
CS3	8,285	-140,082	**-131,797**	6,940	-135,214	**-128,274**
CS5	13,875	-162,266	**-148,391**	7,551	-151,883	**-144,332**
CS6	10,781	-271,570	**-260,789**	7,549	-254,746	**-247,197**
CS7	14,007	-245,542	**-231,535**	11,679	-243,048	**-231,369**
CS8	13,801	-197,832	**-184,031**	5,793	-185,564	**-179,771**
CS9	7,710	-106,495	**-98,785**	5,387	-101,146	**-95,759**
CS11	7,427	-1,980	**5,447**	5,401	-344	**5,057**
CS12	6,883	-80,617	**-73,734**	4,276	-76,788	**-72,512**
CS13	14,654	-152,674	**-138,020**	6,311	-152,621	**-146,310**
CS14	14,164	-113,744	**-99,580**	6,551	-108,971	**-102,420**
CS15	8,190	-99,473	**-91,283**	5,102	-96,851	**-91,749**

The effect of grid decarbonisation can also be seen in the results for solar PV compared with solar thermal panels (Table 8.17). Solar thermal panels make greater lifecycle savings for 10 of the 13 cases, even though these solar PV figures include electricity exported to the grid. The solar thermal panels make significant savings for most cases because they replace energy from gas or oil which have high carbon emissions. If cases were to switch to lower carbon fuels, solar thermal panels would lead to less carbon savings. Solar PV, along with IWI are the only measures to make lifecycle savings for CS11 and even then, the solar PV savings are small over 50 years (38.4kgCO_2e/y).

Table 8.17: Solar PV and solar thermal lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e						
	Solar PV E	Solar PV O	Solar PV L	Solar Thermal E	Solar Thermal O	Solar Thermal L
CS1	9,863	-23,134	**-13,271**	2,257	-75,765	**-73,508**
CS2	3,986	-8,505	**-4,519**	2,320	-2,348	**-28**
CS3	3,033	-4,594	**-1,561**	4,798	-35,127	**-30,329**
CS5	5,332	-12,060	**-6,728**	2,281	-6,482	**-4,201**
CS6	8,052	-16,727	**-8,675**	3,287	-45,835	**-42,548**
CS7	11,954	-27,380	**-15,426**	2,318	-48,923	**-46,605**
CS8	4,423	-7,711	**-3,288**	4,490	-25,754	**-21,264**
CS9	1,007	-2,453	**-1,446**	2,288	-14,182	**-11,894**
CS11	3,049	-4,969	**-1,920**	1,772	-242	**1,530**
CS12	1,703	-2,633	**-930**	2,300	-11,766	**-9,466**
CS13	4,427	-7,359	**-2,932**	3,167	-18,356	**-15,189**
CS14	4,422	-6,313	**-1,891**	3,679	-22,296	**-18,617**
CS15	3,511	-7,727	**-4,216**	2,286	-21,834	**-19,548**

The LCA showed that replacing existing lighting with LEDs would use more carbon than leaving the existing lighting (Table 8.18). Even CS7, who already have all LED bulbs and were only modelled as having a behavioural change of not leaving lights on when there was sufficient daylight, had increased lifecycle carbon. The inclusion of grid decarbonisation contributed to the poor lifecycle performance of LED lightbulbs. This is because LED lights produce less heat and therefore slightly increase the use of fossil fuel heating systems, despite reducing electricity for lighting. As electricity decarbonises, the carbon from the electricity savings reduces, while the carbon increase from the heating remains the same. If the case studies used low carbon heating such as CS11, then the LED bulbs would be more likely to make operational savings over time. As a test, replacing the same number of existing bulbs with CFLs was also modelled, and based on manufacturer data, the CFLs were considered to be replaced twice as often as LEDs. This has no operational difference because the current bulbs are CFLs. It can be seen however that the LEDs have much higher embodied carbon than the CFLs. It would therefore appear that replacing working bulbs with LEDs is not a current carbon saving measure for the examined dwellings from a lifecycle perspective.

Table 8.18: LED lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e						
	EE Light E	EE Light O	EE Light L	CFL Light E	CFL Light O	CFL Light L
CS1	136	678	814	136	0	136
CS2						
CS3	184	379	563	184	0	184
CS5	152	1,121	1,273	152	0	152
CS6	61	466	527	61	0	61
CS7	0	204	204			
CS8	199	2136	2,335	199	0	199
CS9	179	5,131	5,310	179	0	179
CS11	87	-31	56	87	0	87
CS12						
CS13	104	1,116	1,220	104	0	104
CS14						
CS15	309	1,396	1,705	309	0	309

Wall hangings made limited lifecycle savings for 10 of the 13 cases (Table 8.19). Operational savings for CS11 and CS12 were outweighed by the embodied costs. The wall hangings for CS9 were modelled in their cellar living room and failed to make operational savings in the simulation. As with the floor insulation this is likely to relate to an error in the ground definition. This measure may make only limited carbon savings but might have a positive effect on residents' comfort which is not visible in the modelling. This is also true of the draught proofing which made larger but still modest carbon savings for all of the cases except CS11 (Table 8.20).

Table 8.19: Wall hanging lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e				
	Wallhanging E	Wallhanging B	Wallhanging O	Wallhanging L
CS1	909	28	-5,050	**-4,141**
CS2	230	13	-326	**-96**
CS3	493	21	-807	**-314**
CS5	722	25	-1,450	**-728**
CS6	962	29	-6,600	**-5,638**
CS7	445	19	-3,750	**-3,305**
CS8	558	22	-947	**-389**
CS9	374	18	797	**1,171**
CS11	173	12	-100	**73**
CS12	269	14	-230	**39**
CS13	1,035	30	-2,844	**-1,809**
CS14	478	20	-1,543	**-1,065**
CS15	405	149	-2,000	**-1,595**

Table 8.20: Draught proofing lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e				
	Draught proofing E	Draught proofing B	Draught proofing O	Draught proofing L
CS1	264	22	-9,792	**-9,528**
CS2	262	20	-798	**-536**
CS3	213	19	-4,918	**-4,705**
CS5	255	20	-4,750	**-4,495**
CS6	350	20	-9,600	**-9,250**
CS7	506	26	-4,386	**-3,880**
CS8	268	25	-6,887	**-6,619**
CS9	201	9	-2,897	**-2,696**
CS11	169	17	-45	**124**
CS12	194	19	-3,557	**-3,363**
CS13	311	19	-4,000	**-3,689**
CS14	279	19	-3,405	**-3,126**
CS15	269	26	-3,300	**-3,031**
Note	This is for the combination of draught proofing measures identified above. The operational effect is modelled as a 20% reduction in whole house infiltration (based on literature and expert interviews, see Appendix I.4)			

The smart heating controls made lifecycle savings for all the applicable case studies (Table 8.21), having the greatest savings for CS15, CS7 and CS6 who have the largest buildings amongst the cases and for whom separately controllable rooms have the most impact. The controls have significant embodied carbon because one control unit is modelled for each room. Data was not available for a more efficient system so it may be that the embodied carbon figures presented here are higher than they would be in reality for this measure.

Table 8.21: Smart heating controls lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e			
	Smart control E	Smart control O	Smart control L
CS1	4,398	-16,577	**-12,179**
CS2			
CS3	5,257	-28,865	**-23,608**
CS5	4,000	-24,724	**-20,724**
CS6	5,288	-52,700	**-47,412**
CS7	7,122	-62,326	**-55,204**
CS8	4,871	-19,407	**-14,536**
CS09	3,140	-45,813	**-42,673**
CS11			
CS12	2,722	-5,242	**-2,520**
CS13	3,579	-46,883	**-43,304**
CS14	4,022	-15,881	**-11,859**
CS15	3,136	-181,154	**-178,018**
Note:	Controls were not applicable for CS2 who already has individually controlled storage heaters, or for CS11 who only heats one room		

The adjustments to heating settings had the potential to make significant lifecycle carbon savings, particularly reducing heating set points (Table 8.22), although no bedroom heating also made significant savings for some cases (Table 8.23). This is partly because they have no embodied carbon cost. For heating temperature reduction, clearly greater reductions lead to greater lifecycle savings. These measures also make lifecycle reductions for CS11. Unlike some other measures, these changes would also save related amounts of energy as well as carbon, thus reducing fuel bills. Based on participants' comments, if other measures which increase comfort could be installed, heating setting adjustments could potentially be acceptable.

Table 8.22: Heating set point reduction lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e												
	Rd heat 0.5 E	Rd heat 0.5 O	Rd heat 0.5 L	Rd heat 1 E	Rd heat 1 O	Rd heat 1 L	Rd heat 1.5 E	Rd heat 1.5 O	Rd heat 1.5 L	Rd heat 2 E	Rd heat 2 O	Rd heat 2 L
CS1	0	-45,124	**-45,124**	0	-87,018	-87,018	0	-126,224	-126,224	0	-162,933	-162,933
CS2	0	-1,999	**-1,999**	0	-3,882	-3,882	0	-5,649	-5,649	0	-7,319	-7,319
CS3	0	-8,368	**-8,368**	0	-16,381	-16,381	0	-24,009	-24,009	0	-31,290	-31,290
CS5	0	-11,514	**-11,514**	0	-22,684	-22,684	0	-33,448	-33,448	0	-43,783	-43,783
CS6	0	-17,654	**-17,654**	0	-34,399	-34,399	0	-50,615	-50,615	0	-66,130	-66,130
CS7	0	-20,108	**-20,108**	0	-41,753	-41,753	0	-63,436	-63,436	0	-81,137	-81,137
CS8	0	-12,744	**-12,744**	0	-24,976	-24,976	0	-36,693	-36,693	0	-47,968	-47,968
CS9	0	-9,532	**-9,532**	0	-17,685	-17,685	0	-24,427	-24,427	0	-30,793	-30,793
CS11	0	-275	**-275**	0	-540	-540	0	-800	-800	0	-1,015	-1,015
CS12	0	-5,849	**-5,849**	0	-11,517	-11,517	0	-16,806	-16,806	0	-21,828	-21,828
CS13	0	-12,514	**-12,514**	0	-24,269	-24,269	0	-36,903	-36,903	0	-48,868	-48,868
CS14	0	-6,427	**-6,427**	0	-12,789	-12,789	0	-19,003	-19,003	0	-25,115	-25,115
CS15	0	-7,272	**-7,272**	0	-14,124	-14,124	0	-20,699	-20,699	0	-26,826	-26,826

Table 8.23: No bedroom and no holiday heating lifecycle carbon savings for each case over 50-years

Embodied (E), Biogenic (B), Operational (O) and Lifecycle (L) in kgCO2e						
	No bed heat E	No bed heat O	No bed heat L	No holiday heat E	No holiday heat O	No holiday heat L
CS1	0	-32,157	-32,157	0	-1,575	-1,575
CS2	0	-10,903	-10,903	0	-1,013	-1,013
CS3	0	-23,141	-23,141			
CS5	0	-20,709	-20,709			
CS6	0	-36,014	-36,014			
CS7	0	-11,893	-11,893			
CS8	0	-18,017	-18,017	0	-1,237	-1,237
CS9	0	-3,820	-3,820			
CS11						
CS12	0	-6,372	-6,372			
CS13	0	-19,717	-19,717			
CS14	0	-12,751	-12,751			
CS15	0	-13,712	-13,712			

The average lifecycle savings across the case studies were also calculated and ordered by the greatest savings (Table 8.24). The four measures that make the greatest average savings are all heating system replacements, followed by wall insulation and heating reduction. Only the biomass boiler, GSHP, ASHP and EE boiler make average reductions resulting in more than a tonne of carbon saved each year over fifty years. The difference in the savings that measures make for individual case studies is very varied, from increasing the lifecycle carbon to making substantial reductions.

Solar thermal panels, on average, made significantly greater savings than solar PV. Timber window replacements make average savings greater than windows additions, while shutters and secondary glazing make greater savings than the UPVC window replacements. As seen above however, the most effective measure varied for individual cases. LED bulbs and all suspended floor insulation materials are the only changes that on average increase lifecycle carbon. The suspended floor insulation is affected by the operational modelling challenges for CS1 and CS5's suspended floors.

Table 8.24: Average, maximum and minimum lifecycle carbon savings for measures across cases in order of greatest savings

Retrofit measure	Average lifecycle carbon	Life min	Life max
Biomass pellet boiler	**-154,771**	3,173	-447,776
GSHP	**-146,034**	5,447	-445,119
ASHP: high temperature with radiators	**-144,931**	5,057	-443,990
EE boiler	**-59,195**	161	-217,731
EWI standard: Knauf	**-47,605**	68	-160,307
EWI natural: Gutex	**-47,276**	440	-157,641
Reduce heating: 2°C	**-45,770**	-1,015	-162,933
IWI standard: Knauf	**-42,794**	-427	-136,402
IWI technical: Aerogel	**-41,996**	-442	-133,468
EWI technical: Isohemp blocks	**-41,183**	762	-141,268
IWI natural: Gutex	**-40,807**	-313	-130,804
IWI heritage: Diathonite	**-35,561**	188	-122,284
Reduce heating: 1.5°C	**-35,286**	-800	-126,224
Smart heating controls: Wi-Fi room thermostat	**-34,772**	0	-178,018

Retrofit measure	Average lifecycle carbon	Life min	Life max
Reduce heating: 1°C	**-24,001**	-540	-87,018
Solar thermal: evacuated tubes	**-22,436**	1,530	-73,508
No heated bedrooms	**-17,434**	-3,820	-36,014
Solid Floor insulation standard: Kingspan	**-14,029**	1,744	-133,505
Reduce heating: 0.5°C	**-12,260**	-275	-45,124
Solid Floor insulation technical: aerogel bonded chipboard	**-10,677**	2,418	-120,084
Solid floor insulation natural: Geocell	**-9,986**	6,790	-134,055
Solar PV: Maxeon 3 black	**-5,139**	-930	-15,426
Ceiling insulation standard: Knauf	**-4,697**	261	-11,689
Ceiling insulation natural: Gutex	**-4,691**	178	-11,628
Draught proofing	**-4,215**	124	-9,528
Loft insulation technical: Ultrawool	**-4,170**	69	-26,363
Loft insulation natural: Cosywool	**-4,155**	19	-25,690
Loft insulation standard: Supersoft	**-4,043**	23.2	-25,230
Window replacement: Low e triple glazed, hardwood frames	**-4,041**	5,154	-14,313
Ceiling insulation heritage: Diathonite	**-3,804**	704	-8,311
Window replacement: Low e double glazed, hardwood frames	**-3,728**	870	-11,429
Ceiling insulation technical: Aerogel	**-3,671**	23	-8,468
Window alterations: Secondary glazing	**-3,615**	877	-10,075
Window alterations: Interior shutters	**-3,129**	62	-7,018
Window replacement: Low e triple glazed, UPVC frames	**-2,868**	6,784	-12,590
Window replacement: Low e double glazed, UPVC frames	**-2,852**	1,210	-9,890
Thick wall hangings	**-1,369**	1,171	-5,638
No holiday heating	**-1,275**	-1,013	-1,575
Window alterations: Curtains	**-1,253**	63	-3,162
EE lighting: LED bulbs	**1,077**	5,310	56
Suspended floor insulation natural: Thermofloc	**1,747**	16,424	-1,858
Suspended floor insulation standard: Knauf	**1,766**	16,553	-1,860
Suspended floor insulation technical: Aerogel bonded to chipboard	**2,174**	12,706	-593

Another way of visualising the embodied costs of retrofit is by identifying how many years of operational savings it will take to recover the embodied costs of each measure and what percentage of the operational savings is required to offset these embodied costs (Table 8.25). This calculation is equivalent to the commonly used financial calculations of payback periods. CS11 was excluded from this analysis as the vast majority of measures take longer than fifty years for the operational savings to outweigh the embodied costs. The averages for all materials for roof, floor, and internal and external wall insulation are combined to save space (see the full embodied, operational and lifecycle results for each insulation material above in Table 8.7, Table 8.8, Table 8.9, Table 8.10, Table 8.11, and Table 8.12).

It can be seen from this assessment that the overall contribution of the embodied carbon costs to the lifecycle balance is the equivalent of 15 years, or 31%, of the operational carbon savings over 50 years across all the retrofit measures, except solid floor insulation which is excluded due to the error previously identified in the operational modelling.

The embodied costs of IWI and biomass boilers are recovered the most quickly (1 year and 3 years respectively) because they have medium embodied costs but are predicted to lead to significant operational savings. Meanwhile window replacements of triple glazing with UPVC (58 years, 117%) and wooden frames (50 years, 100%) do not make lifecycle savings on average across the case studies as it takes longer than fifty years for the operational savings to offset the embodied costs, although they do make lifecycle savings for some individual cases. For both double and triple glazing, the UPVC frames take 8-10 years longer to offset the embodied carbon than the wooden framed equivalents because the UPVC has both higher embodied costs and lower operational savings. Solar PV (26 years, 53%) also takes on average 15 years longer than solar thermal panels (11 years, 22%) for the operational savings to offset the embodied costs. For the categories, window replacement (44 years) has the highest payback time, followed, by energy system measures (13 years), insulation materials (12 years) and other retrofit measures (11 years). Window additions collectively have the shortest average payback time at 10 years, although shutters take four years, curtains ten and secondary glazing 15 years.

Table 8.25 Average number of years of operational savings to recover the embodied costs and average percentage of operational savings required to offset embodied costs

Measures and categories	Average across all cases excluding CS11	
	Years of operational savings to cover the embodied costs	% of operational savings to offset embodied costs
Loft insulation	18	36%
Ceiling insulation	16	32%
Internal wall insulation	1	3%
External wall insulation	4	9%
Solid floor insulation	388	776%
Suspended floor insulation	19	39%
Window replacements		
Double glazed wood frames	28	56%
Double glazed UPVC frames	38	76%
Triple glazed wood frames	50	100%
Triple glazed UPVC frames	58	117%
Window Additions		
Curtains	10	20%
Shutters	5	10%
Secondary glazing	16	32%
Heating systems and renewable technologies		
EE Boiler	25	50%
Biomass boiler	3	6%
Solar PV	26	53%
Solar thermal	11	22%
GSHP[1]	7	14%
ASHP[1]	4	8%
Other retrofit measures		
EE lighting	N/A because LEDs are not predicted to make operational savings	
Thick wall hangings	18	37%
Smart heating controls	9	18%
Draught proofing	4	8%
Averages for categories of measures		

Measures and categories	Average across all cases excluding CS11	
	Years of operational savings to cover the embodied costs	% of operational savings to offset embodied costs
Insulation materials (excluding solid floor insulation)	12	23%
Window replacements	44	87%
Window additions	10	20%
Energy system measures	13	25%
Other retrofit measures	11	21%
Overall (excluding solid floor insulation)	15	31%
Note: Due to grid decarbonisation, the operational savings will be higher in earlier years. However for simplicity, in this calculation the total operational savings have been divided evenly across the fifty assessment years. 1 Note that there is particular uncertainty in the operational modelling parameters for GSHP and ASHP and more detailed modelling would be beneficial to increase the confidence in the operational savings and therefore in these pay back times		

Considering the percentages of operational savings required to offset the embodied costs, it is clear that, if embodied carbon is neglected and only operational carbon is calculated, the level of carbon reduction provided by retrofit will be significantly overestimated. It is also important to identify the embodied cost for each measure for each building so that lifecycle savings can be ensured, and maximised, through effective measure and material choices. It can therefore be seen that including embodied carbon and calculating the lifecycle impact of retrofit is critical to making significant carbon reductions.

8.6 Discussion

A detailed and dynamic modelling tool is required to provide a reasonable representation of the case studies buildings and their residents' behaviours. Neither of the two standard UK policy modelling tools investigated had the required capability to enable models to be developed that could be tailored to individual behaviours and calibrated to actual energy use. There were still issues with the Design Builder modelling around its lack of ability to model anything other than direct electric heating, challenges modelling window shutters, and difficulties with floor insulation results for some case studies. This model however provided a much better approximation of reality than the other two tools investigated, despite the implicit uncertainties relating to the assumptions required for the input data.

The operational modelling showed the importance of considering both energy and carbon impacts in an assessment, with some measures predicted to make greater carbon savings than they did energy savings and vice a versa. This may also have an effect on residents' experience of comfort in their buildings and their ability to meet energy costs. Switching to a low carbon heating system was found to make the greatest carbon savings. However in some cases this had a limited effect on the amount of energy used, thus failing to make the building more efficient and comfortable or to provide cost savings for residents which could help recoup the financial cost of retrofit measures. Measures that reduce both energy and carbon will therefore have a more beneficial overall effect.

The embodied assessment showed that those measures with the greatest predicted operational savings also appeared to be amongst those with the greatest embodied costs. Some synergies were found between measures with low embodied carbon and those with a limited heritage impact, such as window additions rather than window replacements, and natural materials more compatible with traditional construction. This supports other similar research findings (Historic England, 2020; Curtis, 2010). The time factor of emissions means that while operational savings are spread evenly over fifty years, the majority of the embodied impacts (apart from replacement and maintenance) take place at the beginning of the assessment period. Because the window of opportunity to reduce global carbon emissions to mitigate climate change is time limited, the embodied carbon emitted now is in some ways more important than the operational savings beyond the next 20 years. Options with lower initial emissions may therefore be preferable, even if they have slightly lower overall savings.

Measures which include higher levels of biogenic carbon storage potential may also be beneficial in this respect as they can be considered to ameliorate the initial embodied emissions, offsetting them for the lifespan of the measure, thus creating an emission time shift. If biogenic carbon is considered for shutters for example, it in fact outweighs the embodied emissions. Shutters may also be more acceptable to residents' heritage values and have reduced planning constraints for designated buildings when comparted with window replacement, as well as being likely to have a reduced financial cost.

Solar PV panels are more commonly installed than solar thermal however this research suggest that solar thermal panels in fact make much greater lifecycle carbon savings than solar PV if they are replacing or supplementing a carbon intensive heating system. This demonstrates the importance of considering context and of assessing the embodied and lifecycle carbon impact of retrofit as well as their operational effects. This is particularly critical because a number of measures failed to make lifecycle savings, despite making operational savings, actually leading to increased lifecycle carbon. Embodied carbon must therefore be calculated when retrofitting to prevent the possibility of increasing, rather than reducing, carbon emissions and thus placing climate targets in jeopardy.

The most effective measures were also found to vary when making a lifecycle rather than merely operational assessment, and also varied between cases. Most measures for example, failed to make lifecycle savings for CS11 because their operational baseline is already so low. This is a result of their extremely frugal energy behaviours, only heating one room of their home for short periods each day, and their choice of a wood burning stove to provide low carbon heating, which together lead to very low baseline emissions of only 263kgCO_2e per year. This highlights the importance of understanding the specific energy demands of individual resident-building cases when examining retrofit approaches, because -even if the heritage acceptability of measures is excluded- on a technical level there are still very few one-size-fits-all solutions.

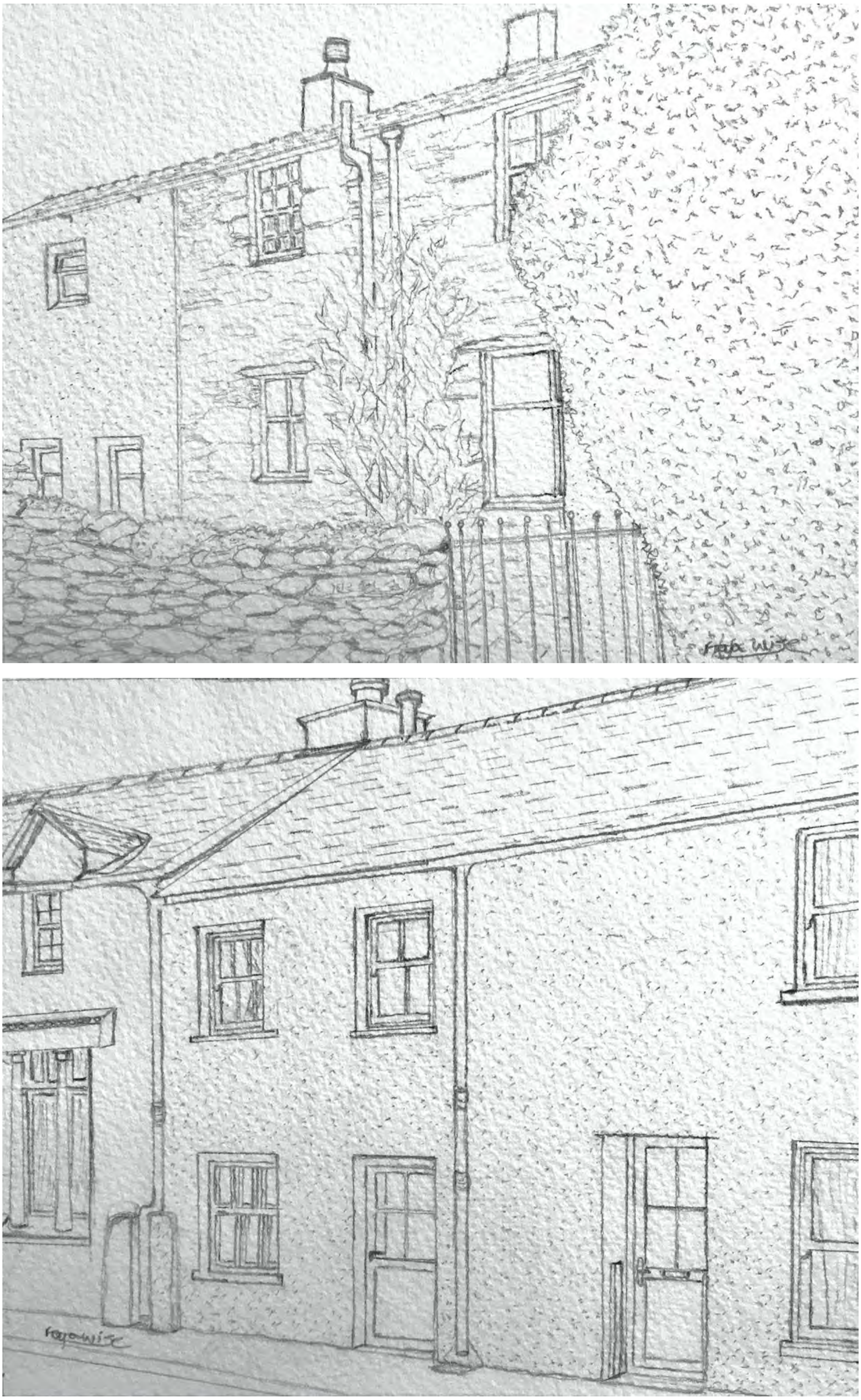
8.7 Conclusion

This chapter compared the performance of three energy modelling tools, RdSAP, SBEM, and Design Builder, assessing their functionality and accuracy before choosing Design Builder to create detailed models of the case study buildings and calibrating these as closely as possible with actual energy use (RsQ2c). The predicted operational, embodied and lifecycle carbon impact for 40 retrofit measures was then calculated (RsQ3a).

Heating system replacement, wall insulation and heating setting adjustments were found to make the greatest average operational and lifecycle carbon savings across the case studies, although the first two of these also had some of the highest embodied emissions. The critical importance of undertaking lifecycle assessment of retrofit measures to identify those which fail to make lifecycle savings was emphasised by the results of this research. The measures which made the greatest savings were found to vary across the cases, emphasising the need to take account of individual behaviours and energy demand. Potential synergies were highlighted between measures which have low embodied carbon and those which might be more compatible with vernacular construction and acceptable to residents' heritage values.

The EU has identified the need for retrofit which makes average energy and carbon reductions of 60% for all buildings to meet climate goals (European Commission, 2020). None of the individual retrofit measures examined were predicted by the modelling to achieve this level of energy and carbon reduction for the case study buildings, meaning that combinations of measures are required. This chapter has also mainly considered the technical potential of retrofit measures, giving little consideration to residents' heritage values or other issues that influence their retrofit decisions. These aspects must be considered if potential retrofits are to be enacted and therefore produce savings in reality.

Figure 8.2: CS11 and CS12



Chapter 9. Realistic Retrofit Packages

9.1 Introduction

The importance of examining the lifecycle carbon of individual retrofit measures has been identified. However, these individual measures do not make savings consistent with internationally identified climate goals, meaning a combination of measures is required. For retrofitting to make actual savings the likelihood of it being enacted in reality must also be considered and this will be affected by residents' heritage values and the range of constraints they perceive to retrofitting.

This chapter models the potential carbon impact of five packages of retrofit measures tailored to each of the case studies (RsQ3b) and considers the acceptability of these packages to residents to form a picture of how realistic they might be (RsQ3c). The results of the individual packages are identified, and the impact of the packages is compared.

9.2 Package overview

Single measure retrofits will not provide the required levels of energy and carbon savings and only assessing the technical potential of measures is not enough to identify whether they might realistically be enacted by residents. The acceptability of measures to residents' heritage values, barriers such as disruption and planning constraints, the likely compatibility of measures with vernacular construction and residents' behaviours, and the policy landscape, all need to be considered as part of holistic retrofit approaches. Retrofit measures also interact with each other in complex ways, so just considering single measures does not allow conclusions to be drawn about how a combination of measures might perform. Five packages and two sub packages of retrofit measures (Figure 9.1) were therefore selected and modelled in Design Builder for each of the cases, to provide an assessment of their potential operational performance. The embodied carbon of these packages was then calculated to obtain their lifecycle impact.

The first package considered covers the measures recommended by the EPC for each study to reach band C, based on the RdSAP modelling (Chapter Seven). This can be considered the current policy package as UK targets call for all homes to reach at least EPC band C by 2035 (CCC, 2020). The second and third packages consider the technically possible savings that could be made from the retrofit combinations; package two combines the measures predicted to make the greatest operational savings for each case while package three combines those which make the greatest lifecycle savings. Package four meanwhile takes a heritage sensitive approach, combining only those measures that residents identified as acceptable to their heritage values.

The final package, package 5, combines measures that are or might be acceptable to residents' heritage values, that are likely to be acceptable to local planning policy, and which consider other constraints such as disruption and compatibility with vernacular construction. This package therefore offers a balance of some of the issues identified as affecting the likelihood of retrofitting being enacted in reality. Two sub versions of this package are also modelled, investigating the same measures but without heating setting adjustments (P5a) or wall insulation (P5b) to see what difference these changes make as they are some of the most likely to be unacceptable to residents. The individual measures selected for each case study for each of the five main packages are shown in Appendix N.

Figure 9.1: Overview of retrofit packages

Package	Description
Package 1: Policy recommended	Measures recommended by RdSAP generated EPC to improve each case's energy rating to band C
Package 2: Operational	Measures that make the greatest operational carbon savings in each category
Package 3: Lifecycle	Measures that make the greatest lifecycle carbon savings in each category
Package 4: Acceptable	Measures acceptable to residents, excluding those which increase lifecycle carbon
Package 5: Balanced	Measures balancing resident and policy acceptability, construction compatibility, and lifecycle carbon
Package 5a: No heating adjustments	Package 5 without heating system adjustment measures
Package 5b: No wall insulation	Package 5 without internal or external wall insulation measures

9.3 Package 1: Policy recommended

Package 1 models the combination of measures for each case study which enables them to reach EPC band C and thus meet current UK policy targets for residential buildings. The measures are selected using the EPC recommendations which were generated by the RdSAP modelling for each of the case studies. No measures are modelled for CS9 and CS12 as they are already rated band C. The EPC does not differentiate between internal and external wall insulation; IWI has been assumed for designated buildings and EWI for undesignated buildings. For insulation measures the standard material has been modelled, and for window replacement, UPVC double glazing. This package does not consider any heating system adjustments or soft retrofits measures such as window additions or wall hangings.

These measures were modelled as a package for each case study in Design Builder to provide an indication of the operational impact of these measures and the embodied and lifecycle carbon of the package was calculated

(Figure 9.2). The biogenic carbon storage was also calculated and, in accordance with EN 15978 (BSI, 2012, p. 28), the carbon savings from the solar PV energy which was exported to the grid rather than being used on site is reported separately from the main carbon figures (Table 9.1).

An average saving of 64.5tCO_2e is made by this package, equating to just over a tonne a year. Embodied carbon comes to 5.3% of the operational carbon, varying between 0.5%-17.8% although for CS11 the figure is 567% meaning that this package increases lifecycle costs for CS11. The majority of the embodied carbon is emitted at the beginning of the package's lifespan while the operational savings are spread evenly over the fifty-year period. It would therefore take an average of 4 years for the operational savings to 'offset' this embodied carbon and begin to make lifecycle savings (or 9 years if CS11 is included).

Figure 9.2: Actual embodied, operational and lifecycle carbon savings for retrofit Package 1: EPC C, for each case study

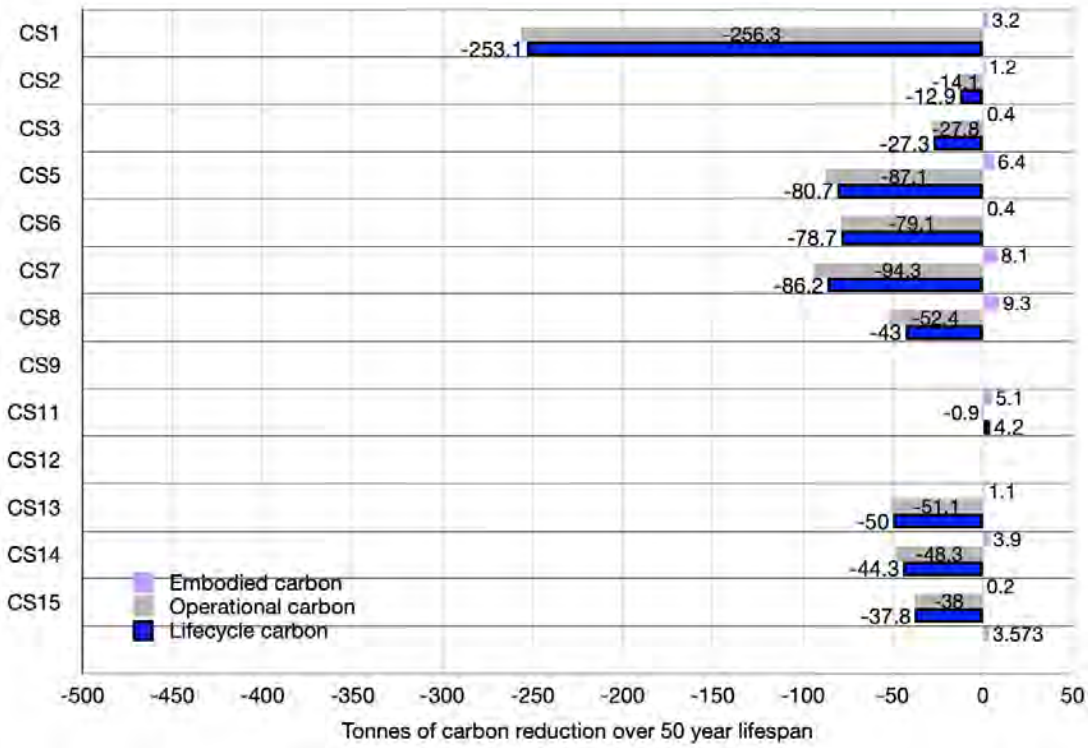


Table 9.1: Package 1 carbon savings

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	3.2		-256.3		**-253.1**
CS2	1.2		-14.1		**-12.9**
CS3	0.4		-27.8		**-27.3**
CS5	6.4	-0.2	-87.1		**-80.7**
CS6	0.4		-79.1		**-78.7**
CS7	8.1	-0.2	-94.3		**-86.2**
CS8	9.3		-52.4	-2.6	**-43**
CS9					
CS11	5.1	-0.1	-0.9		**4.2**
CS12					
CS13	1.1		-51.1		**-50**
CS14	3.9	-0.1	-48.3		**-44.3**
CS15	0.2		-38		**-37.8**

A significant number of the measures recommended by RdSAP are unacceptable to the case study participants and are therefore unlikely to be enacted. These include solid wall insulation, which is recommended for 12 of the 13 case studies and is generally unacceptable, as is window replacement, which is recommended for 10 of the cases. The recommendations and their acceptability to participants were summarised (Figure 9.3). The total measures recommended for each case study are also included in Figure 9.3 and the potential predicted EPC band for all cases is shown, in several cases going beyond band C.

9.4 RdSAP modelling of recommended measures

In addition to modelling the operational impact of Package 1 in Design Builder as reported above, this package was also modelled in RdSAP to compare the different levels of predicted savings between the two models. The RdSAP model also shows the predicted savings if all recommendations were installed which for example, would equate to band B (91) for CS1. The baseline figures for RdSAP and Design Builder, the impact of the Package 1 measures for RdSAP and Design Builder, and the RdSAP predicted impact of enacting all recommendations are compared (Table 9.2). Only the main fuel (used for heating, DHW, and cooking) is compared because RdSAP does not include electricity plug loads.

The RdSAP baseline overestimates energy and carbon for all of the case study buildings compared with the Design Builder baseline. After modelling the measures for improvement to band C, the energy demand predicted by RdSAP for six of the case studies (CS3, CS7, CS11, CS13, CS14, CS15) was still higher than the Design Builder baseline. The RdSAP carbon emissions at band C were still higher than the actual emissions for all of the cases except CS1. This inaccuracy leads to RdSAP significantly overestimating the average annual operational carbon savings that the Package 1 retrofit measures would make (775kgCO_2e/y or 52.8%). Using RdSAP to inform retrofit would therefore lead to much lower than predicted carbon savings for the case study buildings.

If all recommended retrofit measures, were enacted it can be seen that RdSAP's predicted energy use after retrofit is still higher than the current Design Builder baseline for four of the case studies (CS3, CS7, CS13, CS15). This confirms the findings in Chapter Seven that RdSAP is not suitable as a tool to inform retrofit decision making or to accurately assess building energy demand.

Figure 9.3: EPC recommendations for each case study colour coded by acceptability to residents

Case study	Curent rating	First recommendation	Second recommendation	Third Recomendation	Fourth recommendation	Fifth recommendation	Sixth Recommendation	Seventh recommendation	Eighth recommendation	Ninth recommendation	Tenth recommendation	Eleventh recommendation	Potential rating after all changes
Key:	The recommended measures are shown in the order they appear on the EPC and the rating impact of each measure is shown, Measures before the black barrier are those required to reach EPC band C. Measures are colour coded by their acceptability: Blue = already have, green = would consider, yellow = maybe/unsure, red = would not do.												
CS1	34 (F)	Increase loft insulation to 270mm (35 F)	Internal or external wall insulation (54 E)	Suspended floor insulation (57 D)	Increase hot water cylinder insulation (58 D)	Low energy lighting (59 D)	Hot water cylinder thermostat (61 D)	**Replace boiler with condensing boiler (70 C)**	Solar water heating (71 C)	Replace single with double glazing (74, C)	Solar PV panels (79 C),	Wind turbine (91 B)	91 (B)
CS2	47 (E)	Internal or external wall insulation (66 D)	**Solid floor insulation (69 C)**	Solar water heating (71 C)	Replace single with double glazing (76, C)	Solar PV panels (87 B).	Wind turbine (111 A)						111 (A)
CS3	68 (D)	**Internal or external wall insulation (74 C)**	Draught proofing (76 C)	Low energy lighting (76 C)	Replace single with double glazing (79, C)	Solar PV panels (84 B)							84 (B)
CS5	55 (D)	Flat roof or sloping ceiling insulation (57 D)	**Internal or external wall insulation (71 C)**	Solid floor insulation (72 C)	Draught proofing (72 C)	Low energy lighting (73 C)	Solar water heating (74 C)	Replace single with double glazing (76, C)	Solar PV panels (84 B)				84 (B)
CS6	68 (D)	**Cavity wall insulation (69 C)**	Internal or external wall insulation (74 C)	Solar PV (79 C)									79 (C)
CS7	54 (E)	Flat roof or sloping ceiling insulation (59 D)	Internal or external wall insulation (67 D)	**Replace boiler with new condensing boiler (69 C)**	Solar water heating (70 C)	Solar PV panels (74 C).	Wind turbine (82 B)						82 (B)
CS8	59 (D)	Flat roof or sloping ceiling insulation (61 D)	Internal or external wall insulation (65 D)	Draught proofing (66 D)	Replace single with double glazing (68, D)	**Solar PV panels (74 C).**							74 (C)
CS9	**70 (C)**	Internal or external wall insulation (74 C)	Draught proofing (75 C)	Low energy lighting (75 C)	Solar water heating (76 C)	Replace single with double glazing (79, C)	Solar PV panels (87 B)						87 (B)
CS11	25 (F)	Flat roof or sloping ceiling insulation (38 F)	Internal or external wall insulation (53 E)	Solid floor insulation (55 D)	Draught proofing (57 D)	Solar water heating (62 D)	Replace single with double glazing (69 C)	High performance external doors (70 C)	Solar PV panels (82 B)	Wind turbine (108 A)			108 (A)
CS12	**75 (C)**	Solar water heating (77 C)	Solar PV panels (87 B)										87 (B)
CS13	59 (D)	Internal or external wall insulation (67 D)	**Solid floor insulation (69 C)**	Replace single with double glazing (70, C)	Solar water heating (76 C)								76 (C)
CS14	62 (D)	Flat roof or sloping ceiling insulation (64 D)	**Internal or external wall insulation (72 C)**	Suspended floor insulation (74 C)	Draught proofing (75 C)	Replace single with double glazing (77, C)	Solar PV panels (84 B)	Wind turbine (98 A)					98 (A)
CS15	64 (D)	**Internal or external wall insulation (71 C)**	Draught proofing (71 C)	Low energy lighting (72, C)	Replace single with double glazing (74, C)	Solar PV panels (80 C).							80 (C)
Note:	RdSAP only counts LED bulbs as low energy lighting while residents considered CFLs to count as well. Residents were not asked about some of the measures recommended by RdSAP these are shown in grey												

Table 9.2: Comparison of Design Builder and RdSAP modelling to EPC band C

Case study	Baseline values for RdSAP and DB					Improvement to EPC band C for RdSAP and DB					Carbon savings for band C		RdSAP predicted values for all measures	
	EPC rating	RdSAP kWh	RdSAP $kgCO_2e$	DB kWh	DB $kgCO_2e$	EPC rating	RdSAP kWh	RdSAP $kgCO_2e$	DB kWh	DB $kgCO_2e$	RdSAP $kgCO_2e$	DB $kgCO_2e$	Final kWh	Final EPC rating
CS1	34	48,045	14,065	37,746	9,354	69	22,044	6,376	17,311	4,290	7,689	5,064	13,783	91
CS2	47	16,016	8,312	13,889	3,210	69	9,100	4,722	7,464	1,725	3,590	1,485	1,624	111
CS3	68	43,485	7,291	17,718	3,245	74	32,455	5,503	14,694	2,691	1,788	554	25,892	84
CS5	55	29,997	6,479	19,893	3,644	70	17,533	3,787	10,383	1,902	2,692	1,742	12,784	84
CS6	68	35,259	7,616	33,661	6,165	69	33,341	7,201	25,023	4,583	415	1,582	26,110	79
CS7	54	42,661	12,595	21,230	5,261	69	32,564	8,507	13,662	3,386	4,088	1,875	26,331	82
CS8	59	32,414	7,808	24,134	4,420	69	22,941	5,500	18,507	3,390	2,308	1,030	23,344	77
CS9	70	18,902	4,028	14,114	2,585								10,726	87
CS11	25	28,416	2,003	5,126	78	69	9,717	717	4,328	65	1286	13	4,528	108
CS12	75	10,498	2,267	10,062	1,843								8,224	87
CS13	59	29,879	6,498	19,749	3,617	72	23,551	5,111	14,166	2,595	1,387	1,022	21,738	76
CS14	62	30,597	6,608	14,051	2,574	69	24,754	4,663	8,783	1,609	1,945	965	13,790	98
CS15	64	29,522	6,377	12,638	2,315	73	26,075	4,426	8,313	1,523	1,951	792	19,378	80
Mean	57	30,438	7,073	18,770	3,716	70	21,910	4,831	12,967	2,524	2,241	1,466	16,019	88
Median	59	29,997	6,608	17,718	3,245	69	22,941	8,507	13,662	2,595	1,945	1,030	13,790	84

Note: The colour shading relates to the Design Builder (DB) baseline. Red indicates RdSAP values higher than this baseline, green indicates RdSAP values lower than this baseline

9.5 Package 2: Operational technical potential

Package 2 considers the technical potential of retrofit measures, aiming to combine measures to make the greatest operational savings. No consideration is given to heritage impact or other constrains in this package. It just selects the measures identified in Chapter Eight as predicted to make the greatest operational carbon savings for each case. These include changing heating systems to biomass boilers, using mainly standard insulation materials and commonly selecting triple glazed window replacement. Solar PV panels have been modelled for all cases as they make greater operational savings than solar thermal if export energy is included. Other measures which make operational savings are also modelled. The list of measures for each case can be seen in Appendix N.

The average lifecycle saving for Package 2 is 150.4tCO_2e per case study which equates to around three tonnes of carbon saving per year for each case (Figure 9.4). The embodied carbon comes to an average of 14.4% of the operational carbon (varying between 6.6%-19.4%). The average time to payback the initial embodied carbon is nine years, excluding CS11 whose payback time is 105 years, and which is the only case where the package does not make lifecycle savings (Table 9.3).

Figure 9.4: Carbon savings for retrofit Package 2: Operational, for each case study

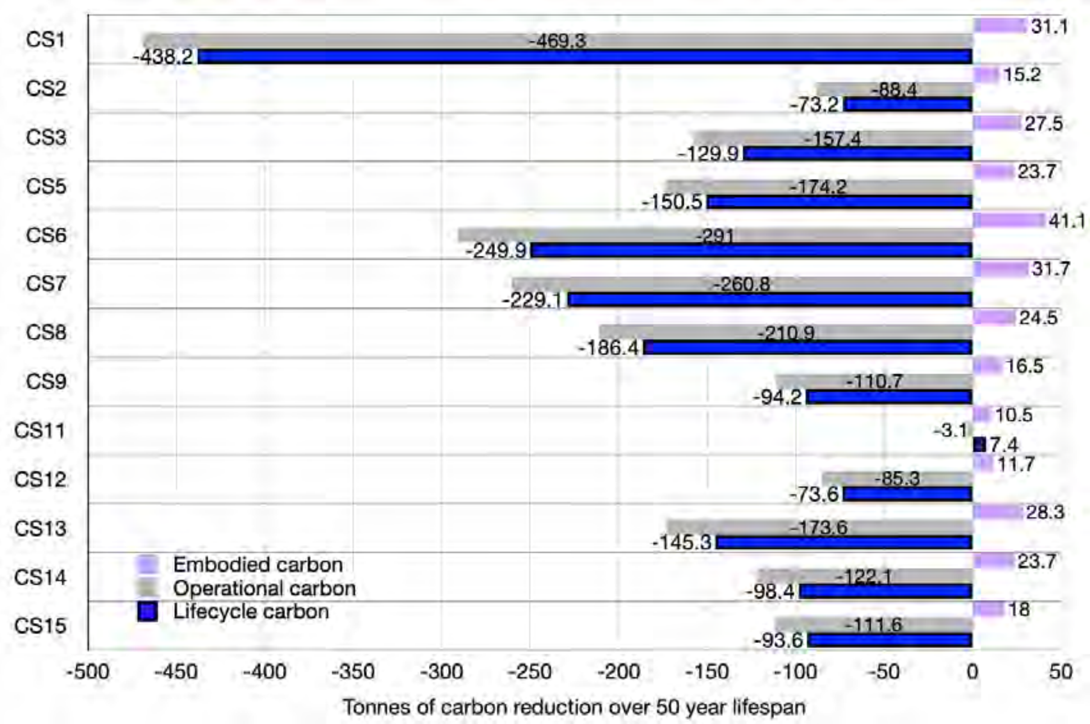


Table 9.3: Package 2 carbon savings

Case	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	31.1	-0.9	-469.3	-21.5	**-438.2**
CS2	15.2	-0.2	-88.4	-7.5	**-73.2**
CS3	27.5	-0.5	-157.4	-3.4	**-129.9**
CS5	23.7	-0.6	-174.2	-5	**-150.5**
CS6	41.1	-0.8	-291	-6.6	**-249.9**
CS7	31.7	-1.3	-260.8	-11.1	**-229.1**
CS8	24.5	-0.4	-210.9	-2.6	**-186.4**
CS9	16.5	-0.3	-110.7	-0.8	**-94.2**
CS11	10.5	-0.5	-3.1	-2.1	**7.4**
CS12	11.7	-0.2	-85.3	-0.9	**-73.6**
CS13	28.3	-0.3	-173.6	-2.7	**-145.3**
CS14	23.7	-0.8	-122.1	-2.2	**-98.4**
CS15	18	-0.3	-111.6	-2.9	**-93.6**

9.6 Package 3: Lifecycle technical potential

Retrofit Package 3, like Package 2, considers the technical potential of combining measures; in this package the measures with the greatest lifecycle savings for each case are selected. Measures which fail to make lifecycle savings are excluded. The measures with the greatest lifecycle savings include heating system changes and solar panels, with four cases receiving solar PV and nine solar thermal. Insulation measures include a greater variety of material types, with six cases receiving natural materials for wall insulation and six standard materials, while CS11 receives the technical aerogel. Window improvement measures include triple glazing (CS1, CS6, CS8, CS9, CS12, CS13), internal shutters (CS2, CS5, CS7), and secondary glazing (CS3, CS14, CS15).

Package 3 makes average savings per building of 149.2tCO_2e equating to just under three tonnes per building per year (Figure 9.5 and Table 9.4). Average embodied carbon is 12.3% (6.7-14.9%) of the operational carbon and the average payback time for the embodied carbon is eight years. This rises to 17 years if CS11 is included, as their payback time is 124 years, meaning that, despite the individual measures making lifecycle savings for CS11, in combination they increase lifecycle carbon.

Figure 9.5: Carbon savings for Package 3: Lifecycle, for each case

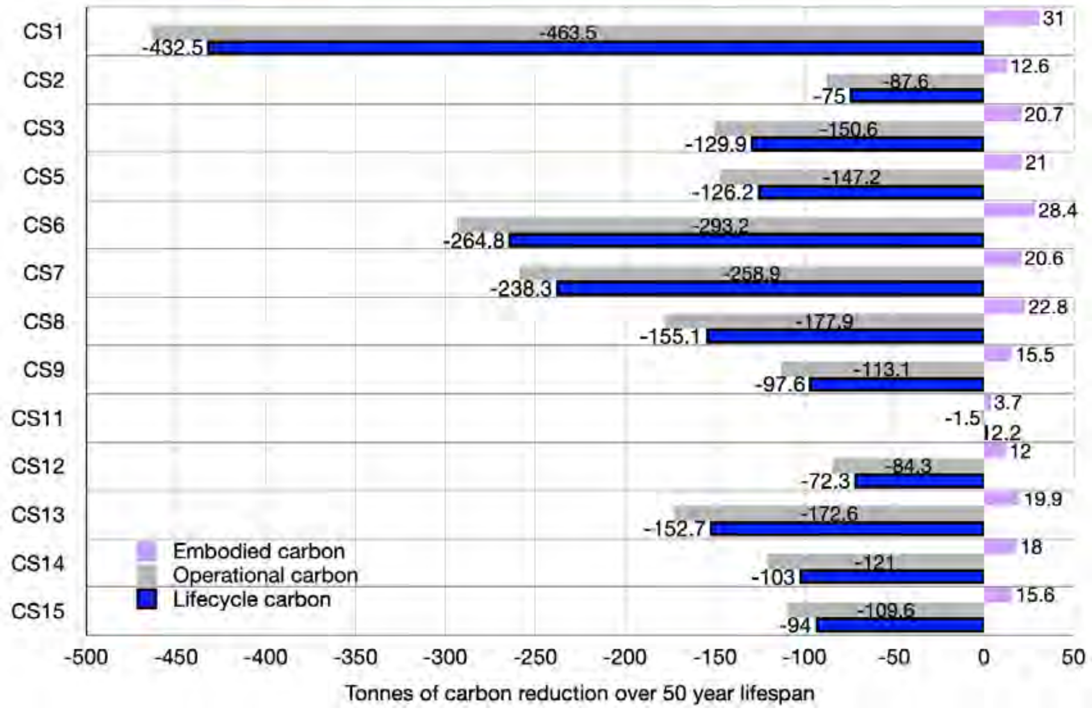


Table 9.4: Package 3: carbon savings

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	31	-0.9	-463.5		**-432.5**
CS2	12.6	-2.4	-87.6	-3.4	**-75**
CS3	20.7	-3	-150.6		**-129.9**
CS5	21	-1	-147.2	-4.9	**-126.2**
CS6	28.4	-1.2	-293.2		**-264.8**
CS7	20.6	-5.7	-258.9		**-238.3**
CS8	22.8	-0.2	-177.9		**-155.1**
CS9	15.5	-0.1	-113.1		**-97.6**
CS11	3.7		-1.5	-2.1	**2.2**
CS12	12	-0.2	-84.3		**-72.3**
CS13	19.9	-3.3	-172.6		**-152.7**
CS14	18	-3.3	-121		**-103**
CS15	15.6	-3	-109.6		**-94**

9.7 Package 4: Acceptable measures

For Package 4 the measures acceptable to the residents of each case study were combined, providing that these measures did not increase lifecycle carbon. These measures varied significantly between the different case studies based on their heritage values (Chapter Five) but in general did not include wall insulation or window replacement, although some window additions were acceptable. For insulation where there was a choice between materials, that with the best lifecycle performance was chosen. While all participants found LED lighting acceptable this measure was excluded because it failed to make lifecycle savings.

The average carbon saving for this package is 49.1tCO_2e per case which equates to savings of just under one tonne a year (Figure 9.6 and Table 9.5). The embodied carbon is on average 17.7% of the operational carbon (1.4-50%). The average time required to pay back the embodied carbon for this package is 13 years (excluding CS11). For CS11 this package would take 55 years to pay back.

Figure 9.6: Carbon savings for retrofit Package 4: Acceptable, for each case study

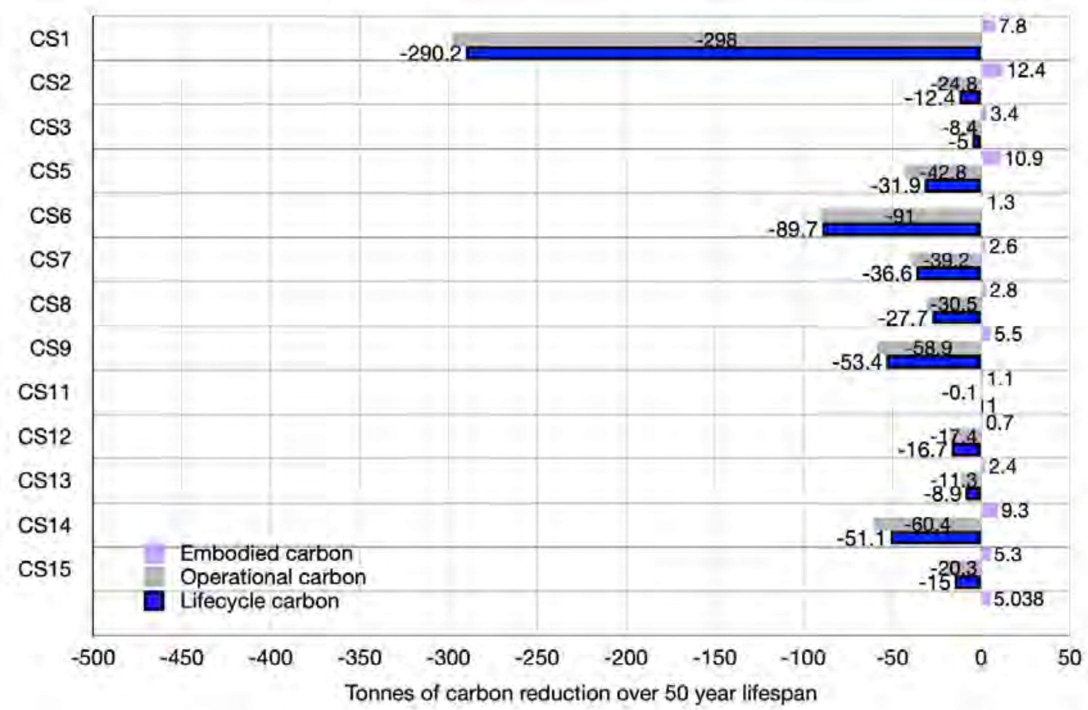


Table 9.5: Package 4 carbon savings

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	7.8	-1.8	-298		**-290.2**
CS2	12.4		-24.8	-6.4	**-12.4**
CS3	3.4		-8.4	-3.4	**-5**
CS5	10.9	-0.9	-42.8	-12	**-31.9**
CS6	1.3	-0.5	-91		**-89.7**
CS7	2.6	-0.2	-39.2		**-36.6**
CS8	2.8	-0.2	-30.5		**-27.7**
CS9	5.5	-0.2	-58.9		**-53.4**
CS11	1.1		-0.1		**1**
CS12	0.7	-0.1	-17.4		**-16.7**
CS13	2.4	-0.7	-11.3		**-8.9**
CS14	9.3	-0.7	-60.4		**-51.1**
CS15	5.3		-20.3		-15

9.8 Package 5: Balanced measures

Package five selects measures for each case that take technical aspects, planning and practical constraints, and residents' heritage values into account, to create a balance between a range of, sometimes conflicting, priorities. Only measures that reduced lifecycle carbon were included.

Planning constraints were considered for wall insulation and visible solar panels for designated buildings. IWI rather than external wall insulation was modelled for the majority of cases as most residents considered it to have a lower impact on heritage values than EWI and this applied to all the designated buildings. No solar was modelled for CS2 (Grade II* curtilage) and cases in conservation areas were modelled both with and without solar if it was acceptable to residents, as it was unclear whether it would be permitted development. Solar thermal was modelled for CS1 and CS13 (Grade II) as ground mounted panels in the rear garden for CS1 and on a hidden rear roof for CS13, whose front façade is the only listed part of the building.

The retrofits which residents would or might consider acceptable to their heritage values were taken into account when selecting measures. CS7 and CS14 were modelled with EWI as both were already rendered and CS14 value their internal wall textures. No wall insulation was modelled for CS11 as they also value their internal wall textures and EWI would increase lifecycle carbon. Package 5b modelled all cases without wall insulation as this measure was generally unacceptable to residents' heritage values but because it is such a common measure it effects were worth examining. Where other measures which were potentially unacceptable to residents and which were not easily reversible, such as floor insulation, were included, the package was modelled both with and without these measures.

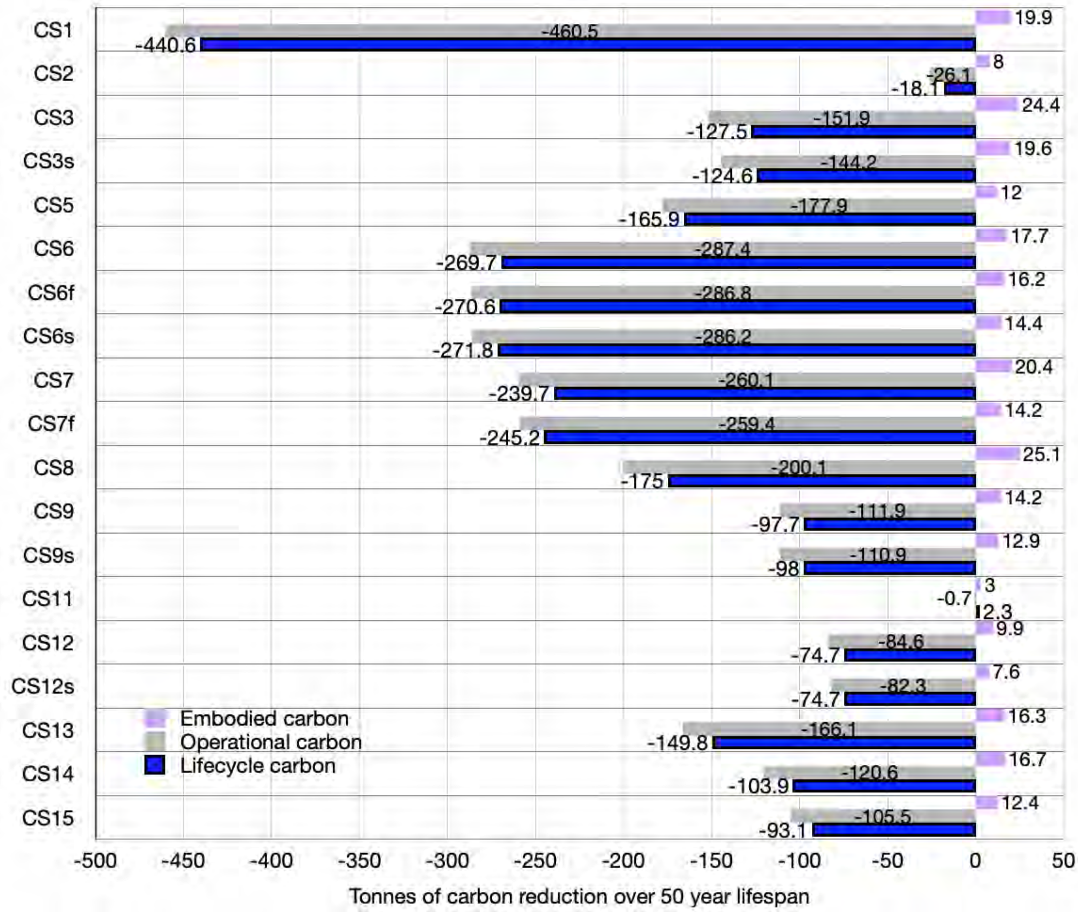
Window additions rather than replacements were modelled for all of the cases except CS6 who has UPVC double glazing and for whom triple glazed timber sashes made the most difference from a carbon perspective. The choice of heating system was informed by practical issues such as not having biomass in highly built-up areas or in cases without storage space or with delivery access issues. GSHPs were modelled where there was considered to be enough outside space to have a flat collector or, in the case of CS12, where biomass was impractical, and the residents found ASHP unacceptable for both heritage and noise reasons. Despite CS15 being unconvinced by the efficiency of ASHP it was modelled for them because the effort required to run a biomass system was considered too disruptive and they have no suitable outdoor space for a GSHP.

Practical issues around space constraints were also considered for IWI, with thin aerogel insulation for CS2, CS5 and CS9. Standard floor insulation was generally specified for the cases with solid floors because its lifecycle savings were significantly greater than the other material options. For other insulation options the natural material was generally chosen as being more compatible with the buildings' construction. The operational modelling of floor insulation had previously presented challenges for some of the cases (Chapter Eight) however, when paired with underfloor heating and a GSHP, the package made greater savings with floor insulation than without it. This was tested for all the cases where GSHPs were modelled.

Heating setting adjustments were modelled for all of the cases as applicable. A reduction in heating set point temperatures of 1°C was modelled for all the cases as part of this package. Package 5a modelled Package 5 without heating setting changes however so that the impact of these measures could be tested. A package of measures was therefore developed for each case which balances some of the varied factors which must be taken into account when considering retrofit projects.

The average carbon savings for Package 5 over fifty years is 150.9tCO_2e per case equating to just over 3 tonnes per year (Figure 9.7 and Table 9.6). The balanced package provides an average of 11% of the embodied carbon to the operational carbon (4.3- 30.7%) and it would take an average of 7 years to offset the embodied carbon and start to make lifecycle savings. CS11 would take 300 years to pay back the embodied carbon meaning this package does not make lifecycle savings. For some cases the exclusion of solar thermal panels and floor insulation from the package leads to greater savings than when they are included (CS6 and CS7). However, including solar thermal panels makes greater savings for CS6 and has a very limited difference for CS9 and CS12.

Figure 9.7: Carbon savings for package 5: balanced, for each case



Note: An (s) after the case study number indicates the package without solar thermal, an (f) indicates the package without floor insulation.

Table 9.6: Package 5 carbon savings

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	19.9	-3.4	-460.5	0	**-440.6**
CS2	8	0	-26.1	0	**-18.1**
CS3	24.4	-1.7	-151.9	0	**-127.5**
CS3s	19.6	-1.7	-144.2	0	**-124.6**
CS5	12	-0.9	-177.9	-4.9	**-165.9**
CS6	17.7	-2.8	-287.4	0	**-269.7**
CS6f	16.2	-2.5	-286.8	0	**-270.6**
CS6s	14.4	-2.8	-286.2	0	**-271.8**
CS7	20.4	-4.9	-260.1	0	**-239.7**
CS7f	14.2	-4.6	-259.4	0	**-245.2**
CS8	25.1	-1.4	-200.1	0	**-175**
CS9	14.2	-0.3	-111.9	0	**-97.7**

	Embodied $tCO_{2}e$	Biogenic $tCO_{2}e$	Operational $tCO_{2}e$	Solar generation export $tCO_{2}e$	Lifecycle $tCO_{2}e$
CS9s	12.9	-0.3	-110.9	0	**-98**
CS11	3	0	-0.7	-2.1	**2.3**
CS12	9.9	-0.3	-84.6	0	**-74.7**
CS12s	7.6	-0.3	-82.3	0	**-74.7**
CS13	16.3	-2.2	-166.1	0	**-149.8**
CS14	16.7	-3.8	-120.6	0	**-103.9**
CS15	12.4	-0.7	-105.5	0	**-93.1**

9.9 Package 5a: No heating setting adjustments

Package 5a excludes the measures involving heating setting adjustments to provide a measure of the carbon savings possible for that building, independent of residents' future behaviours. These behaviours are uncertain and may also change if new residents move in. Package 5a is therefore the same as Package 5 but without heating reduction, smart heating controls and reduced bedroom and holiday heating. Where alternatives in Package 5 were examined, those that make the greatest lifecycle savings for each case were taken forward in Package 5a, so CS3 with solar thermal for example.

The average carbon savings for Package 5a is 149.9tCO_{2}e per case which equates to just under three tonnes per year (Table 9.7). The average percentage of operational to embodied carbon is 10.4% (3.4%-31.9%) and the average number of years to payback the embodied carbon is 6, excluding CS11.

Table 9.7: Package 5a: carbon savings

	Embodied $tCO_{2}e$	Biogenic $tCO_{2}e$	Operational $tCO_{2}e$	Solar generation export $tCO_{2}e$	Lifecycle $tCO_{2}e$
CS1	15.5	-3.4	-452.9	0	**-437.4**
CS2	8	0	-25.1	0	**-17.1**
CS3	19.1	-1.7	-151.1	0	**-132**
CS5	8	-0.9	-170.3	-4.9	**-162.3**
CS6	17.7	-2.8	-284	0	**-266.3**
CS7	13.3	-4.9	-256.4	0	**-243.1**

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS8	20.2	-1.4	-196.6	0	**-176.4**
CS9	11.1	-0.3	-108.2	0	**-97.1**
CS11	3	0	-0.09	-2.1	**2.91**
CS12	9.9	-0.3	-82.1	0	**-72.2**
CS13	12.8	-2.2	-162.5	0	**-149.7**
CS14	12.7	-3.8	-117.2	0	**-104.5**
CS15	9.3	-0.7	-103.3	0	**-94**

9.10 Package 5b: No wall insulation

Solid wall insulation is a commonly recommended retrofit measure for vernacular buildings and can lead to significant carbon savings, as found in Chapter Eight. However it is also generally unacceptable to the case study participants, and, more widely, to the survey respondents (Chapter Five). Package 5b therefore modelled the same measures as Package 5 but without internal or external wall insulation (there is no change for CS11 or CS12 where wall insulation was not included in Package 5).

Package 5b makes average carbon savings of 143.7tCO_2e per case, equating to 2.9 tonnes per year (

Table 9.8). The embodied carbon is an average of 9.8% of the operational carbon (3.2-26.5%) and it would take an average of 7 years to offset the embodied carbon for Package 5b (excluding CS11).

Table 9.8: Package 5b carbon savings

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS1	19.1	-1.8	-457	0	**-437.9**
CS2	7.8	0	-21.1	0	**-13.3**
CS3	23.5	-0.3	-168	-4.9	**-144.5**
CS5	11.7	-0.9	-167.4	-6.7	**-155.7**
CS6	16.7	-0.9	-284.1	0	**-267.4**
CS7	15.7	-0.2	-256.9	0	**-241.2**

	Embodied tCO_2e	Biogenic tCO_2e	Operational tCO_2e	Solar generation export tCO_2e	Lifecycle tCO_2e
CS8	24.6	-0.4	-197.2	0	**-172.6**
CS9	14.1	-0.3	-110.3	0	**-96.2**
CS11	3	0	-0.09	-2.1	**2.91**
CS12	9.9	-0.3	-84.6	0	**0**
CS13	15.5	-0.7	-162.3	0	**-146.8**
CS14	13.9	-1	-118.7	0	**-104.8**
CS15	11.8	-0.4	-102.1	0	**-90.3**

9.11 Package 5 Comparisons

A comparison of the lifecycle carbon for the three variations of Package 5 show that they are all relatively similar but that the package with the highest savings varies for individual cases (Table 9.9). Package 5 results in the greatest savings for eight of the cases (CS1, CS2, CS5, CS6, CS7, CS9, CS12, CS13). However, Package 5a results in the greatest savings for CS8 and CS15. This is surprising because the heating setting changes should result in greater savings and three of them have no embodied emissions. The smart heating controls have significant embodied emissions however and the resultant embodied savings for Package 5a are likely to be the cause of the greater overall savings for these three cases.

There is only a small difference in lifecycle savings between Package 5 where 11 of the 13 cases have wall insulation and Package 5b where none have wall insulation. Package 5 saves 7.4tCO_2e more on average across the cases over 50 years than package 5b (148$kgCO_2e$ per year). In two cases (CS3 and CS14) the package without wall insulation actually leads to greater savings, meaning that, in the context of the package, wall insulation actually *reduces* lifecycle savings. For the other cases not including wall insulation would also lead to reduced embodied emissions for only a limited reduction in operational savings, as well as being likely to be more acceptable to, and therefore enacted by, residents.

Table 9.9: Comparison of embodied, operational and lifecycle carbon for Package 5, 5a, 5b

	P5 E	P5 O	P5 L	P5a E	P5a O	P5a L	P5b E	P5b O	P5b L
CS1	19.9	-460.5	-440.6	15.5	-452.9	-437.4	19.1	-457	-437.9
CS2	8	-26.1	-18.1	8	-25.1	-17.1	7.8	-21.1	-13.3
CS3	24.4	-151.9	-127.5	19.1	-151.1	-132	23.5	-168	-144.5
CS5	12	-177.9	-165.9	8	-170.3	-162.3	11.7	-167.4	-155.7
CS6	14.4	-286.2	-271.8	17.7	-284	-266.3	16.7	-284.1	-267.4
CS7	14.2	-259.4	-245.2	13.3	-256.4	-243.1	15.7	-256.9	-241.2
CS8	25.1	-200.1	-175	20.2	-196.6	-176.4	24.6	-197.2	-172.6
CS9	14.2	-111.9	-97.7	11.1	-108.2	-97.1	14.1	-110.3	-96.2
CS11	3	-0.7	-2.3	3	-0.09	2.91	3	-0.09	2.91
CS12	9.9	-84.6	-74.7	9.9	-82.1	-72.2	9.9	-84.6	0
CS13	16.3	-166.1	-149.8	12.8	-162.5	-149.7	15.5	-162.3	-146.8
CS14	16.7	-120.6	-103.9	12.7	-117.2	-104.5	13.9	-118.7	-104.8
CS15	12.4	-105.5	-93.1	9.3	-103.3	-94	11.8	-102.1	-90.3

E = embodied carbon, O = operational, L = lifecycle, greatest lifecycle savings for each case are colour coded green, second greatest orange, and lowest savings black,

9.12 Comparisons of Packages 1-5

The carbon savings from all packages are compared, although only the variation of Package 5 which makes the greatest lifecycle savings is compared with Packages 1-4 (Table 9.10). Surprisingly Package 5 leads to the greatest lifecycle savings for nine of the 13 cases (CS1, CS3, CS5, CS6, CS7, CS9, CS12, CS14, CS15), while Package 3, which would be expected to lead to the greatest lifecycle savings for all cases, in fact only leads to the greatest savings for CS2 and CS13. This shows that the individual measures with the greatest savings may not lead to the greatest overall savings in combination. Package 5 also leads to the greatest average savings across the cases (152.3tCO_2e), followed by Package 2 which prioritised operational savings (150.4tCO_2e). Package 3 (149.2tCO_2e) on average makes only slightly lower savings than Package 2, making greater savings than Package 2 for seven of the individual cases (CS2, CS6, CS7, CS9, CS13, CS14, CS15).

Package 1 (Policy) and Package 4 (Acceptable) make significantly lower savings than Packages 2, 3 and 5. Package 1 (54.6tCO_2e) makes slightly greater average savings than Package 4 (49.1tCO_2e), although Package 4 makes greater savings for three of the individual cases (CS1, CS6, CS14) and of course for CS9 and CS12 for whom the policy package recommended no measures. Importantly however, many of the measures included in Package 1 are unacceptable to residents' heritage values and would have a significant impact on the building (Figure 9.3). Package 4 in contrast only included measures that residents considered acceptable, and which are therefore much more likely to be enacted, and to thus make actual carbon savings, than those included for Package 1.

The two technical Packages (2 and 3) also include measures that are unacceptable to residents, while Package 5 takes more account of residents' values in the selection of measures. Package 5b, without wall insulation makes average savings of 143.7tCO_2e (Table 9.8) which is only slightly less than the savings made by Packages 2 and 3 and still nearly three times as much as those recommended for Package 1, with a much lower visual impact.

Table 9.10: Total lifecycle carbon savings for the five main packages

	P1 Policy recommendations (tCO_2e)	P2 Operational (tCO_2e)	P3 Lifecycle (tCO_2e)	P4 Acceptable (tCO_2e)	P5 Balanced (tCO_2e)
CS1	-253.1	-438.2	-432.5	-290.2	-440.6
CS2	-12.9	-73.2	-75	-12.4	-18.1
CS3	-27.3	-129.9	-129.9	-5	-144.3
CS5	-80.7	-150.5	-126.2	-31.9	-165.9
CS6	-78.7	-249.9	-264.8	-89.7	-271.8
CS7	-86.2	-229.1	-238.3	-36.6	-245.2
CS8	-43	-186.4	-155.1	-27.7	-176.4
CS9	N/A	-94.2	-97.6	-53.4	-97.7
CS11	4.2	7.4	2.2	1	2.3

	P1 Policy recommendations (tCO_2e)	P2 Operational (tCO_2e)	P3 Lifecycle (tCO_2e)	P4 Acceptable (tCO_2e)	P5 Balanced (tCO_2e)
CS12	N/A	-73.6	-72.3	-16.7	-74.7
CS13	-50	-145.3	-152.7	-8.9	-149.8
CS14	-44.3	-98.4	-103	-51.1	-103.9
CS15	-37.8	-93.6	-94	-15	-94
Total saving	-709.8	-1,954.9	-1939.2	-637.6	-1,980.1
Avg. saving	-54.6	-150.4	-149.2	-49.1	-152.3

The operational energy and lifecycle carbon savings for Package 1-5 were calculated for each of the case studies, along with the percentage carbon saving from the baseline for each case (Table 9.11). The carbon figures are an average value across the fifty-year assessment period taking the decarbonisation of the electricity grid into account, this means that, in reality, carbon savings would be greater in earlier years and lower in later years. Package 5 makes the greatest yearly energy and carbon savings across the case studies (56.6%), Package 2 and Package 3 make similar average energy and carbon savings (53.7% and 56.1% respectively). Package 4 (15.4%) makes slightly lower savings than Package 1 (16.1%).

Table 9.11: Average operational energy and lifecycle carbon savings per year for each retrofit package for each of the case studies

	Baseline		Package 1: Policy			Package: 2 Operational			Package 3: Lifecycle			Package 4: Acceptable			Package 5: Balanced		
	kWh	$kgCO_2e$	kWh	$kgCO_2e$	% saving	kWh	$kgCO_2e$	% saving	kWh	$kgCO_2e$	% saving	kWh	$kgCO_2e$	% saving	kWh	$kgCO_2e$	% saving
CS1	42,390	10,419	21,870	5,062	48.6%	36,133	8,764	84.1%	35,839	8,650	83%	24,076	5,804	55.7%	32,885	8,812	84.6%
CS2	14,896	3,443	6,425	258	7.5%	11,466	1,464	42.5%	11,206	1,500	43.6%	11,288	248	7.2%	11,887	362	10.5%
CS3	21,693	4,164	3,060	546	13.1%	9,868	2,598	62.4%	9,927	2,598	62.4%	1,343	100	2.4%	14,124	2,886	69.3%
CS5	22,189	4,174	9,515	1,614	38.7%	14,611	3,010	72.1%	14,271	2,524	60.5%	5,093	638	15.3%	9,855	3,318	79.5%
CS6	38,058	7,182	8,646	1,574	21.9%	20,666	4,998	69.6%	23,231	5,296	73.7%	9,938	1,794	25%	11,017	5,436	75.7%
CS7	27,727	6,763	7,830	1,724	25.5%	15,985	4,582	67.8%	15,417	4,766	70.5%	3,199	732	10.8%	14,642	4,904	72.5%
CS8	28,513	5,432	6,491	860	15.8%	13,821	3,728	68.6%	14,860	3,102	57.1%	3,318	554	10.2%	14,257	3,528	64.9%
CS9	19,301	3,784	0	0	0	9,586	1,884	49.8%	9,338	1,952	51.6%	6,475	1,068	28.2%	10,129	1,954	51.6%
CS11	5,905	258	911	-84	-32.6%	4,077	-148	-57.4%	1,963	-44	-17.1%	147	-20	-7.8%	809	-46	-17.8%
CS12	12,765	2,468	0	0	0	5,953	1,472	59.6%	6,001	1,446	58.6%	1,901	334	13.5%	8,039	1,494	60.5%
CS13	22,591	4,274	5,590	1,000	23.4%	13,022	2,906	68%	13,776	3,054	71.5%	1,224	178	4.2%	14,066	2,996	70.1%
CS14	19,974	3,943	5,272	886	22.5%	8,909	1,968	49.9%	9,601	2,060	52.2%	5,668	1,022	25.9%	6,478	2,078	52.7%
CS15	15,745	3,033	4,157	756	24.9%	8,518	1,872	61.7%	9,136	1,880	62%	2,210	300	9.9%	7,727	1,880	62%
Mean	**22,442**	**4,564**	**6,136**	**1,092**	**16.1%**	**13,278**	**3,008**	**53.7%**	**13,428**	**2,983**	**56.1%**	**5,837**	**981**	**15.4%**	**11,993**	**3,046**	**56.6%**

The greatest energy savings do not necessarily relate to the greatest carbon savings, with package 2 and 3 making higher average energy savings than Package 5. This will be influenced by the specific heating system changes which are modelled for a package. While all measures make energy savings for CS11, none make carbon savings because they already have such low carbon emissions. The best package for each case is therefore varied, although versions of Balanced Package 5 make the greatest savings for the majority of the cases.

9.13 Discussion

All of the retrofit packages made lifecycle carbon savings for all of the cases, except CS11. Packages 2 and 4 were intended to demonstrate the technical carbon savings that could be possible from an operational and lifecycle perspective while making no allowances for residents' heritage values, planning constraints or practicality. Package 5 however, which took a more balanced approach to these constraints, in fact made greater savings for the majority of cases than the more technical packages, demonstrating the fact large carbon savings are still possible in a more realistic retrofit scenario. Package 5b found that even without wall insulation significant carbon savings were still possible, even leading to greater savings than Package 5 with wall insulation in some cases. Given the apparent unacceptability of wall insulation to the vast majority of residents of vernacular buildings identified in this research (Chapter Four) it is very positive that significant lifecycle savings can still be made without it.

Package 2, 4 and 5 included heating setting adjustments as proxies for various levels of behavioural change as these measures were shown individually to lead to significant reductions in energy and carbon (Chapter Eight). Retrofit has often been shown to result in rebound effects, where savings post retrofit are lower than predicted because residents alter their behaviours to increase comfort levels (Galvin, 2015). Larger rebounds are expected for households that are not content with current conditions (Sorrell et al., 2009). In contrast, because nearly all of the case studies are comfortable with current conditions in their homes, no rebound effect has been modelled. However Package 5a did not include heating setting reductions to test the effect of behavioural changes, finding that these changes make a limited difference when combined with other measures in a package. This is likely to be because the case study residents already have relatively low energy behaviours and because heating behaviours will have less effect on carbon emissions if heating fuels are switched to low carbon sources and if the efficiency of the building fabric is increased.

Package 1, the current policy package, reinforced the findings of this research (Chapter Seven) that RdSAP is a poor predictor of both current performance and future retrofit savings for the case study buildings, and also supports previous research on other EPC modelling tools (Gram-Hanssen, Georg, et al., 2018; Sunikka-Blank and Galvin, 2012). Six of the 11 cases already have lower current energy demand than that predicted for them by RdSAP at EPC band C. Most of the measures recommended are unlikely to be enacted as they are not acceptable to residents' heritage values and furthermore lead to 53% less carbon savings on average across the case study buildings than predicted by RdSAP. This could have significant implications for the level of carbon savings that could be made nationally by retrofitting buildings to band C if predictions of savings are based on the RdSAP model, with implications for the effectiveness of this policy for national carbon reduction targets. It appears clear that RdSAP is unsuitable for use as a modelling tool for the retrofit of vernacular buildings or for being used as a policy instrument to encourage carbon reduction, as it will misinform effective decision making.

Full cost analysis was not included in the modelling but the data showed that this was always a factor that residents had to balance in their decision making. Generally, measures which have a low heritage impact such as shutters or curtains are also likely to have significantly lower costs than their alternatives such as window replacement. Package 1 (policy) can be compared with Package 4 (acceptable) on this basis. While they make a similar level of lifecycle carbon savings, Package 4 includes measures with a much lower financial cost than Package 1. It may also be possible for some of the measures in Package 4 to be installed by the homeowner themselves, thus reducing pressure on the construction industry. Many of the measures are also flexible and easily reversible, which may have advantages to support heritage retention and in terms of their adaptability to changing conditions and building usage. Package 5b meanwhile shows that significant carbon savings can still be made without wall insulation which is likely to have a significant financial cost.

The importance of considering the specific context and condition of each of the cases study buildings and the individual situation of its residents was identified when considering the measures to be included in Package 5. While measures were chosen using a precautionary principle with regard to reducing moisture risks for example, improvements to current conditions prior to retrofit would be needed for some cases, as well as much more detailed investigation, to avoid risks of maladaption. The results showed that some cases had much greater savings than others, with CS1 making absolute carbon savings nearly twice as great as the next closest case because of their high current emissions, while none of the packages made savings for CS11 because they already have such low emissions. This emphasises the importance of understanding current energy demand from buildings and their residents, and the need to take a lifecycle perspective. It also suggests that prioritising households with greater emissions for earlier retrofit might have a positive, disproportionate effect, on national carbon emissions.

These results demonstrate significant potential to reduce carbon from vernacular buildings through retrofitting. Package 5 makes average lifecycle carbon savings of 56.6% and average operational energy savings of 53.4%. This package balances a range of constraints and takes account of residents' heritage values, so the potential savings identified are relatively realistic. Package 4 meanwhile only considers those changes that are currently acceptable to residents and still makes an average saving of 15.4% of the case studies' current carbon emissions. To put this into context, if this level of saving was applied across all of the 10.2 million UK homes built before 1944, taking the average carbon emissions of the case study buildings as a baseline, it could equate to savings of 7.4MtCO_2e per year. This represents a 11.3% reduction in UK residential emissions, based on 2019 total carbon emissions (65.2MtCO_2e (BEIS 2020d)). The Cumbrian case study buildings are not representative of all UK vernacular buildings hence this figure is highly speculative, but it nonetheless gives some impression of the value of considering even the most conservative of the retrofit packages when scaled up.

In fact, because this is the package that only considers measures that are currently acceptable to residents, these changes are more likely to be enacted and therefore to lead to actual, rather than only potential, carbon savings. Assuming that cost barriers could be overcome, for example through government funding, these measures could be scaled up more rapidly because of their acceptability to residents. The time critical nature of the climate crisis means that rapid action is imperative.

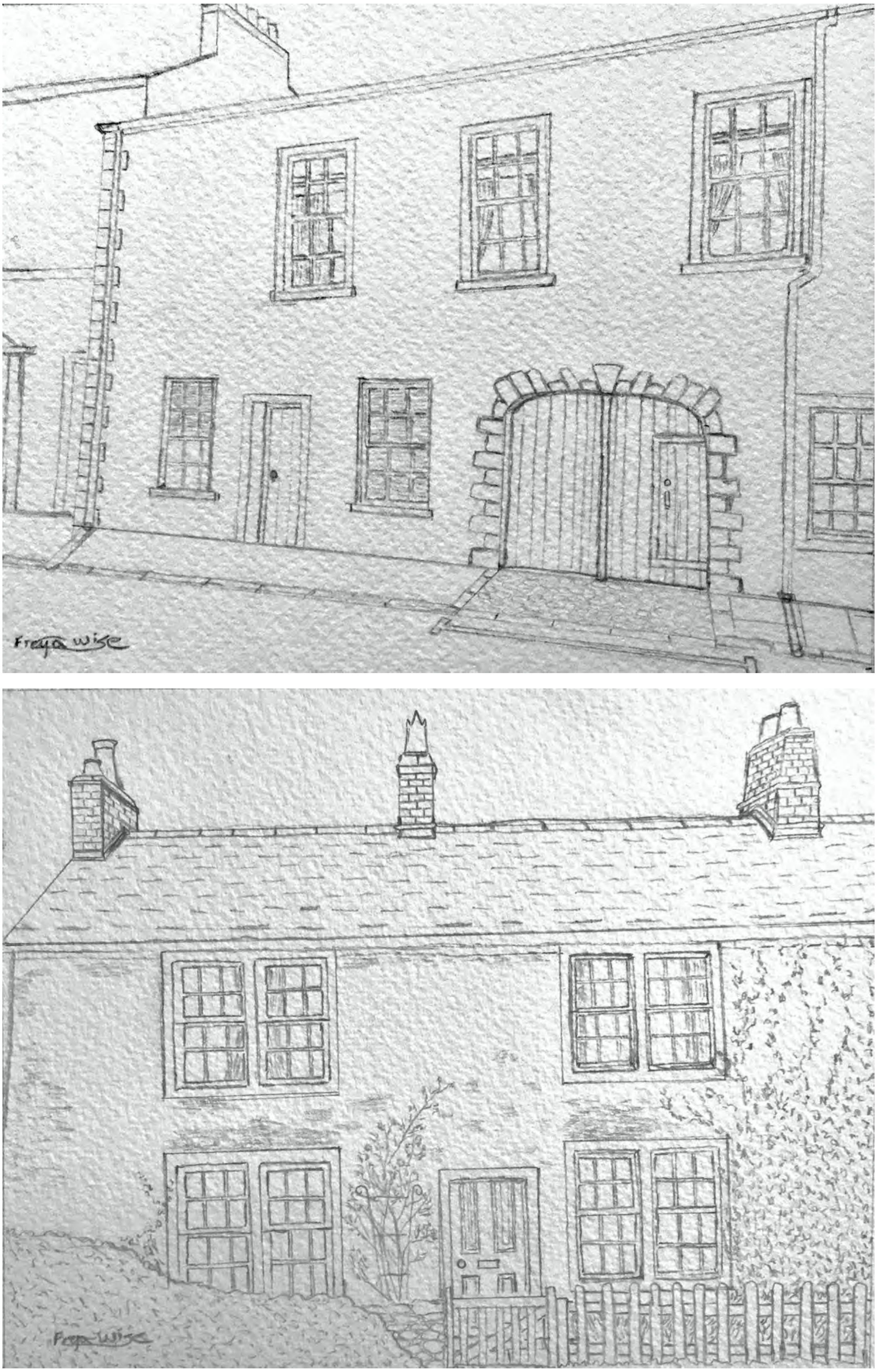
9.14 Conclusion

This chapter has examined the carbon impact of retrofit measures when they are combined into packages (RsQ3b) and considered how realistic these measures may be, given the heritage values and barriers that residents identify to retrofitting, as well as the compatibility of measures with residents' buildings (RsQ3c).

Seven retrofit packages which modelled a combination of measures were explored. Package 4, which considered acceptable retrofits, made smaller savings than most of the other packages but still had the potential for significant savings while retaining heritage values. Package 1, considering current policy recommended changes, had the lowest savings, alongside Package 4. However Package 4 has much more potential to be enacted than Package 1. Packages 2 and 3 considered the greatest technically potential savings, regardless of acceptability, although they were found to mainly make lower carbon savings than Package 5. Package 5 examined a realistic scenario of measures, balancing constraints identified by residents and considering their heritage values. Finally, two variations of Package 5 provided alternative scenarios based on specific acceptability factors. The different variations of Package 5, 5a, and 5b in fact provided the greatest carbon savings for 10 of the 13 case studies. Package 5b meanwhile showed that substantial carbon savings are possible without wall insulation which is generally unacceptable to residents but is the retrofit measure that gains the most attention from policy makers for vernacular buildings.

This modelling highlights the need to move away from simple, single measures, to consider more complex and nuanced combinations that will make savings while reducing the barriers identified by residents. This chapter has therefore built on the results of the previous chapters to examine the potential carbon reductions that are possible while retaining heritage values in vernacular buildings and thus contributing to reducing carbon emissions from the built environment and mitigating the effects of climate change.

Figure 9.8: CS13 and CS14



Chapter 10. Discussion and implications of key findings

10.1 Introduction

The previous six chapters have developed a picture of the current views, values, and behaviours of residents (RQ1), which influenced the building's actual energy demand (RQ2), identification of which enabled examination of the potential for retrofit measures to make realistic lifecycle carbon savings (RQ3).

Chapters' Four and Five examined the heritage values that residents invest in their buildings (RsQ1a), how these values affect the acceptability of retrofit measures (RsQ1d) and the types of barriers that residents perceive to carbon reduction (RsQ1e). Chapter Six identified the energy behaviours that residents engage in within their buildings (RsQ1c) and their perceptions of comfort and environmental quality (RsQ1b). The actual energy use and carbon emissions of the case study buildings were identified (RsQ2a) and compared with the results of standard UK energy models (RsQ2b) in Chapter Seven. Chapter Eight investigated the opportunities provided by three modelling tools to create reasonably representative baseline energy models (RsQ2c) and calculated the operational, embodied, and lifecycle impact of a range of individual retrofit measures (RsQ3a). Finally, the lifecycle implications of these retrofit measures in combination were identified (RsQ3b) in Chapter Nine and their ability to reduce carbon while retaining heritage was considered (RsQ3c).

This chapter draws together the findings from this work to discuss the results and consider the broader implications for both policy and practice: exploring some of the ways that retrofitting approaches for vernacular buildings could be improved to align better with residents' values, account for their behaviours and make actual and realistic carbon savings in the future. Five broad themes of results are discussed and then specific recommendations for policy and practice are identified.

10.2 Acknowledging residents' heritage values

The official heritage designation of buildings is often considered to determine the types of changes that can be made to these buildings without adversely affecting their heritage values. It is recognised however that not all buildings with heritage value are designated (Herrera-Avellanosa et al., 2019), something which was confirmed by this research, and that the designation of heritage is often developed in a top down manner which may neglect the values of residents and communities (Tweed and Sutherland, 2007).

The vast majority of residents in this study invested significant heritage values in their buildings, with designation seeming to have little effect on their recognition of these values (Section 4.2). This is important because it suggests that significantly higher proportions of the residential building stock are perceived to have heritage value by their residents than is recognised in policy. If this finding is more broadly reflective in the UK, then, based on the survey results, it could equate to around eight million (28%), or almost one in three UK homes.

The survey and case studies identified that the heritage values that residents invest in their buildings are unique, individual, and context specific. These values were found to relate both to specific, tangible building elements such as windows or woodwork, and to intangible aspects such as character, feel, and sense of age. The specific values that residents invest in their buildings, both designated and undesignated, may also differ to the values recognised by heritage designation in planning policy. Residents for example, appeared more likely to value the social and micro-history of their homes, and the sense of connection to previous residents and craftspeople through features like wear on beams and steps, or original fixtures such as ironwork and woodwork, as identified in the photo elicitation, interviews and building walk-throughs (Section 4.5-4.7). These features, on a national scale, may not be deemed historically important but their value to residents is pertinent in terms of resident led retrofit decisions and the types of changes that may be acceptable or unacceptable to them (Chapter Five).

For the residents in this research, the very clear connection to local materials, vernacular styles and character within the landscape is likely to be enhanced by the specific location of Cumbria, and the Lake District National Park, which is inscribed as a cultural landscape World Heritage Site precisely because of this connection between the natural and manmade elements of the historic landscape (LDNPA, 2020). However the sense of connection that residents had with their wider landscape mirrors findings in other contexts with a clear sense of regional or local distinction (Bieling, 2014). Appreciation of connection to landscapes and local vernacular styles and materials is therefore unlikely to be limited to Cumbrian residents.

When residents' values are neglected, opportunities to reduce carbon will be missed. In the UK the majority of homes are owner occupied and any retrofit is generally instigated, managed, and largely funded by residents. If a proposed retrofit measure is not compatible with their values, it is very unlikely to be enacted (Chapter Five). The take up of retrofit for existing buildings is often lower than expected and is currently much lower than needed for the scale of carbon reduction that is required from the existing built environment (European Commission, 2020). From the findings of this research, it seems probable that one reason for this low rate of retrofit in vernacular buildings is that residents do not find the standard measures that they are commonly presented with acceptable to their heritage values. This came through clearly in the case study interviews. These unacceptable measures include external wall insulation and window replacement which have a clear external visual impact (Section 5.4), despite being commonly recommended in retrofit.

Residents can therefore feel that it is not possible to retrofit their homes in a way that is acceptable to their values. These values were also applicable to survey respondents and case study participants in undesignated buildings. Therefore, and in contrast to the views expressed by some policy makers, such as Jenrick (Anon, 2021)(section 1.2), using designation as an arbiter of acceptable retrofit is not appropriate and will not lead to the required carbon savings. This research suggests that there needs to be more recognition and understanding of the heritage values that residents invest in their homes, both designated and undesignated, and the influence that these values have on their retrofit decisions. This recognition needs to lead to a retrofit ‘offer’ which will be more acceptable, and therefore more likely to be undertaken. Without this, carbon emissions from this significant proportion of the buildings stock are very unlikely to be reduced at the scale needed to mitigate climate change.

10.3 Informational barriers to retrofit

There is significant information readily available from a wide range of sources on potential retrofit options and approaches. This includes from heritage organisations who often provide a range of useful resources and information on heritage sensitive alterations (Historic Environment Scotland, n.d.; Historic England, 2022; STBA 2020). Residents in this research however highlighted that identifying appropriate and heritage sensitive options for their buildings was, after cost, the most important barrier to carbon reduction from their homes (Section 5.5). Residents’ and professionals’ access to relevant information on heritage sensitive retrofit is often identified as a key barrier (Herrera-Avellanosa et al., 2019). There therefore appears to be an issue with the types of information that residents are seeing or accessing and/or this is not providing them with the knowledge that they feel they need to inform their decisions. This was evidenced in the survey results on information sources that respondents would or had accessed (Section 5.6).

Information from heritage organisations such as Historic England may be less likely to be accessed by residents who live in undesignated buildings. While designation appeared to have little effect on the heritage values that residents invested in their homes, it did seem to provide a distinction in how they described and identified them. Case study participants in designated, and particularly listed buildings were more likely to describe their homes as heritage buildings and therefore to potentially access information from heritage organisations. Participants in undesignated buildings in contrast, while sure that their homes had heritage value, generally did not describe them as heritage buildings, this being a term that they seemed to associate primarily with listed or ‘significant’ buildings. Several participants emphasised the modest and unpretentious nature of their own homes -which fits well with some definitions of vernacular architecture- in contrast to their idea of what a heritage building might be (Section 4.2). There is no clearly agreed definition of a heritage building, so it is perhaps unsurprising that residents have a range of understandings and a level of uncertainty about the term and its criteria. Improving access to relevant information, in particular for residents in undesignated buildings, is therefore a clear priority in order to increase the uptake of retrofit activity.

The source of the information was found to be just as critical, with residents wanting such sources to be trustworthy and ‘disinterested’, supporting previous research (Herrera-Avellanosa et al., 2019). For many participants this meant that information should not come from the company selling the measure, or indeed necessarily from the government. Residents were concerned about ‘being convinced’ to install specific measures promoted as part of policy or industry agendas, which they might not actually require, or which might not be the best choice for their building. This fed into their desire for specific advice which took their individual circumstances and values into account to help them to identify the most appropriate options for their behaviours and values and for the performance of their specific building (Section 5.5).

In Europe an increasing number of ‘one stop shops’ have been set up by community groups or local governments, which provide advice on retrofit, help put residents in contact with local tradespeople, and can even manage the retrofit process for residents. Some successful examples of one stop shops include People Powered Retrofit in Manchester (Carbon Coop, 2022) and the Energy Communities Tipperary Cooperative (2022), although these are not specifically related to homes with heritage value. These initiatives may have the potential to provide relevant and trusted information to residents. One stop shops may still be seen as ‘selling’ their own solutions but if they are community based and not for profit, such as these examples, then they may be more likely to be trusted by residents. Local authority planning services and building control were not seen by residents as useful places to access retrofit information (Section 5.6 and Figure 5.14). However, if these services had more capacity, through increased funding and training, they could potentially be well placed to offer the local, context specific, and commercially independent advice that residents desire.

A further trusted source of information identified in this research is other owners of older buildings. Survey respondents and case study participants both emphasised that they valued information from those that they knew had undertaken certain measures when they were considering them for their own buildings. They also valued recommendations from acquaintances on the quality of work by tradespeople because finding skilled tradespeople who understood how to work sympathetically with older buildings was a challenge, confirming previous research (Mallaband et al., 2013). This could either be related to concerns about the quality of work due to gaps in the knowledge of tradespeople, or to challenges for residents in finding appropriate tradespeople (Section 5.5). A minority of residents also identified that having the time and capacity to investigate, decide on, and manage the often complex and messy process of retrofit was a significant challenge, especially in vernacular buildings.

Providing support or facilitation to encourage residents to create and engage in local peer-to-peer networks which could share learning from previous experiences and identify suitable tradespeople could be beneficial. Open home events, where residents allow others to visit their homes and ask questions, may also be useful in enabling participants to learn experientially and to see materials and systems in reality. This type of learning could help residents to develop an understanding of how measures might work in their own buildings.

Information provided to residents therefore needs to be individual and context specific, and to come from trusted sources, for these barriers to be overcome and retrofit to be enacted on the scale required.

10.4 Energy behaviours and comfort perceptions in policy and reality

The complexity and variation of energy behaviours in buildings is rarely accounted for in policy, despite the critical effects these have on energy demand from residential buildings (Bordass, 2020; Gram-Hanssen, Georg, et al., 2018). Standard behavioural assumptions are often used in place of information about actual behaviours, especially in relation to heating practices for national energy models. Residents' behaviours in this study were found to be very different to these standard assumptions, with varied and individual heating practices and lower than average temperatures revealed by the survey and case study site visits and energy diaries (Sections 6.4 and 6.5). Part of the reason for these behaviours may be because many residents have broader concerns about the need to reduce their carbon emissions, as identified in the survey and interviews. The majority felt that they, governments, businesses, and other groups all had a clear collective responsibility to reduce carbon emissions, but that governments had to take the lead to provide a framework to enable carbon reduction on the scale required to mitigate the climate crisis (Section 6.2 and Figure 6.2).

The range of heating practices that residents engage in was found to result in lower energy use than standard assumptions (Chapter Seven) because residents' heating practices tend to focus on providing localised heat instead of heating the whole building. These behaviours were found to be consistent with theories of adaptive thermal comfort (Hellwig et al., 2019; Nicol and Humphreys, 1973) and to affect the most appropriate retrofit measures for individual case studies (Chapter Eight). Considering the potential of future behavioural changes, the more detailed modelling in this research showed that individual behavioural alterations, such as temperature reductions and heating fewer spaces could make significant carbon savings (Section 8.3). These behavioural changes also did not have an embodied carbon impact, unlike measures which require physical changes (Sections 8.4 and 8.5).

Linked to the individual heating practices and energy behaviours that residents engage in are their perceptions of comfort. The need to retrofit vernacular buildings is often presented as imperative to improving comfort as these buildings are frequently represented as cold, draughty, and damp. This research found however that, in contrast to these assumptions, the vast majority of residents were satisfied with comfort in their buildings (Section 6.6 and Figure 6.22), extending this finding to cooler climates and supporting similar research on vernacular buildings in warm climates (Li et al., 2013; Dili et al., 2010). Vernacular buildings are often well suited to their micro climates and can have original features that can be utilised by residents to improve comfort (Hawkes and Lawrence, 2021; Khan, 2018; Henry, 2007), something also demonstrated by some of the case studies' soft retrofits (Section 5.3). Improvements to comfort may therefore not a be substantial driver for retrofit for a significant number of residents. This is likely to have implications for the amount of time and money that residents are prepared to spend on retrofitting activities and the levels of disruption that they are prepared to tolerate (Section 5.4).

There were also indications that, although survey respondents and case study participants identified some challenges with comfort in their buildings - for example around moisture management, limited window size, or draughts- they may have greater tolerance of these issues due to the historic nature of the building (Section 6.6). Residents' comfort perceptions therefore appeared to be informed by their heritage values, suggesting that some heritage buildings may acquire 'heritage residents' who actively reframe some of the inconveniences of their homes as 'part of the character'.

Energy behaviours however do not tend to form part of retrofit policy, which instead focusses on the standard technical characteristics of buildings. One of the reasons for this may be that policy makers' comments on energy behaviours can often be negatively linked to people suffering from the devastating effects of fuel poverty (Ambrose, 2022; Mason, 2013; Wintour, 2013). This is especially the case in times of rising fuel bills, and it is critical that people in fuel poverty receive appropriate, substantial, and effective support. There is therefore a need to conduct reasonable national conversations about the potential benefits of low energy behaviours, and appropriate and desirable standards of comfort.

10.5 Differences in modelled energy performance

Older buildings are routinely identified as inefficient, high energy users, which is commonly used as a key justification for retrofitting (European Commission, 2020). However, this was not reflected in the actual energy performance of the vernacular buildings in this research (Section 7.3). The individual energy performance of the case studies was around average for the UK and collectively slightly lower than average if calculated per building area (Section 7.3 and Figure 7.5).

Some aspects of vernacular building performance were found to be better than that of more modern buildings, such as the very positive performance of these buildings in warm weather, which was highlighted by most residents in the survey and case study interviews and supported by the energy diary data (Section 6.7). This aspect is particularly important given the predictions of higher future temperatures and increased numbers of extreme heat events. It also contrasts well with some more modern buildings which are increasingly being highlighted as suffering from overheating (Bateson, 2018; Adekunle and Nikolopoulou, 2014). These findings add to previous research showing that some vernacular buildings perform better in reality than generally assumed (Hawkes and Lawrence, 2021; Pracchi, 2014; Cardinale et al., 2013; Cantin et al., 2010).

Some residents also identified that, in contrast to the older parts of their buildings, it was their more modern extensions which tended to have poor performance and therefore often led to discomfort (Section 6.6). This is appeared to be a result of poor-quality construction for these extensions but may also be enhanced by some residents' heritage perceptions and general dislike of modern construction (Section 4.6).

It is therefore important to understand all aspects of vernacular buildings' technical performance, such as an ability to keep cool in hot weather, and opportunities to make use of any existing features -such as traditional shutters, draught porches, or high levels of thermal mass- as part of sensitive and effective retrofitting approaches. Retrofits should therefore be undertaken which recognise, enhance, and take advantage of, these features and do not prejudice their performance. Retrofits which reduce the effect of the building's thermal mass through excessive internal wall insulation for example, could negatively affect its ability to keep cool in hot weather.

At the same time however there needs to be recognition of the moisture challenges that affect some older buildings, often as a result of previous maladaptions, and of the support that residents may need to help to mitigate or manage these issues and undertake appropriate maintenance (Section 6.6). This research has emphasised that helping vernacular buildings to perform as well as they can and helping residents to manage their buildings' performance most effectively, is an important first step prior to undertaking retrofit. Understanding how the building currently functions is also important to avoid future retrofits leading to maladaption.

There is a broad trend for the energy simulation models used to create energy performance certificates across Europe to overestimate the actual energy demand of older buildings (Majcen et al., 2013; Sunikka-Blank and Galvin, 2012). While the actual energy demand of the case study buildings was found to be around or slightly lower than average for the UK, based on fuel bills and meter readings, RdSAP substantially overestimated energy use for almost all buildings (Section 7.2 and 7.3). It is therefore probable that poor representation of vernacular buildings in standard models is partly responsible for these buildings' reputation for high energy demand.

These simulation models assume standard energy behaviours, and the very clear differences between these assumptions and the actual behaviours that residents were found to engage in is one of two main factors that make such simulation models inaccurate for vernacular buildings. For the case study buildings this led to significant overestimations of demand for space heating and DHW (Section 7.3 and Figure 7.11). Meanwhile electricity use was underestimated because RdSAP does not include electricity demand other than lighting or heating, ignoring plug loads. As a compliance and comparison tool, the use of standard behaviours may be logical and is designed to show the energy efficiency of the building fabric, unobscured by individual behaviours (BRE and DECC, 2014). RdSAP though, because of its ubiquity, limited data requirements, and use in government schemes (Godefroy et al., 2021), has become a standard tool used to inform energy retrofitting. EPCs are also being increasingly used across Europe to encourage energy retrofitting through mandating Minimum Energy Efficiency Standards (CCC, 2020). EPC data is also often used to develop Government policy. For these types of use - informing and encouraging retrofitting and shaping future policy- it is critical that an accurate picture of actual building energy demand is developed, which needs to take account of residents' real energy behaviours.

The second reason that these models are inaccurate for vernacular buildings is the poor representation of traditional construction types and materials. RdSAP was found in this research to significantly overestimate u-values for the case study buildings compared with more detailed modelling tools (Section 7.4), supporting findings in other research (Li et al., 2015; Hulme and Doran, 2014). It was also found to have very poor options for modelling specific building constructions and their variations, (Section 8.2 and Table 8.1) and does not take account of a building's state of repair (Alembic Research et al., 2019). The actual condition and performance of building fabric and systems should therefore be accounted for if these models are to inform retrofitting.

The fact that RdSAP significantly overestimates energy demand and associated carbon emissions from vernacular buildings means that any carbon savings will also be overestimated and could lead to retrofits which are neither cost nor carbon effective. In the case studies, the carbon savings from improvement to the future policy target of EPC band C were overestimated by more than 50% by RdSAP (Section 9.4). This was partly because of inaccuracies in the calculated baseline energy demand and partly because of RdSAP's out-of-date carbon factors (Section 7.3). The majority of the recommended measures were also unacceptable to the heritage values of the case study residents, meaning that they would be highly unlikely to be enacted in reality (Section 9.4 and Figure 9.3). This research therefore supports findings across Europe on the unsuitability of the models which inform EPCs for existing buildings. This study suggests that RdSAP, as a policy tool to promote and inform the retrofitting of vernacular buildings, is not fit for purpose in its current form. This clearly means that national carbon targets will be jeopardised if, as shown by this research, the suggested measures are unlikely to be enacted and, even if they are, will lead to much lower than predicted carbon savings.

In order to reduce carbon emissions through retrofit, an improved understanding of the actual performance of vernacular buildings is required, based on actual data and accurate, calibrated models, rather than the predictions of current standard models. Consistently good decisions need to be based on accurate and specific data and appropriate and relevant information. More detailed models than the two standard UK modelling tools were found to be required for all cases to enable a reasonable representation of actual energy demand (Section 8.2). Improved models are therefore needed which better reflect the construction of vernacular buildings and the interaction between residents' behaviours and their homes.

10.6 Calculations of realistic carbon reduction potential

The carbon saving potential of a range of retrofit measures was examined. When lifecycle carbon, rather than just operational carbon, was considered the measures that led to the greatest savings were varied, and some measures failed to make savings, in fact leading to increased lifecycle carbon (Section 8.5). It is therefore critical to ensure that lifecycle, rather than only operational, carbon is calculated for retrofit projects.

A range of 'soft retrofits' which some residents already used, where found in this research to lead to potential carbon reduction (Section 5.3 and 8.5). There is a lack of technical data on the veracity and efficiency of some of these types of measures but there is significant qualitative data to show their value to residents, and, for the more traditional measures, clear historical antecedents for their efficacy in vernacular buildings (Pender and Lemieux, 2020; Khan, 2018). These types of measures are often neglected in current retrofit approaches.

It was possible to at least partially model curtains, shutters and wall hangings in this research and they were found to have useful carbon reduction potential, with shutters for example providing greater lifecycle savings than window replacement for some cases (Section 8.8, Table 8.13-14). These soft retrofits are likely be more acceptable in planning policies as well as to residents, be more flexible to changing future needs and present less risk of maladaption (Section 5.4). They were found to have low embodied carbon and are also likely have less financial cost. While individually these measures may not lead to significant carbon savings, they could play an important role as part of a broader retrofit strategy and be easier to enact more rapidly and at scale.

The modelling and analysis of a range of retrofit packages as opposed to single measures, meanwhile demonstrated that significant lifecycle carbon savings were readily achievable through retrofit (Chapter Nine). The retrofit packages examined a range of different scenarios, which made lifecycle savings for all but one of the case studies. The package of measures that were acceptable to residents led to potential carbon reductions which, if scaled up, could have a substantial effect on national emissions from the existing built environment (Section 9.7). In fact, because these changes *were* acceptable to residents and would be likely to mainly have a lower financial cost, they are more likely to be enacted by residents. This contrasts with Package 1, modelling measures to reach EPC band C, which made a similar level of lifecycle carbon savings but with measures that would have much greater heritage impact and therefore be much less likely to be undertaken (Section 9.3). The window of opportunity to mitigate the climate crisis is very limited, so retrofit measures that have the potential to be applied rapidly and which could be acceptable at scale will have significant benefits, even if their individual savings on a household level are modest.

It is likely however that a deeper level of retrofitting will be required for most vernacular buildings if climate goals are to be met (Wade and Visscher, 2021). This research showed that there was potential to reduce annual carbon emissions by around two thirds and energy demand by around a half, while taking into account some of the factors which constrain retrofitting in these buildings, with tailored measures for each case study (Section 9.8). Substantial lifecycle savings were still found to be possible without internal or external wall insulation, which is rarely acceptable to residents. These savings were possible as a result of the other fabric improvements, such as floor insulation, loft insulation and window improvements, and through behavioural and heating system changes (Section 9.8 and 9.10). Significant lifecycle savings can therefore be made while retaining much of the heritage value that residents were found to identify in their homes. This level of predicted savings would be quite consistent with the goals of the European Renovation Wave strategy, which suggests that carbon emissions from European buildings need to be reduced by 60% by 2030 and that deep retrofit is considered to be that which reduces energy consumption by at least 60% (European Commission, 2020).

10.7 Recommendations for policy and practice

The context of this research, and the individual case studies, are highly specific. However, the findings are broadly applicable to vernacular buildings in other regions and countries, and therefore to both national and international policies on carbon reduction from existing buildings.

One key message is that retrofit professionals and policy makers must recognise that many residents are likely to invest significant values in their vernacular buildings, both designated and undesignated (Section 4.2). Residents do not currently feel that standard retrofit ‘offers’ in policy are suitable for their building or consistent with their values, showing that there is currently a lack of such recognition (Section 5.5). If retrofits are not acceptable to residents’ values, they will not enact them, thus failing to reach retrofit targets for a considerable percentage of the building stock.

The key barrier to retrofit in these properties was identified as being around the complex factors that residents have to negotiate when making retrofit decisions (Section 5.4 and 5.5). Importantly the research suggests that retrofit recommendations for a particular building need to be, and be seen to be, independent, and not associated with business interests or with government funding for specific, single measure solutions. This may have implications for the current policy focus on heat pump installation for example and was emphasised by the case study interviews and survey results (Section 5.5). Instead, local authorities could lead the dissemination of information, so that residents receive appropriate information targeted at their heritage -including undesignated- buildings which recognises their heritage values. Community-led one stop shops may also have useful potential to reduce the management burden of retrofitting on residents, while retrofit networks through which residents could share knowledge, could help with the provision of information that is both relevant and perceived as trustworthy. Increased support for the upskilling of tradespeople may also be required to enable the upscaling of retrofit (Simpson et al., 2021), especially for vernacular buildings.

Residents’ energy behaviours and comfort perceptions are also currently neglected in building policies, which generally focus on the technical potential of buildings (Bordass, 2020). Increased recognition of the role that residents play in energy demand is required (Chapter Six and Chapter Seven). This suggests that there is a need for a national conversation about the importance of behavioural change in helping to reduce carbon from residential buildings, as highlighted by the detailed modelling results (Chapter Eight and Nine). This discussion could be informed by the behaviours identified in some of the case studies around localised heating practices and personal insulation (Section 6.4 and 6.5). However, this conversation should be clearly separated from discussions of fuel poverty, which separately requires a policy focus.

A further key finding is that current energy models are unsuited to heritage buildings. EPC results have been frequently shown to vary from measured performance and this research has shown that this is significantly exacerbated for heritage buildings. This is because these models tend to significantly underestimate the performance of traditional materials (Section 7.3), fail to reflect heritage residents' behaviours (Chapters Six and Seven), and produce recommendations that are mainly unacceptable to residents' heritage values, and which are therefore highly unlikely to be enacted (Section 9.4).

These models should not, therefore, be used as a policy tool to encourage or even mandate retrofit measures, without significant improvements to their accuracy. Better standard models are required, and retrofitting should be informed by actual, current, building performance and condition.

Within the UK it has been suggested that RdSAP for existing buildings should be replaced with the full Standard Assessment Procedure (SAP), currently used for new buildings, which is much more detailed (Godefroy et al., 2021). SAP however still uses standardised behavioural assumptions (BRE and DECC, 2014) and would require improvement to the way it represents the performance of traditional materials. The benefits and challenges of using steady state versus dynamic calculation tools should also be considered. The ability to tailor models to residents' specific behaviours and calibration with actual energy demand is also necessary to enable modelling tools to inform retrofitting and identify more realistic savings (Section 8.2). Behaviours could be included in a separate model or module. The calibrated model including behaviours should however be a requirement in policies to mandate for the retrofit of buildings via MEES. Assessments of actual performance after retrofit should also be required to help identify and reduce performance gaps.

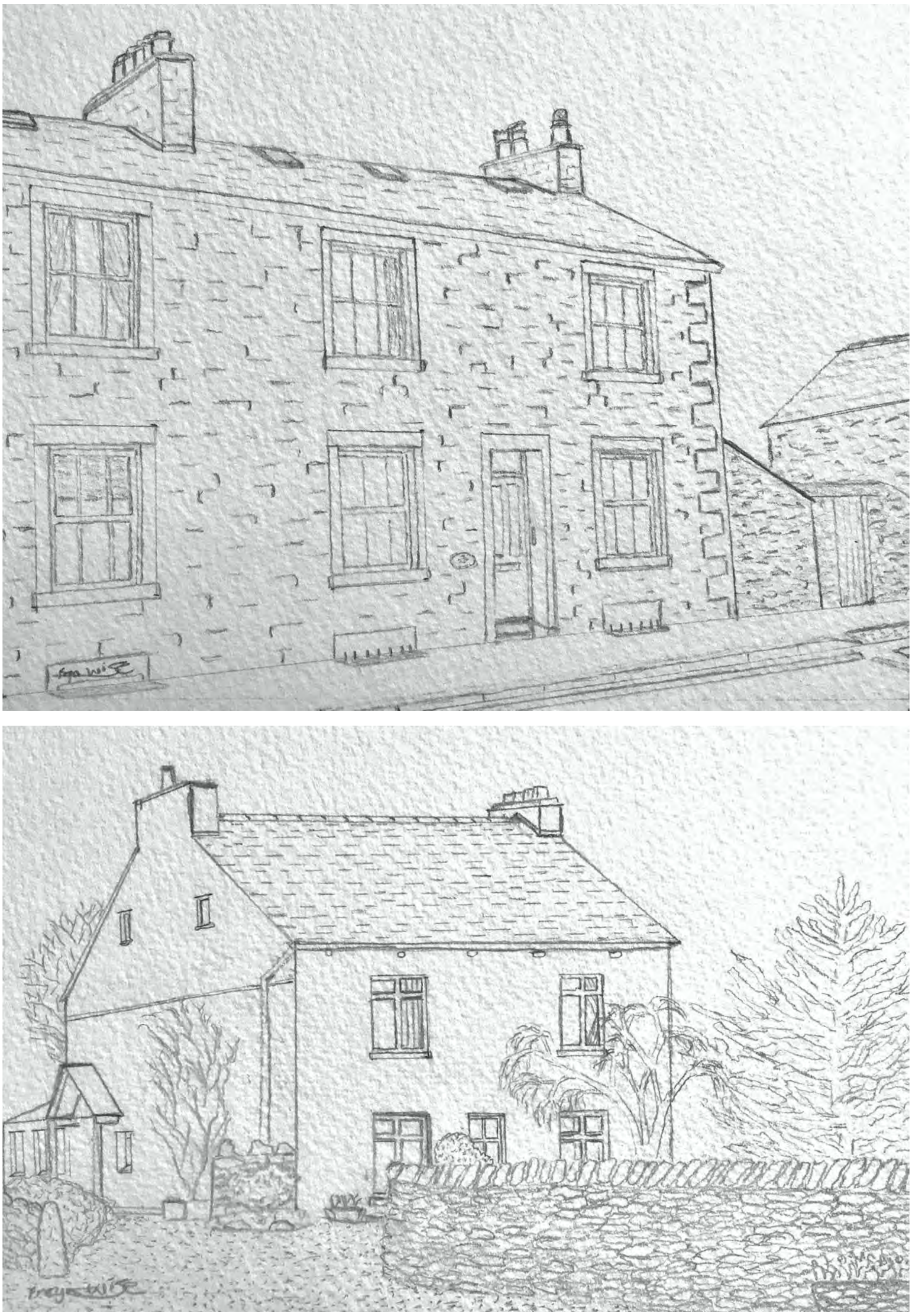
While significant carbon reductions from all buildings should be mandated, this study also found that many vernacular buildings are perceived to perform well by their residents and demonstrated the importance of identifying and retaining positive aspects of vernacular building performance (Section 6.6 and 6.7). Commonly used justifications for retrofitting vernacular buildings should be interrogated and may need revising, as poor energy and comfort performance may be less of an issue than is generally assumed. The recent PAS35 standard may help to encourage a more detailed approach to the assessment of actual building performance. The potential benefits of ‘soft’ retrofits has been another important finding of this research and suggests that there may be significant opportunities for carbon reduction through the deployment of these measures, either individually, or as complementary actions to a larger package of retrofit (Sections 5.3, 8.5 and 9.8). There may also be positive synergies between these measures and an increased consideration of residents’ energy behaviours. Many soft retrofits furthermore have the potential to be installed by the residents themselves, thus reducing pressure on the construction industry.

Linked to this finding is the importance of lifecycle carbon. Policymakers should ideally mandate the consideration of embodied carbon costs as well as operational carbon savings for all retrofit projects, as this has important ramifications (Section 8.4). Further, it should be ensured that retrofit measures and projects do in fact achieve lifecycle savings, as the lifecycle analysis in this research has shown that this is not a guarantee (Section 8.5). In some countries the calculation of lifecycle carbon is now being mandated through inclusion in building regulations and linked to the granting of planning permission for new build and substantial retrofit (Kuittinen and

Häkkinen, 2020). The calculation of lifecycle carbon is likely to continue to become less onerous as environmental product declarations (EPDs) become available for ever more products (Anderson, 2022a). This research has emphasised the critical importance of a lifecycle approach for retrofit.

Overall, this research has found that an approach is needed that considers residents and their buildings as having individual and context specific interdependent relationships. Such an approach must take a holistic view of factors including the values, views, and behaviours of residents and the actual construction, condition, and energy performance of their buildings, from a lifecycle perspective, to inform the most appropriate retrofit measures. There is no single solution or set of solutions that will be appropriate for every context and every home, but there will be ways to reduce carbon while retaining heritage if an approach that acknowledges and accounts for these varied factors is taken. Such an approach is needed if the retrofit of vernacular buildings is to be increased to the scale required to meet climate goals and to mitigate climate change, while retaining the heritage values of the buildings that shape our urban and rural built environments.

Figure 10.1: CS15 and CS16



Chapter 11. Retrofit to retain heritage and reduce carbon

11.1 Limitations and future research recommendations

The findings of this research have begun to fill some of the gaps identified in the literature, and a number of areas for further research have been identified as a result, and because of the inherent limitations of a single piece of research by one individual.

Because this research has focussed on a particular geographic area it is context specific. However since the findings suggest vernacular buildings and residents, -and therefore appropriate retrofits- are individual and context specific, it is likely that the results are relevant to other vernacular buildings in other contexts. Because participation in the research was voluntary those who took part are likely to have a prior interest in the issues investigated, thus providing a level of positive confirmation bias. The cases and survey however covered a good range of different attitudes, behaviours, demographics, and levels of wealth and energy demand. In addition, because a range of topics around heritage and energy were considered, some residents were more focussed on heritage aspects and some on sustainability, thus providing a range of views.

Further research with residents in rented accommodation would be likely to produce a different perspective on the barriers and opportunities for retrofitting. Residents might also have a different relationship with their building and the heritage values that they might invest in it than owner-occupiers. Further research with residents in rented properties could therefore be useful.

It would also be interesting to undertake similar research in a very different area to Cumbria, for example a densely populated urban setting or another country, to see how much findings differed in different contexts. It may be that residents in an alternative setting would have less of a connection with their wider environment, or local materials for example. However their connection might just be expressed differently since previous urban studies have identified that residents still invest heritage values in their homes (Fouseki et al., 2020; Eriksson, 2018; Sunikka-Blank and Galvin, 2016).

Large scale research into the comfort perceptions of residents in both heritage and non-heritage buildings would also be valuable. Research into residents' perceptions of comfort could also be supported by quantitative measurements of indoor environmental quality across a range of parameters to form a fuller view of how the UK building stock actually performs. This type of research would provide a better understanding of residents' motivations for retrofit and potentially help to identify groups or building types to prioritise. Residents who identify as being in fuel poverty for example are likely to have much more negative perceptions of thermal comfort and therefore probable different attitudes to retrofit (de Chavez et al., 2017).

This research has found some suggestions that residents' energy behaviours may be influenced by the historic nature of their buildings. It would be valuable to pursue this further, perhaps through a comparative study of the behaviours of similar households in vernacular and more modern buildings. This could help inform retrofit policy and tools for these buildings.

Cost was identified as a significant barrier to retrofit by the residents in this research and general consideration of the likely financial impact of the modelled retrofit measures was provided. However, in the future, financial calculations could add a more nuanced and detailed understanding of the likely scalability of the measures identified and their economic viability for individuals and at a national level.

There were some challenges with the more detailed energy modelling. The appropriate modelling of insulation to ground floors and the use of specific sizing data for ground source heat pumps could not be resolved. This means that these results are likely to be less accurate. Efforts were made to mitigate these challenges as much as possible and to explicitly acknowledge where they might affect the results.

Further opportunities to test baseline models and calibrate them with additional data would therefore be beneficial to improve the veracity of models and to improve understanding of the retrofit effects for these buildings. Additional data collection methods such as the use of data loggers to gather temperature and energy data over a prolonged period, on site weather monitoring, the use of blower door tests, or similar, to determine specific air infiltration for each case study building, and in-situ u-value measurements of key construction assemblies would all be beneficial in a future project if greater financial resources were available.

The need for enhanced ventilation post retrofit was considered unlikely and thus not included in modelling because of high baseline ventilation levels and residents' active engagement in managing ventilation but more detailed consideration would be valuable. Assessments of the hygrothermal impact of the retrofit measures were also not undertaken due to time and cost constraints. Measures considered likely to present issues were highlighted in the text and precautionary principles were used. However further, more detailed investigation of this topic would be valuable to understand maladaption risks.

There were also challenges with data for some of the operational and embodied assessments, such as modelling the effect of wall hangings or calculating the embodied impact of curtains. These challenges required a number of assumptions to be made and for proxies to be used in some cases. These proxies and assumptions were based on conservative estimates to reduce over-reporting of their efficiency. Furthermore, for the embodied assessment some elements were not possible to assess, such as the impact of the scaffolding which would be required to install some measures. Most A5 stage impacts were therefore not assessed, although for retrofitting it is unlikely that this phase would result in a significant proportion of the total embodied emissions. The lifespans of products were also taken from manufacturer data, which may not be reflective of real-world performance. The cumulative effect of these aspects is that the embodied impact of the individual retrofit measures will have been underestimated.

Where possible, the assumptions that have been made have been explicitly stated so that they can be interrogated and so that the process is replicable. Underlying data has also been made available where this does not prejudice participant anonymity.

Much more data on, and assessment of, the embodied and lifecycle impact of different retrofit measures and packages to identify measures that lead to the greatest lifecycle savings is therefore needed. Studies which just focus on operational impacts should be encouraged to also consider an embodied and lifecycle perspective and this needs to be a significant area of future research.

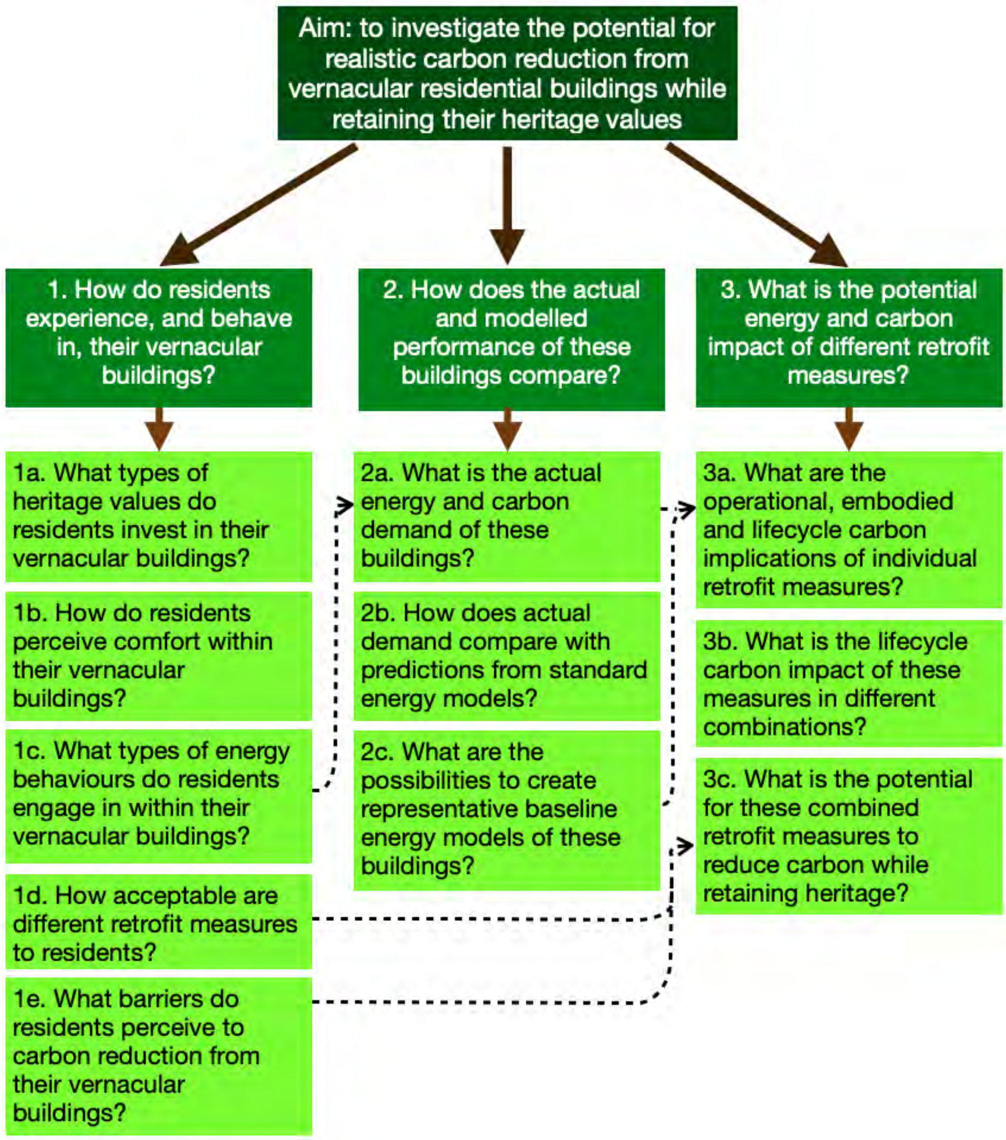
Finally, further investigation into what this research has termed 'soft retrofits' would be beneficial, to quantify the energy and comfort impacts of these soft retrofits through experimental empirical research. It would also be worth examining how these effects could be assessed in energy simulation models, given that these measures have some of the greatest potential to be rapidly enacted and therefore begin making savings.

11.2 Conclusions

Reducing emissions from the built environment, including the significant proportion of vernacular buildings with heritage values, is a critical priority to help meet climate targets and prevent devastating climate change (IPCC, 2022b). Both the scale and effectiveness of retrofitting these buildings needs to be significantly accelerated, in order to reduce carbon while retaining the heritage values that shape the character of urban and rural areas (Wade and Visscher, 2021; Herrera-Avellanosa et al., 2019).

The aim of this research was to investigate the potential for realistic carbon reduction from vernacular residential buildings while retaining their heritage values. Three research questions and eleven sub-questions framed the research (Figure 11.1) and were explored in the context of vernacular buildings in the County of Cumbria through a case study research design and a range of mixed methods, involving a wide range of different buildings, and residents with a range of household characteristics, behaviours, and views. The questions were informed by an exploration of the literature. This identified that the views, values, and behaviours of residents required more investigation to understand their impact on energy use and retrofit decisions, as did the ability of energy simulation models to reflect heritage building performance, and the lifecycle impacts of retrofit measures.

Figure 11.1 Research aim, questions and sub-questions revisited



In responding to the research questions, it was found that, to identify the potential for retrofitting to reduce carbon and retain values, residents and their buildings must be understood as having an interdependent relationship. Residents' heritage values, and the connections that they feel to their buildings, determine the acceptability of retrofitting. Heritage values also affect perceptions of comfort. These comfort perceptions play a significant role in determining residents' energy behaviours which strongly influence the energy used in the building. This energy use then needs to be more accurately reflected in energy simulation models in order to identify the energy and carbon-reduction potential of retrofit measures. These measures, or packages of measures, also need to be assessed from a lifecycle perspective to ensure actual carbon savings are achieved. This intermeshed relationship of residents and their buildings is currently not understood, nor included in retrofit policies. It must therefore be given much greater prominence in both policy and practice if the maximum carbon savings are to be made.

The significant values that residents invest in their buildings are currently unacknowledged in policy approaches and have received very little research attention (RsQ1a). Given their significant effect on the acceptability of retrofit options and therefore their enactment by residents, however, this needs to change (RsQ1d). If retrofit activity is to be scaled up, retrofit 'offers' through government schemes need to take account of these values and help residents to negotiate measures that are acceptable to their values. The values of Cumbrian residents appear to have a strong and specific local connection however this is likely to have parallels in other areas. Informational barriers mean that residents are often not aware of any acceptable retrofit measures or lack trust in the information sources. Access to specific and trusted information is therefore a key barrier which needs to be addressed, along with the cost of measures and access to suitable tradespeople (RsQ1e). One stop retrofit shops and local peer-to-peer information networks may help mitigate some of these barriers.

The energy behaviours that heritage residents engage in (RsQ1c), and their comfort perceptions (RsQ1b), also differ from standard assumptions and may be influenced by their heritage values. Climate goals will not be met without widespread behavioural, as well as technical changes (IEA, 2021), so greater engagement with actual residential behaviours is critical. There is a need for national conversations on acceptable and desirable levels of comfort and on the types of behavioural changes that could be encouraged for carbon reduction. Approaches to retrofit should engage with residents' behaviours and motivations to encourage positive low energy behaviours. This research has also shown that more attention should be paid to 'soft retrofits' which, while challenging to model and often considered to be outside the traditional scope of retrofitting, have the potential to improve comfort and reduce carbon at low financial cost.

Better models are needed to assess the energy used in vernacular buildings and thus reduce the performance gap between actual and predicted carbon savings (RQ2). In particular, RdSAP, the model used for producing EPCs, should not be used to inform the retrofit of vernacular buildings in its current form as it is not fit for purpose (RsQ2b). To provide a more accurate representation of building energy demand, and to inform retrofit, models need to take residents' behaviours into account, better reflect traditional construction and be calibrated with actual measured energy demand (RsQ2a and RsQ2c). The positive aspects of older buildings, such as excellent summer performance, should be acknowledged in retrofit approaches and retrofits should enhance or at least not inhibit these aspects. More recognition of, and support for, maintenance and moisture management for older buildings is also required.

Retrofit approaches must consider the lifecycle impact of different measures, not only their operational impact, because embodied carbon was found to significantly affect the carbon saving potential of measures (RsQ3a). These measures need to be considered in combination (RsQ3b) and in the context of residents' views, values, and behaviours, if they are to lead to actual carbon savings (RsQ3c). Single measure approaches will not produce sufficient levels of carbon reduction and there is no one-size-fits all solution.

In conclusion, this research has identified significant constraints resulting from current retrofit approaches which often focus on technical aspects, rely on inaccurate standard assumptions and models which are not fit for purpose, and neglect the role of residents. Current levels of retrofit are therefore not leading to the carbon reductions required from the existing built environment to mitigate climate change. However this research has also shown that lifecycle carbon reductions from heritage buildings, which are consistent with crucial global (IPCC, 2022b) and European (European Commission, 2020) carbon reduction targets for 2030, *are* both *possible* and *realistic* while still retaining heritage values. To do this however requires an approach which treats residents and their buildings as having a symbiotic relationship. This holistic approach must take into account the specific values, motivations and behaviours of residents, the actual performance of vernacular buildings, and the lifecycle carbon of retrofit measures. Only then will it lead to the scale of retrofit for existing residential buildings which is urgently needed to help mitigate the climate crisis and avoid devastating climate change.

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References

Abdul Hamid, A., Johansson, D. and Bagge, H. (2020) ‘Ventilation measures for heritage office buildings in temperate climate for improvement of energy performance and IEQ’, *Energy and Buildings*, vol. 211, p. 109822 [Online]. DOI: 10.1016/j.enbuild.2020.109822.

ACT (2014) *The State of Rural Cumbria - Fuel Poverty Update*, Penrith, ACTion with Communities in Cumbria [Online]. Available at http://www.cumbriaaction.org.uk/Resources-Publications/Research-Other-Publications (Accessed 1 June 2020).

Adams, C., Douglas-Jones, R., Green, A., Lewis, Q. and Yarrow, T. (2014) ‘Building with History: Exploring the Relationship between Heritage and Energy in Institutionally Managed Buildings’, *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 167–181 [Online]. DOI: 10.1179/1756750514Z.00000000053.

Adekunle, T. O. and Nikolopoulou, M. (2014) ‘Post-occupancy and indoor monitoring surveys to investigate the potential of summertime overheating in UK prefabricated timber houses’, *Proceedings of 8th Windsor Conference:*, Cumberland Lodge, Windsor, Network for comfort and energy use in buildings, p. 19.

Adekunle, T. O. and Nikolopoulou, M. (2018) ‘Post-occupancy evaluation on people’s perception of comfort, adaptation and seasonal performance of sustainable housing: a case study of three prefabricated structural timber housing developments’, *Intelligent Buildings International*, no. 0, pp. 1–29 [Online]. DOI: 10.1080/17508975.2018.1493677.

AECB (n.d.) *The AECB CarbonLite™ Retrofit course* [Online]. Available at https://aecb.net/the-aecb-carbonlite-retrofit-online-training-course/ (Accessed 24 March 2022).

Akande, O. K., Odeleye, D. and Coday, A. (2014) ‘Energy efficiency for sustainable reuse of public heritage buildings: the case for research’, *International Journal of Sustainable Development and Planning*, vol. 9, no. 2, pp. 237–250 [Online]. DOI: 10.2495/SDP-V9-N2-237-250.

Akkurt, G. G., Aste, N., Borderon, J., Buda, A., Calzolari, M., Chung, D., Costanzo, V., Del Pero, C., Evola, G., Huerto-Cardenas, H. E., Leonforte, F., Lo Faro, A., Lucchi, E., Marletta, L., Nocera, F., Pracchi, V. and Turhan, C. (2020) ‘Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions’, *Renewable and Sustainable Energy Reviews*, vol. 118, p. 109509 [Online]. DOI: 10.1016/j.rser.2019.109509.

Alaszewski, A. (2020) ‘Diaries’, in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J., W., and Williams, R., A. (eds), *SAGE Research Methods Foundations*, London, SAGE Publications Ltd, vol. a [Online]. DOI: 10.4135/9781526421036760284 (Accessed 15 March 2022).

Albrecht, J. and Hamels, S. (2021) ‘The financial barrier for renovation investments towards a carbon neutral building stock – An assessment for the Flemish region in Belgium', *Energy and Buildings*, vol. 248, p. 111177 [Online]. DOI: 10.1016/j.enbuild.2021.111177.

Alembic Research, Energy Action Scotland and Waterfield, P. (2019) *A Review of Domestic and Non-Domestic Energy Performance Certificates in Scotland: Research report for the Scottish Government, Heat, Energy Efficiency and Consumers Unit - Final Report*, Scottish Government.

Almeida, M., Ferreira, M. and Barbosa, R. (2018) 'Relevance of Embodied Energy and Carbon Emissions on Assessing Cost Effectiveness in Building Renovation—Contribution from the Analysis of Case Studies in Six European Countries', *Buildings*, vol. 8, no. 8, p. 103 [Online]. DOI: 10.3390/buildings8080103.

Altomonte, S., Allen, J., Bluyssen, P. M., Brager, G., Heschong, L., Loder, A., Schiavon, S., Veitch, J. A., Wang, L. and Wargocki, P. (2020) 'Ten questions concerning well-being in the built environment', *Building and Environment*, vol. 180, p. 106949 [Online]. DOI: 10.1016/j.buildenv.2020.106949.

Ambrose, J. (2022) 'E.ON says sorry for sending socks to customers with advice to keep warm', *The Guardian*, Online, 14th January [Online]. Available at https://www.theguardian.com/business/2022/jan/14/eon-says-sorry-for-sending-socks-to-customers-with-advice-to-keep-warm (Accessed 14 February 2022).

American Assocation of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) (2019) *ASHRAE Terminology* [Online]. Available at https://www.ashrae.org/technical-resources/authoring-tools/terminology (Accessed 20 May 2019).

Anderson, B. (2016) 'Laundry, energy and time: Insights from 20 years of time-use diary data in the United Kingdom', *Energy Research & Social Science*, vol. 22, pp. 125–136 [Online]. DOI: 10.1016/j.erss.2016.09.004.

[Anderson, B] and Kosmina, L. (2019) *Conventions for U-value calculations*, BRE Report, Watford, BRE [Online]. Available at https://www.brebookshop.com/details.jsp?id=328041 (Accessed 1 June 2021).

Anderson, J. (2022a) *Environmental Product Declarations (EPD) for UK manufactured construction products* [Online]. Available at https://constructionlca.co.uk/uk_epd/ (Accessed 16 March 2022).

Anderson, J. (2022b) 'Biogenic carbon and EPDs (personal communication)',.

André, M., De Vecchi, R. and Lamberts, R. (2020) 'User-centered environmental control: a review of current findings on personal conditioning systems and personal comfort models', *Energy and Buildings*, vol. 222, p. 110011 [Online]. DOI: 10.1016/j.enbuild.2020.110011.

Andres, L. (2012) *Designing & Doing Survey Research*, London, SAGE Publications, Ltd [Online]. DOI: 10.4135/9781526402202 (Accessed 5 July 2019).

Anon (2021) ‘The World at One’, *The World at One*, Broadcasting House, London, BBC Radio Four [Online]. Available at https://www.bbc.co.uk/programmes/m000x6vw (Accessed 14 February 2022).

Arksey, H. and Knight, P. (1999) *Interviewing for Social Scientists*, London, SAGE Publications, Ltd [Online]. DOI: 10.4135/9781849209335 (Accessed 15 March 2022).

Ascione, F., Bianco, N., De Masi, R. F., Mastellone, M., Mauro, G. M. and Vanoli, G. P. (2020) ‘The role of the occupant behavior in affecting the feasibility of energy refurbishment of residential buildings: Typical effective retrofits compromised by typical wrong habits’, *Energy and Buildings*, vol. 223, p. 110217 [Online]. DOI: 10.1016/j.enbuild.2020.110217.

Ascione, F., Bianco, N., De Masi, R. F., de’Rossi, F. and Vanoli, G. P. (2015) ‘Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value’, *Energy and Buildings*, vol. 95, pp. 172–183 [Online]. DOI: 10.1016/j.enbuild.2014.10.072.

Ascione, F., Cheche, N., Masi, R. F. D., Minichiello, F. and Vanoli, G. P. (2015) ‘Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building’, *Energy and Buildings*, vol. 99, pp. 162–176 [Online]. DOI: 10.1016/j.enbuild.2015.04.027.

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G. and Guattari, C. (2019) ‘Energy and environmental payback times for an NZEB retrofit’, *Building and Environment*, vol. 147, pp. 461–472 [Online]. DOI: 10.1016/j.buildenv.2018.10.047.

ASHRAE (2021) *ASHRAE Handbook Online* [Online]. Available at https://www.ashrae.org/technical-resources/ashrae-handbook/ashrae-handbook-online (Accessed 25 March 2022).

Aste, N., Torre, S. D., Adhikari, R. S., Buzzetti, M., Del Pero, C., Leonforte, F. and Manfren, M. (2016) ‘Sustainable church heating: The Basilica di Collemaggio case-study’, *Energy and Buildings*, vol. 116, pp. 218–231 [Online]. DOI: 10.1016/j.enbuild.2016.01.008.

Attia, S., Santos, M. C., Al-Obaidy, M. and Baskar, M. (2021) ‘Leadership of EU member States in building carbon footprint regulations and their role in promoting circular building design’, *IOP Conference Series: Earth and Environmental Science*, vol. 855, no. 1, p. 012023 [Online]. DOI: 10.1088/1755-1315/855/1/012023.

Australia ICOMOS (2013) *The Burra Charter: the Australia ICOMOS charter for places of cultural significance 2013*, International Council on Monuments and Sites [Online]. Available at http://australia.icomos.org/wp-content/uploads/The-Burra-Charter-2013-Adopted-31.10.2013.pdf (Accessed 3 December 2018).

Azmi, N. A. and Ibrahim, S. H. (2020) ‘A comprehensive review on thermal performance and envelope thermal design of mosque buildings’, *Building and Environment*, vol. 185, p. 107305 [Online]. DOI: 10.1016/j.buildenv.2020.107305.

Baker, H., Moncaster, A. and Al Tabbaa, A. (2017) ‘Decision-making for the demolition or adaptation of buildings’, *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, vol. 170, pp. 144–156.

Baker, H., Moncaster, A., Remøy, H. and Wilkinson, S. (2021) ‘Retention not demolition: how heritage thinking can inform carbon reduction’, *Journal of Architectural Conservation*, pp. 1–19 [Online]. DOI: 10.1080/13556207.2021.1948239.

Baker, P. (2011) *Historic Scotland Technical Paper 10: U-values and traditional buildings*, Technical Paper, Edinburgh, Historic Scotland.

Bakonyi, D. and Dobszay, G. (2016) ‘Simulation aided optimization of a historic window’s refurbishment’, *Energy and Buildings*, vol. 126, pp. 51–69 [Online]. DOI: 10.1016/j.enbuild.2016.05.005.

Balderstone, S. (2012) ‘Sustainable Heritage: How does it rate?’, *Historic Environment*, vol. 24, no. 2, p. 6.

Balvedi, B. F., Ghisi, E. and Lamberts, R. (2018) ‘A review of occupant behaviour in residential buildings’, *Energy and Buildings*, vol. 174, pp. 495–505 [Online]. DOI: 10.1016/j.enbuild.2018.06.049.

Bartiaux, F., Gram-Hanssen, K., Fonseca, P., Ozoliņa, L. and Christensen, T. H. (2014) ‘A practice–theory approach to homeowners’ energy retrofits in four European areas’, *Building Research & Information*, Routledge, vol. 42, no. 4, pp. 525–538 [Online]. DOI: 10.1080/09613218.2014.900253.

Bateson, A. (2018) *Residential design quality. Research report.*, Hoare Lea.

Ben, H. and Steemers, K. (2014) ‘Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London’, *Energy and Buildings*, vol. 80, pp. 120–130 [Online]. DOI: 10.1016/j.enbuild.2014.05.019.

Bennett, J. (2014) *Using Diaries and Photo Elicitation in Phenomenological Research: Studying Everyday Practices of Belonging in Place*, 1 Oliver’s Yard, 55 City Road, London EC1Y 1SP United Kingdom, SAGE Publications, Ltd. [Online]. DOI: 10.4135/978144627305014539100 (Accessed 15 March 2022).

Berg, F., Flyen, A.-C., Godbolt, Å. L. and Broström, T. (2017) ‘User-driven energy efficiency in historic buildings: A review’, *Journal of Cultural Heritage*, vol. 28, pp. 188–195 [Online]. DOI: 10.1016/j.culher.2017.05.009.

Berg, F. and Fuglseth, M. (2018) ‘Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway’, *Journal of Architectural Conservation*, vol. 24, no. 2, pp. 152–167 [Online]. DOI: 10.1080/13556207.2018.1493664.

Bertolin, C. and Loli, A. (2018) ‘Sustainable interventions in historic buildings: A developing decision making tool’, *Journal of Cultural Heritage*, Technoheritage 2017, vol. 34, pp. 291–302 [Online]. DOI: 10.1016/j.culher.2018.08.010.

Bieling, C. (2014) ‘Cultural ecosystem services as revealed through short stories from residents of the Swabian Alb (Germany)’, *Ecosystem Services*, vol. 8, pp. 207–215 [Online]. DOI: 10.1016/j.ecoser.2014.04.002.

Biesta, G. (2010) ‘Pragmatism and the Philosophical Foundations of Mixed Methods Research1’, in *SAGE Handbook of Mixed Methods in Social & Behavioral Research*, Thousand Oaks, SAGE Publications, Inc., pp. 95–118 [Online]. DOI: 10.4135/9781506335193.n4 (Accessed 20 June 2019).

Bin Marsono, A. K. and Balasbaneh, A. T. (2015) ‘Combinations of building construction material for residential building for the global warming mitigation for Malaysia’, *Construction and Building Materials*, vol. 85, pp. 100–108 [Online]. DOI: 10.1016/j.conbuildmat.2015.03.083.

Birgisdottir, H., Moncaster, A., Houlihan Wiberg, A., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lützkendorf, T. and Malmqvist, T. (2017) ‘IEA EBC Annex 57 ‘Evaluation of Embodied Energy and CO_{2eq} for Building Construction’’, *Energy and Buildings*, vol. 154, pp. 72–80 [Online]. DOI: 10.1016/j.enbuild.2017.08.030.

Bjarløv, S., Finken, G. and Odgaard, T. (2015) ‘Retrofit with Interior Insulation on Solid Masonry Walls in Cool Temperate Climates – An Evaluation of the influence of Interior Insulation Materials on Moisture Condition in the Building Envelope’, *Energy Procedia*, vol. 78, pp. 1461–1466 [Online]. DOI: 10/gmz4ns.

Bordass, B. (2020) ‘Metrics for energy performance in operation: the fallacy of single indicators’, *Buildings and Cities*, Ubiquity Press, vol. 1, no. 1, pp. 260–276 [Online]. DOI: 10.5334/bc.35.

Brager, G., Zhang, H. and Arens, E. (2015) ‘Evolving opportunities for providing thermal comfort’, *Building Research & Information*, vol. 43, no. 3, pp. 274–287 [Online]. DOI: 10.1080/09613218.2015.993536.

Brandão, F. J. da S., Paio, A., Sousa, J. P. and Rato, V. (2016) ‘Cork Re-Wall: Computational Methods of Automatic Generation and Digital Fabrication of Cork Partition Walls for Building Renovation’, *Gestão & Tecnologia de Projetos*, vol. 11, no. 2, pp. 9–24 [Online]. DOI: 10.11606/gtp.v11i2.114602.

Braun, V. and Clarke, V. (2006) ‘Using thematic analysis in psychology’, *Qualitative Research in Psychology*, vol. 3, no. 2, pp. 77–101 [Online]. DOI: 10.1191/1478088706qp063oa.

BRE (2018) *How to use iSBEM: Compliance Assessment UK (version 5.6.a)*, iSBEM User Guides, London [Online]. Available at https://www.uk-ncm.org.uk/download.jsp?id=13 (Accessed 7 January 2020).

BRE (2020a) ‘iSBEM’, [Online]. Available at https://www.uk-ncm.org.uk/index.jsp (Accessed 20 November 2020).

BRE (2020b) *Building Energy Performance Assessment* [Online]. Available at https://www.ncm-pcdb.org.uk/sap/pcdbsearch.jsp?pid=26 (Accessed 5 January 2021).

BRE and Department for Energy and Climate Change (DECC) (2014) 'The Government's Standard Assessment Procedure for Energy Rating of Dwellings: 2012 edition', BRE, Watford.

Bristol City Council (2015) *A Bristolian's Guide to Solid Wall Insulation: A guide to the responsible retrofit of traditional homes in Bristol*, Bristol, Bristol City Council [Online]. Available at http://files.site-fusion.co.uk/webfusion58199/file/2015_bristolsolidwallinsulationguidance.pdf (Accessed 10 January 2019).

British Standards Institute (2020) *BS EN ISO 6946:2017 Building components and building elements-Thermal resistance and thermal transmittance-Calculation methods*, British Standards Institute.

British Standards Institute (BSI) (2020) *PAS2035:2019 Retrofitting dwelling for improved energy efficiency - specification and guidance*, British Standards Institute.

Broderick, Á., Byrne, M., Armstrong, S., Sheahan, J. and Coggins, A. M. (2017) 'A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing', *Building and Environment*, vol. 122, pp. 126–133 [Online]. DOI: 10.1016/j.buildenv.2017.05.020.

Broström, T., Eriksson, P., Liu, L., Rohdin, P., Ståhl, F. and Moshfegh, B. (2014) 'A Method to Assess the Potential for and Consequences of Energy Retrofits in Swedish Historic Buildings', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 150–166 [Online]. DOI: 10.1179/1756750514Z.00000000055.

Brunskill, R. W. (2010) *Traditional Buildings of Cumbria: The County of the Lakes*, 2nd edn, Yale University Press in Association with Peter Crawley.

BSI (2012) *BS EN 15978:2011 Sustainability of construction works-Assessment of environmental performance of buildings-calculation method*, British Standards Institute [Online]. (Accessed 21 November 2021).

BSI (2019) *BS EN 16798-2019: Energy performance of buildings -ventilation for buildings*, Standard, British Standards Institute [Online]. (Accessed 1 February 2022).

BSI (2020) *BS EN ISO 14040:2006+A1:2020 Environmental management - life cycle assessment - principles and framework*, British Standards Institute.

Bullen, P. A. and Love, P. E. D. (2011) 'Adaptive reuse of heritage buildings', *Structural Survey*, vol. 29, no. 5, pp. 411–421 [Online]. DOI: 10.1108/02630801111182439.

Byrne, D. (2020) 'Case-Based Methods', in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J., W., and Williams, R., A. (eds), *SAGE Research Methods Foundations*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781526421036884898 (Accessed 9 March 2022).

Byrne, D. and Ragin, C. (2009) *The SAGE Handbook of Case-Based Methods*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781446249413 (Accessed 13 November 2019).

Cabeza, L. F., de Gracia, A. and Pisello, A. L. (2018) 'Integration of renewable technologies in historical and heritage buildings: A review', *Energy and Buildings*, vol. 177, pp. 96–111 [Online]. DOI: 10.1016/j.enbuild.2018.07.058.

Cadw (2011) *Criteria for assessing historic buildings for the purposes of grant assistance*, Welsh Government [Online]. Available at https://cadw.gov.wales/docs/cadw/publications/Criteria_assessing_grant_assistance_ENG.pdf (Accessed 5 April 2019).

Cadw (2018) *Understanding Listing in Wales*, Advice and support, Cardiff, Cadw [Online]. Available at https://cadw.gov.wales/advice-support/historic-assets/listed-buildings/understanding-listing#section-introduction.

Cantin, R., Burgholzer, J., Guarracino, G., Moujalled, B., Tamelikecht, S. and Royet, B. G. (2010) 'Field assessment of thermal behaviour of historical dwellings in France', *Building and Environment*, vol. 45, no. 2, pp. 473–484 [Online]. DOI: 10.1016/j.buildenv.2009.07.010.

Carbon Coop (2022) *People Powered Retrofit* [Online]. Available at https://retrofit.coop/ (Accessed 14 February 2022).

Cardinale, N., Rospi, G. and Stefanizzi, P. (2013) 'Energy and microclimatic performance of Mediterranean vernacular buildings: The Sassi district of Matera and the Trulli district of Alberobello', *Building and Environment*, vol. 59, pp. 590–598 [Online]. DOI: 10.1016/j.buildenv.2012.10.006.

Carlucci, S., Bai, L., de Dear, R. and Yang, L. (2018) 'Review of adaptive thermal comfort models in built environmental regulatory documents', *Building and Environment*, vol. 137, pp. 73–89 [Online]. DOI: 10.1016/j.buildenv.2018.03.053.

Carratt, A., Kokogiannakis, G. and Daly, D. (2020) 'A critical review of methods for the performance evaluation of passive thermal retrofits in residential buildings', *Journal of Cleaner Production*, vol. 263, p. 121408 [Online]. DOI: 10.1016/j.jclepro.2020.121408.

Cassar, M. (2009) 'Sustainable heritage: challenges and strategies for the twenty-first century', *Journa of Preservation Technology*, vol. 40, no. 1, p. 9.

Cassar, M. and Fouseki, K. (2014) 'My Historic Environment', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 226–228 [Online]. DOI: 10.1179/1756750514Z.00000000057.

Cellura, M., Ciulla, G., Guarino, F., Longo, S., Cellura, M., Ciulla, G., Guarino, F. and Longo, S. (2017) 'Redesign of a Rural Building in a Heritage Site in Italy: Towards the Net Zero Energy Target', *Buildings*, vol. 7, no. 3, p. 68 [Online]. DOI: 10.3390/buildings7030068.

CEN (2017) 'EN 16883:2017 Conservation of cultural heritage - guidelines for improving the energy performance of historic buildings', British Standards Institute (BSI) [Online]. Available at https://shop.bsigroup.com/en/ProductDetail/?pid=000000000030322690.

Chambers, J., Gori, V., Biddulph, P., Hamilton, I. and Oreszczyn, T. (2020) 'How solid is our knowledge of solid walls? - Comparing energy savings through three different methods', Lausanne, pp. 107–112.

Chartered Institution of Building Services Engineers (CIBSE) (2022) *New Embodied Carbon Calculator for Building Services* [Online]. Available at https://www.cibse.org/news-and-policy/february-2022/new-embodied-carbon-calculator-for-building-servic (Accessed 4 March 2022).

de Chavez, A. C., Gilbertson, J., Tod, A. M., Nelson, P., Powell-Hoyland, V., Homer, C., Lusambili, A. and Thomas, B. (2017) 'Using environmental monitoring to complement in-depth qualitative interviews in cold homes research', *Indoor and Built Environment*, vol. 26, no. 7, pp. 937–950 [Online]. DOI: 10.1177/1420326X17719491.

Chiang, Y. H., Li, J., Zhou, L., Wong, F. K. W. and Lam, P. T. I. (2015) 'The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong', *Journal of Cleaner Production*, vol. 109, pp. 326–335 [Online]. DOI: 10.1016/j.jclepro.2014.07.069.

CIBSE (2016) *Environmental Design: CIBSE Guide A*, 8th edn, London, CIBSE Publications [Online]. Available at https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I79JAAS (Accessed 1 April 2021).

Clarke, L., Gleeson, C. P. and Winch, C. (2016) 'What kind of expertise is needed for low energy construction', *Construction Management and Econonomics*, Taylor & Francis, vol. 35, no. 3, pp. 78–89.

Climate.OneBuilding (2021) *Repository of free climate data for building performance simulation* [Online]. Available at http://climate.onebuilding.org/default.html (Accessed 13 October 2021).

Coghlan, D. and Brydon-Miller, M. (2014) *The SAGE Encyclopedia of Action Research*, Thousand Oaks, SAGE Publications Ltd [Online]. DOI: 10.4135/9781446294406 (Accessed 20 June 2019).

Committee on Climate Change (CCC) (2020) *The Sixth Carbon Budget: The UK's path to Net Zero*, UK Committee on Climate Change [Online]. Available at https://www.theccc.org.uk/publication/sixth-carbon-budget/ (Accessed 29 March 2021).

Conejos, S., Langston, C., Chan, E. H. W. and Chew, M. Y. L. (2016) 'Governance of heritage buildings: Australian regulatory barriers to adaptive reuse', *Building Research & Information*, vol. 44, no. 5–6, pp. 507–519 [Online]. DOI: 10.1080/09613218.2016.1156951.

Cosar-Jorda, P., Buswell, R. A. and Mitchell, V. A. (2019) 'Quantifying energy demand reduction considering householder willingness to apply measures', *Building Research & Information*, vol. 0, no. 0, pp. 1–15 [Online]. DOI: 10.1080/09613218.2019.1630245.

Cozza, S., Chambers, J., Deb, C., Scartezzini, J.-L., Schlüter, A. and Patel, M. K. (2020) 'Do energy performance certificates allow reliable predictions of actual energy consumption and savings? Learning from the Swiss national database', *Energy and Buildings*, vol. 224, p. 110235 [Online]. DOI: 10.1016/j.enbuild.2020.110235.

Crawford, R. H., Czerniakowski, I. and Fuller, R. J. (2010) 'A comprehensive framework for assessing the life-cycle energy of building construction assemblies', *Architectural Science Review*, vol. 53, no. 3, pp. 288–296 [Online]. DOI: 10.3763/asre.2010.0020.

Creswell, J. W. and Creswell, J. D. (2018) *Research Design: Qualitative, quantitative, and mixed methods approaches*, 5th edn, London, Sage Publications Ltd.

Crilly, N., Blackwell, Alan. F. and Clakson, J. (2013) 'Graphic Elicitation: Using Research Diagrams as Interview stimuli', in Jason, H. (ed), *SAGE Visual Methods*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781446268520 (Accessed 15 March 2022).

Crishna, N., Goodsir, S., Banfill, P. F. G. and Baker, K. (2010) *Embodied Carbon in Natural Building Stone in Scotland*, Tehcnical Paper, Historic England [Online]. Available at https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=8c3ebef1-ba50-40cb-ab75-a59400e2b74b.

Cumbria Intelligence Observatory (2020a) *Cumbria Observatory – Environment.webloc* [Online]. Available at https://www.cumbriaobservatory.org.uk/environment/ (Accessed 20 April 2020).

Cumbria Intelligence Observatory (2020b) *Cumbria Observatory – Housing.webloc* [Online]. Available at https://www.cumbriaobservatory.org.uk/housing/ (Accessed 20 April 2020).

Cumbria Local Enterprise Partnership (2019) *Cumbria's Local Industrial Strategy*, Cumbria Local Enterprise Partnership [Online]. Available at https://www.thecumbrialep.co.uk/governance-and-accountability/strategy-plans/.

Curtis, R. (2010) 'Climate Change and Traditional Buildings: The Approach Taken by Historic Scotland', *Journal of Architectural Conservation*, vol. 16, no. 3, pp. 7–27 [Online]. DOI: 10.1080/13556207.2010.10785073.

D'Alessandro, F., Bianchi, F., Baldinelli, G., Rotili, A. and Schiavoni, S. (2017) 'Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance', *Journal of Building Engineering*, vol. 11, pp. 56–68 [Online]. DOI: 10.1016/j.jobe.2017.03.012.

Davenport, M. A. and Anderson, D. H. (2005) 'Getting From Sense of Place to Place-Based Management: An Interpretive Investigation of Place Meanings and Perceptions of Landscape Change', *Society & Natural Resources*, Routledge, vol. 18, no. 7, pp. 625–641 [Online]. DOI: 10.1080/08941920590959613.

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V. S., De Simone, M., Kjærgaard, M. B., Pritoni, M., Schlüter, A., Peng, Y., Schweiker, M., Fajilla, G., Becchio, C., Fabi, V., Spigliantini, G., Derbas, G. and Pisello, A. L. (2020) 'A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort', *Building and Environment*, vol. 178, p. 106920 [Online]. DOI: 10.1016/j.buildenv.2020.106920.

Dayana Networks Ltd (2021) 'Voice Record Pro 7', BejBej Apps [Online]. Available at https://www.bejbej.ca.

De Wolf, C., Pomponi, F. and Moncaster, A. (2017) 'Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice', *Energy and Buildings*, vol. 140, pp. 68–80 [Online]. DOI: 10.1016/j.enbuild.2017.01.075.

Deliotte, R. E. (2017) *Heritage Works: A toolkit of best practice in heritage regeneration*, Historic England [Online]. Available at https://historicengland.org.uk/images-books/publications/heritage-works/ (Accessed 27 March 2019).

Denyer, S. (1991) *Traditional Buildings and Life in The Lake District*, 1st edn, London, Victor Gollancz Ltd/Peter Crawley in association with The National Trust, vol. 1.

Department for Business, Energy and Industrial Strategy (BEIS) (2020a) *Domestic private rented property: minimum energy efficiency standard - landlord guidance* [Online]. Available at https://www.gov.uk/guidance/domestic-private-rented-property-minimum-energy-efficiency-standard-landlord-guidance (Accessed 21 December 2020).

Department for Business, Energy and Industrial Strategy (BEIS) (2020b) *Green Homes Grant: make energy improvements to your home* [Online]. Available at https://www.gov.uk/guidance/apply-for-the-green-homes-grant-scheme (Accessed 21 December 2020).

Department for Business, Energy and Industrial Strategy (BEIS) (2020c) *BEIS 20219 Updated Energy and Emissions Projections: web figures*, Energy and Emissions projections, London, UK Government.

Department for Business, Energy and Industrial Strategy (BEIS) (2020d) *2019 UK greenhouse gas emissions, provisional figures*, National Statistics.

Department for Business, Energy and Industrial Strategy (BEIS) (2021a) *Heat and Buildings strategy*, Westminster, UK Government [Online]. Available at https://www.gov.uk/government/publications/heat-and-buildings-strategy.

Department for Business, Energy and Industrial Strategy (BEIS) (2021b) *Greenhouse gas reporting: conversion factors 2021* [Online]. Available at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021 (Accessed 11 January 2022).

Department for Business, Energy and Industrial Strategy (BEIS) and National Statistics (2021) *NAtional Energy Efficiency Data-Framework (NEED): Summary of Analysis, Great Britain 2021 (for May 2019 to May 2020)*, NEED reports, BEIS [Online]. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1008681/need-report-2021.pdf (Accessed 10 January 2021).

Department for Communities and Local Government (DCLG) (2017) *A guide to energy performance: certificates for the marketing, sale and let of dwellings: Improving the energy efficiency of our buildings.*, London, UK Government.

DesignBuilder Software Ltd (2020a) *Linear Thermal Bridges at Junctions* [Online]. Available at https://designbuilder.co.uk/helpv6.0/#LinearThermalBridges.htm?Highlight=linear%20bridge (Accessed 12 October 2021).

DesignBuilder Software Ltd (2020b) *Construction layer data* [Online]. Available at https://designbuilder.co.uk/helpv6.0/ (Accessed 12 October 2021).

Dili, A. S., Naseer, M. A. and Varghese, T. Z. (2010) 'Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings', *Energy and Buildings*, vol. 42, no. 11, pp. 2139–2150 [Online]. DOI: 10.1016/j.enbuild.2010.07.004.

Doyle, L., Brady, A.-M. and Byrne, G. (2016) 'An overview of mixed methods research – revisited', *Journal of Research in Nursing*, vol. 21, no. 8, pp. 623–635 [Online]. DOI: 10.1177/1744987116674257.

Dubois, M. and Allacker, K. (2015) 'Energy savings from housing: Ineffective renovation subsidies vs efficient demolition and reconstruction incentives', *Energy Policy*, vol. 86, pp. 697–704 [Online]. DOI: 10.1016/j.enpol.2015.07.029.

Ealiwa, M. A., Taki, A. H., Howarth, A. T. and Seden, M. R. (2001) 'An investigation into thermal comfort in the summer season of Ghadames, Libya', *Building and Environment*, vol. 36, no. 2, pp. 231–237 [Online]. DOI: 10.1016/S0360-1323(99)00071-2.

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P. and Castellazzi, L. (2020) 'Review of 50 years of EU energy efficiency policies for buildings', *Energy and Buildings*, vol. 225, p. 110322 [Online]. DOI: 10.1016/j.enbuild.2020.110322.

Edwards, J. (2020) 'Retrofitting traditional buildings for improved energy performance in the context of BSI PAS 2035', *Journal of Building Survey, Appraisal & Valuation*, vol. 9, no. 4, pp. 294–304.

Electronic Temperature Instruments LTD (2020) *Digital Max Min thermometer for home, office or garden* [Online]. Available at https://thermometer.co.uk/home-thermometers/1258-digital-max-min-thermometer-for-home-office-or-garden.html (Accessed 22 December 2020).

Energie Sprong UK (2022) *Energie Sprong Home* [Online]. Available at https://www.energiesprong.uk/ (Accessed 25 February 2022).

Energy Communities Tipperary Cooperative (2022) *Energy Communities Tipperary Cooperative* [Online]. Available at https://energycommunitiestipp.ie/ (Accessed 14 February 2022).

EPD International (n.d.) *International EPD System* [Online]. Available at https://environdec.com/about-us/the-international-epd-system-about-the-system (Accessed 16 March 2022).

Eriksson, P. (2018) ‘Character defining elements : Relations between heritage regulations, user perspectives and energy saving objectives’, *Energy Efficiency in Historic Buildings 2018*, Uppsala University, pp. 549–556 [Online]. Available at https://urn:nbn:se:uu:diva-379648 (Accessed 14 August 2020).

Eriksson, P., Hermann, C., Hrabovszky-Horváth, S. and Rodwell, D. (2014) ‘EFFESUS Methodology for Assessing the Impacts of Energy-Related Retrofit Measures on Heritage Significance’, *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 132–149 [Online]. DOI: 10.1179/1756750514Z.00000000054.

Eriksson, P., Milić, V. and Brostrom, T. (2019) ‘Balancing preservation and energy efficiency in building stocks’, *International Journal of Building Pathology and Adaptation*, Emerald Publishing Limited, vol. 38, no. 2, pp. 356–373 [Online]. DOI: 10.1108/IJBPA-02-2019-0025.

EU Directive (2010) *European Parliament, Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast),* [Online]. Available at https://eur-lex.europa.eu/eli/dir/2010/31/oj (Accessed 18 June 2019).

EU Directive (2018) ‘Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency’, *Official Journal of the European Union*, vol. L 156, no. 75 [Online]. Available at http://data.europa.eu/eli/dir/2018/844/oj.

European Academies Science Advisory Council (EASAC) (2021) *Decarbonisation of buildings: for climate, health and jobs*, EASAC Policy Report, Halle, Germany [Online]. Available at www.easac.eu.

European Commission (2020) *A Renovation Wave for Europe-greening our buildings, creating jobs, improving lives*, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions, Brussels [Online]. Available at https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1835 (Accessed 27 June 2021).

European Commission (2021) *Level(s) European Framework for sustainable buildings* [Online]. Available at https://ec.europa.eu/environment/levels_en (Accessed 4 March 2022).

European Commission (2022) *Energy performance of buildings directive* [Online]. Available at https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (Accessed 3 March 2022).

European Commission: Directorate General for Education, Youth, Sport and Culture (2021) *Workshop on complementary funding for cultural heritage: background paper and selected good practices*, Workplan for Culture 2019-2022, European Commission.

European Consumer Organisation (BEUC) (2021) *How to make green and healthy housing affordable for all consumers*, BEUC Position Paper, Brussels.

Fabbri, K. (2013) 'Energy incidence of historic building: Leaving no stone unturned', *Journal of Cultural Heritage*, vol. 14, no. 3, Supplement, pp. e25–e27 [Online]. DOI: 10.1016/j.culher.2012.12.010.

Fawcett, T. and Topouzi, M. (2019) 'The time dimension in deep renovation: evidence and analysis from across the EU', *ECEEE Summer Study Proceedings*, p. 6 [Online]. Available at https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2019/7-make-buildings-policies-great-again/the-time-dimension-in-deep-renovation-evidence-and-analysis-from-across-the-eu/.

Fawcett, T. and Topouzi, M. (2020) 'Residential retrofit in the climate emergency: the role of metrics', *Buildings and Cities*, Ubiquity Press, vol. 1, no. 1, pp. 475–490 [Online]. DOI: 10.5334/bc.37.

Federal Energy Management Program (2015) *M&V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4*, US Department of Energy.

Ferreira, J., Duarte Pinheiro, M. and de Brito, J. (2015) 'Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction - A Portuguese benchmarking', *Journal of Building Engineering*, vol. 3, pp. 114–126 [Online]. DOI: 10.1016/j.jobe.2015.07.001.

Ferreira, J., Pinheiro, M. D. and Brito, J. de (2013) 'Refurbishment decision support tools review—Energy and life cycle as key aspects to sustainable refurbishment projects', *Energy Policy*, vol. 62, pp. 1453–1460 [Online]. DOI: 10.1016/j.enpol.2013.06.082.

Ferretti, V., Bottero, M. and Mondini, G. (2014) 'Decision making and cultural heritage: An application of the Multi-Attribute Value Theory for the reuse of historical buildings', *Journal of Cultural Heritage*, vol. 15, no. 6, pp. 644–655 [Online]. DOI: 10.1016/j.culher.2013.12.007.

Fisk, W. J., Singer, B. C. and Chan, W. R. (2020) 'Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data', *Building and Environment*, vol. 180, p. 107067 [Online]. DOI: 10.1016/j.buildenv.2020.107067.

Flyvbjerg, B. (2006) 'Five Misunderstandings About Case-Study Research', *Qualitative Inquiry*, vol. 12, no. 2, pp. 219–245 [Online]. DOI: 10.1177/1077800405284363.

Fouseki, K. and Cassar, M. (2014) 'Energy Efficiency in Heritage Buildings — Future Challenges and Research Needs', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 95–100 [Online]. DOI: 10.1179/1756750514Z.00000000058.

Fouseki, K., Newton, D., Murillo Camacho, K. S., Nandi, S. and Koukou, T. (2020) 'Energy Efficiency, Thermal Comfort, and Heritage Conservation in Residential Historic Buildings as Dynamic and Systemic Socio-Cultural Practices', *Atmosphere*, Multidisciplinary Digital Publishing Institute, vol. 11, no. 6, p. 604 [Online]. DOI: 10.3390/atmos11060604.

Franzoni, E., Volpi, L., Bonoli, A., Spinelli, R. and Gabrielli, R. (2018) 'The environmental impact of cleaning materials and technologies in heritage buildings conservation', *Energy and Buildings*, vol. 165, pp. 92–105 [Online]. DOI: 10.1016/j.enbuild.2018.01.051.

Friedman, K. and Cooke, A. (2012) 'Is UK Planning a barrier to energy efficient heritage retrofit: a comparative analysis of a selection of London Boroughs', *Proceedings Retrofit 2012*, Salford, p. 13 [Online]. (Accessed 29 October 2020).

Friedman, K. S. (2015) 'Examining English Planning as a barrier to the thermal improvement of conservation properties', Cambridge, University of Cambridge.

Fugard, A. and Potts, H. W. W. (2020) 'Thematic Analysis', in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J., W., and Williams, R., A. (eds), *SAGE Research Methods Foundations*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781526421036858333 (Accessed 15 March 2022).

Gagliano, A., Patania, F., Nocera, F. and Signorello, C. (2014) 'Assessment of the dynamic thermal performance of massive buildings', *Energy and Buildings*, vol. 72, pp. 361–370 [Online]. DOI: 10.1016/j.enbuild.2013.12.060.

Galvin, R. (2015) *The Rebound Effect in Home Heating : A guide for policymakers and practitioners*, Routledge [Online]. DOI: 10.4324/9781315696942 (Accessed 19 March 2021).

Galvin, R. and Sunikka-Blank, M. (2014) 'The UK homeowner-retrofitter as an innovator in a socio-technical system', *Energy Policy*, vol. 74, pp. 655–662 [Online]. DOI: 10.1016/j.enpol.2014.08.013.

Galvin, R. and Sunikka-Blank, M. (2016) 'Quantification of (p)rebound effects in retrofit policies – Why does it matter?', *Energy*, vol. 95, pp. 415–424 [Online]. DOI: 10.1016/j.energy.2015.12.034.

Gerhardsson, K. M. and Laike, T. (2021) 'Windows: a study of residents' perceptions and uses in Sweden', *Buildings and Cities*, vol. 2, no. 1, p. 467 [Online]. DOI: 10.5334/bc.120.

Ghisleni, C. (2020) '"What is Vernacular Architecture?" [O que é arquitetura vernacular?]' (trans. T. Duduch), *ArchDaily* [Online]. Available at https://www.archdaily.com/951667/what-is-vernacular-architecture (Accessed 16 February 2022).

Gigliarelli, E., Calcerano, F. and Cessari, L. (2016) 'Implementation Analysis and Design for Energy Efficient Intervention on Heritage Buildings', *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*, Springer, Cham, pp. 91–103 [Online]. DOI: 10.1007/978-3-319-48496-9_8 (Accessed 24 October 2018).

Gillich, A., Saber, E. M. and Mohareb, E. (2019) 'Limits and uncertainty for energy efficiency in the UK housing stock', *Energy Policy*, vol. 133, p. 110889 [Online]. DOI: 10.1016/j.enpol.2019.110889.

Gillott, M. C., Loveday, D. L., White, J., Wood, C. J., Chmutina, K. and Vadodaria, K. (2016) 'Improving the airtightness in an existing UK dwelling: The challenges, the measures and their effectiveness', *Building and Environment*, vol. 95, pp. 227–239 [Online]. DOI: 10.1016/j.buildenv.2015.08.017.

Ginks, N. and Painter, B. (2017) 'Energy retrofit interventions in historic buildings: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK', *Energy and Buildings*, vol. 149, pp. 391–399 [Online]. DOI: 10.1016/j.enbuild.2017.05.039.

Giraudet, L.-G., Bourgeois, C. and Quirion, P. (2021) 'Policies for low-carbon and affordable home heating: A French outlook', *Energy Policy*, vol. 151, p. 112140 [Online]. DOI: 10.1016/j.enpol.2021.112140.

Given, L. (2008) *The SAGE Encyclopedia of Qualitative Research Methods: Semi-Structured Interview*, Thousand Oaks, SAGE Publications, Inc. [Online]. DOI: 10.4135/9781412963909 (Accessed 12 October 2021).

Glew, D., Johnston, D., Miles-Shenton, D. and Thomas, F. (2019) 'Retrofitting suspended timber ground-floors; comparing aggregated and disaggregated evaluation methods', *Building Research & Information*, vol. 0, no. 0, pp. 1–15 [Online]. DOI: 10.1080/09613218.2019.1681927.

Glew, D., Smith, M. B., Miles-Shenton, D. and Gorse, C. (2017) 'Assessing the quality of retrofits in solid wall dwellings', *International Journal of Building Pathology and Adaptation*, vol. 35, no. 5, pp. 501–518 [Online]. DOI: 10.1108/IJBPA-05-2017-0022.

Global Alliance for Buildings and Construction, International Energy Agency, and United Nations Environment Program (2021) '2021 Global Status Report for Buildings and Construction: Towards a zero-emission, efficient and resilient buildings and construction sector', p. 105.

Godefroy, J., Mylona, A., Parker, J., Warwick, E., Bagenal George, C., Chorafa, M., Murray, C., Watson, Z., Oreszczyn, T., Evans, B., Jain, S., Brown, C., Collin, R., Gwilliam, T., Tadlock, L., Worboys, C. and Lefevre, T. (2021) *Making SAP and RdSAP 11 fit for Net Zero*, Compiled for BEIS and DCLG [Online]. Available at https://www.cibse.org/getmedia/f2f29503-5af3-4adf-b7e0-dc2d13bd2225/20200344-SAP11-Scoping-project-report-Rev-K-(FULL-REPORT).pdf.aspx.

Gomm, R., Hammersley, M. and Foster, P. (2000) *Case Study Method: Key Issues, Key Texts*, London, SAGE.

Gong, X., Nie, Z., Wang, Z., Cui, S., Gao, F. and Zuo, T. (2012) 'Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing', *Journal of Industrial Ecology*, vol. 16, no. 4, pp. 576–587 [Online]. DOI: 10.1111/j.1530-9290.2011.00415.x.

Goodhew, S. and Griffiths, R. (2005) 'Sustainable earth walls to meet the building regulations', *Energy and Buildings*, vol. 37, no. 5, pp. 451–459 [Online]. DOI: 10.1016/j.enbuild.2004.08.005.

Gram-Hanssen, K. (2013) 'Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption?', *Energy Efficiency*, vol. 6, no. 3, pp. 447–457 [Online]. DOI: 10.1007/s12053-012-9184-4.

Gram-Hanssen, K. (2014) 'Retrofitting owner-occupied housing: remember the people', *Building Research & Information*, Routledge, vol. 42, no. 4, pp. 393–397 [Online]. DOI: 10.1080/09613218.2014.911572.

Gram-Hanssen, K., Georg, S., Christiansen, E. and Heiselberg, P. (2018) 'What next for energy-related building regulations? the occupancy phase', *Building Research & Information*, Routledge, vol. 46, no. 7, pp. 790–803 [Online]. DOI: 10.1080/09613218.2018.1426810.

Gram-Hanssen, K., Jensen, J. O. and Friis, F. (2018) 'Local strategies to promote energy retrofitting of single-family houses', *Energy Efficiency*, vol. 11, no. 8, pp. 1955–1970 [Online]. DOI: 10.1007/s12053-018-9653-5.

Greater London Authority (2021) *The London Plan: The Spacial Development Strategy for Greater London*, London, Greater London Authority [Online]. Available at https://www.london.gov.uk/sites/default/files/the_london_plan_2021.pdf#page=357.

Griffiths, R. and Goodhew, S. (2015) 'Thermal properties of cob retrofitted with external hemp–lime', *Proceedings of the Institution of Civil Engineers - Construction Materials*, vol. 170, no. 1, pp. 55–67 [Online]. DOI: 10.1680/jcoma.15.00029.

Grytli, E., Kværness, L., Rokseth, L. S. and Ygre, K. F. (2012) 'The Impact of Energy Improvement Measures on Heritage Buildings', *Journal of Architectural Conservation*, vol. 18, no. 3, pp. 89–106 [Online]. DOI: 10.1080/13556207.2012.10785120.

Haines, V. and Mitchell, V. (2014) 'A persona-based approach to domestic energy retrofit', *Building Research & Information*, Routledge, vol. 42, no. 4, pp. 462–476 [Online]. DOI: 10.1080/09613218.2014.893161.

Hamot, L., Dugdale, H. and Boennec, O. (2020) *Regrigerants and Environmental Impacts: A best practice guide*, Elementa [Online]. Available at https://www.elementaconsulting.com/news/refrigerants-environmental-impacts/ (Accessed 1 January 2022).

Hampton, S. (2017) 'An ethnography of energy demand and working from home: Exploring the affective dimensions of social practice in the United Kingdom', *Energy Research & Social Science*, vol. 28, pp. 1–10 [Online]. DOI: 10.1016/j.erss.2017.03.012.

Hansen, A. R., Gram-Hanssen, K. and Knudsen, H. N. (2018) 'How building design and technologies influence heat-related habits', *Building Research & Information*, vol. 46, no. 1, pp. 83–98 [Online]. DOI: 10.1080/09613218.2017.1335477.

Harrestrup, M. and Svendsen, S. (2015) 'Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture', *Building and Environment*, vol. 85, pp. 123–133 [Online]. DOI: 10.1016/j.buildenv.2014.12.005.

Hawkes, D. and Lawrence, R. (2021) 'Climate, comfort, and architecture in Elizabethan England: an environmental study of Hardwick Hall', *The Journal of*

Architecture, vol. 26, no. 6, pp. 861–892 [Online]. DOI: 10.1080/13602365.2021.1962389.

Hellwig, R. T., Teli, D., Schweiker, M., Choi, J.-H., Lee, M. C. J., Mora, R., Rawal, R., Wang, Z. and Al-Atrash, F. (2019) 'A framework for adopting adaptive thermal comfort principles in design and operation of buildings', *Energy and Buildings*, vol. 205, p. 109476 [Online]. DOI: 10.1016/j.enbuild.2019.109476.

Henry, M. C. (2007) 'The Heritage Building Envelope as a Passive and Active Climate Moderator: Opportunities and Issues in Reducing Dependency on Air-Conditioning', *Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies, April 2007,* Tenerife, Spain, The Getty Conservation Institute, p. 32 [Online]. Available at http://www.getty.edu/conservation/our_projects/science/climate/paper_henry.pdf.

Herrera-Avellanosa, D., Haas, F., Leijonhufvud, G., Brostrom, T., Buda, A., Pracchi, V., Webb, A. L., Hüttler, W. and Troi, A. (2019) 'Deep renovation of historic buildings: The IEA-SHC Task 59 path towards the lowest possible energy demand and CO2 emissions', *International Journal of Building Pathology and Adaptation*, Emerald Publishing Limited, vol. 38, no. 4, pp. 539–553 [Online]. DOI: 10.1108/IJBPA-12-2018-0102.

Hiller, C. (2015) 'Factors influencing residents' energy use—A study of energy-related behaviour in 57 Swedish homes', *Energy and Buildings*, vol. 87, pp. 243–252 [Online]. DOI: 10.1016/j.enbuild.2014.11.013.

Historic England (2015) *Conservation Areas | Historic England* [Online]. Available at http://historicengland.org.uk/advice/hpg/has/conservation-areas/ (Accessed 27 October 2020).

Historic England (2019a) *Listed Buildings | Historic England* [Online]. Available at https://historicengland.org.uk/listing/what-is-designation/listed-buildings/ (Accessed 17 June 2019).

Historic England (2019b) *Historic England - Its role in heritage protection | Historic England* [Online]. Available at https://historicengland.org.uk/advice/hpg/publicandheritagebodies/eh/ (Accessed 3 July 2019).

Historic England (2020) *There's no place like old homes: Re-use and Recycle to Reduce Carbon*, Heritage Counts, Historic England.

Historic England (2022) *Saving Energy in your Home* [Online]. Available at https://historicengland.org.uk/advice/your-home/saving-energy/ (Accessed 14 February 2022).

Historic Environment Scotland (2019) *Scotland's Listed Buildings*, Edinburgh, Historic Environment Scotland [Online]. Available at https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=34c90cb9-5ff3-45c3-8bc3-a58400fcbc44.

Historic Environment Scotland (n.d.) *Saving Energy in Traditional Buildings* [Online]. Available at https://www.historicenvironment.scot/advice-and-support/your-property/saving-energy-in-traditional-buildings/ (Accessed 14 February 2022).

HM Government (2021) *The Building Regulations 2010: The Merged Approved Documents*, London, HM Government [Online]. Available at https://www.gov.uk/guidance/building-regulations-and-approved-documents-index (Accessed 5 January 2022).

Hong, S. H., Gilbertson, J., Oreszczyn, T., Green, G. and Ridley, I. (2009) 'A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment', *Building and Environment*, vol. 44, no. 6, pp. 1228–1236 [Online]. DOI: 10.1016/j.buildenv.2008.09.003.

House of Commons Environmental Audit Committee (2021) *Energy Efficiency of Existing Homes: Fourth Report of Session 2019-21*, Westminster, the House of Commons [Online]. Available at https://committees.parliament.uk/publications/5171/documents/52521/default/.

Hrovatin, N. and Zorić, J. (2018) 'Determinants of energy-efficient home retrofits in Slovenia: The role of information sources', *Energy and Buildings*, vol. 180, pp. 42–50 [Online]. DOI: 10.1016/j.enbuild.2018.09.029.

Hubbard, D. (2011) 'Ventilation, Infiltration and Air Permeability of Traditional UK Dwellings', *Journal of Architectural Conservation*, vol. 17, no. 3, pp. 59–73 [Online]. DOI: 10.1080/13556207.2011.10785097.

Hubbard, D. (2014) *Scotstarvit Tower Cottage*, Technical Paper, Endinburgh, Historic Scotland.

Hulme, J. and Doran, S. (2014) *In-situ measurements of wall U-values in English Housing*, BRE Report, Watford, BRE [Online]. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/409428/In-situ_u-values_final_report.pdf (Accessed 24 November 2020).

Humphreys, M., Nicol, F. and Roaf, S. (2011) *Keeping warm in a cooler house*, Historic Scotland Technical Papers, Historic Scotland [Online]. Available at https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f2f2ebfd-ff37-4417-be92-a59400bb2665.

IBM Corp (2017) 'SPSS Statistics for Macintosh, Version 25.0', Armonk, NY, IBM Corp.

Ibrahim, A., Ali, H., Abuhendi, F. and Jaradat, S. (2019) 'Thermal seasonal variation and occupants' spatial behaviour in domestic spaces', *Building Research & Information*, vol. 0, no. 0, pp. 1–15 [Online]. DOI: 10.1080/09613218.2019.1681928.

ICOMOS (1964) *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)*, Venice, Italy [Online]. Available at https://www.icomos.org/charters/venice_e.pdf (Accessed 20 May 2019).

IEA (2021) *Do we need to change our behaviour to reach net zero by 2050?*, Paris, IEA [Online]. Available at https://www.iea.org/articles/do-we-need-to-change-our-behaviour-to-reach-net-zero-by-2050?utm_source=SendGrid&utm_medium=Email&utm_campaign=IEA+newsletters (Accessed 15 November 2021).

Ingram, V., Banfill, P. F. G. and Kennedy, C. (2011) 'Towards an Objective Assessment of Energy Efficiency in Heritage Buildings', pp. 2018–2025 [Online]. DOI: 10.3384/ecp110572018 (Accessed 11 October 2018).

Intergovernmental panel on climate change (IPCC) (2022a) *Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future* [Online]. Available at https://www.ipcc.ch/2022/02/28/pr-wgii-ar6/ (Accessed 8 March 2022).

Intergovernmental panel on climate change (IPCC) (2022b) *The evidence is clear: the time for action is now. We can halve emissions by 2030. — IPCC* [Online]. Available at https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/ (Accessed 24 April 2022).

Ip, K. and Miller, A. (2012) 'Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK', *Resources, Conservation and Recycling*, vol. 69, pp. 1–9 [Online]. DOI: 10.1016/j.resconrec.2012.09.001.

ISO (2017) *ISO 10456:2007 Building materials and products -Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values* [Online]. Available at https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/09/40966.html (Accessed 25 March 2022).

Iyer-Raniga, U. and Wong, J. P. C. (2012) 'Evaluation of whole life cycle assessment for heritage buildings in Australia', *Building and Environment*, vol. 47, pp. 138–149 [Online]. DOI: 10.1016/j.buildenv.2011.08.001.

Jain, N., Burman, E., Stamp, S., Mumovic, D. and Davies, M. (2020) 'Cross-sectoral assessment of the performance gap using calibrated building energy performance simulation', *Energy and Buildings*, vol. 224, p. 110271 [Online]. DOI: 10.1016/j.enbuild.2020.110271.

Jensen, N. F., Bjarløv, S. P., Rode, C. and Møller, E. B. (2020) 'Hygrothermal assessment of four insulation systems for interior retrofitting of solid masonry walls through calibrated numerical simulations', *Building and Environment*, vol. 180, p. 107031 [Online]. DOI: 10.1016/j.buildenv.2020.107031.

Jones, R. V., Goodhew, S. and de Wilde, P. (2016) 'Measured indoor temperatures, thermal comfort and overheating risk: Post-occupancy evaluation of low energy houses in the UK', Elsevier [Online]. DOI: 10.1016/j.egypro.2016.06.049 (Accessed 28 April 2020).

Kane, T., Firth, S. and Lomas, K. (2015) 'How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling', *Energy and Buildings*, vol. 86, pp. 817–832 [Online]. DOI: https://doi.org/10.1016/j.enbuild.2014.10.011.

Kayan, B. A. (2017) 'Green maintenance for heritage buildings: paint repair appraisal', *International Journal of Building Pathology and Adaptation*, vol. 35, no. 1, pp. 63–89 [Online]. DOI: 10.1108/IJBPA-05-2016-0011.

Kayan, B. A., Zaid, N. S. M. and Mahmud, N. S. (2017) 'Green Maintenance Approach: Low Carbon Repair Appraisal on St Paul's Church, Melaka, Malaysia', *Journal of Design and Built Environment*, p. 15.

Khan, S. (2018) *Low-tech ways of heating older buildings* [Online]. Available at https://www.ribaj.com/intelligence/traditional-passive-methods-can-improve-thermal-comfort-in-old-buildings-architectural-association-sarah-khan (Accessed 27 July 2021).

Khodeir, L. M., Aly, D. and Tarek, S. (2016) 'Integrating HBIM (Heritage Building Information Modeling) Tools in the Application of Sustainable Retrofitting of Heritage Buildings in Egypt', *Procedia Environmental Sciences*, Improving Sustainability Concept in Developing Countries (ISCDC), vol. 34, pp. 258–270 [Online]. DOI: 10.1016/j.proenv.2016.04.024.

Kohler, N. and Hassler, U. (2012) 'Alternative scenarios for energy conservation in the building stock', *Building Research & Information*, Routledge, vol. 40, no. 4, pp. 401–416 [Online]. DOI: 10.1080/09613218.2012.675714.

Kuittinen, M. and Häkkinen, T. (2020) 'Reduced carbon footprints of buildings: new Finnish standards and assessments', *Buildings and Cities*, Ubiquity Press, vol. 1, no. 1, pp. 182–197 [Online]. DOI: 10.5334/bc.30.

Kyriakidis, A., Michael, A., Illampas, R., Charmpis, D. C. and Ioannou, I. (2018) 'Thermal performance and embodied energy of standard and retrofitted wall systems encountered in Southern Europe', *Energy*, vol. 161, pp. 1016–1027 [Online]. DOI: 10.1016/j.energy.2018.07.124.

Lake District National Park Authority (2018) *Lake District facts and figures* [Online]. Available at https://www.lakedistrict.gov.uk/learning/factsandfigures (Accessed 20 June 2019).

Lake District National Park Authority (LDNPA) (2020) *English Lake District World Heritage Site* [Online]. Available at http://lakesworldheritage.co.uk/world-heritage/souv/ (Accessed 2 June 2020).

Lapenta, F. (2012) 'Some theoretical and methodological veiws on photo-elicitation', in *The SAGE Handbook of Visual Research Methods*, London, SAGE Publications Ltd.

Li, F. G. N., Smith, A. Z. P., Biddulph, P., Hamilton, I. G., Lowe, R., Mavrogianni, A., Oikonomou, E., Raslan, R., Stamp, S., Stone, A., Summerfield, A. J., Veitch, D., Gori, V. and Oreszczyn, T. (2015) 'Solid-wall U-values: heat flux measurements compared with standard assumptions', *Building Research & Information*, Routledge, vol. 43, no. 2, pp. 238–252 [Online]. DOI: 10.1080/09613218.2014.967977.

Li, Q., Sun, X., Chen, C. and Yang, X. (2012) 'Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study', *Energy and Buildings*, vol. 49, pp. 317–326 [Online]. DOI: 10.1016/j.enbuild.2012.02.023.

Li, Q., You, R., Chen, C. and Yang, X. (2013) ‘A field investigation and comparative study of indoor environmental quality in heritage Chinese rural buildings with thick rammed earth wall’, *Energy and Buildings,* vol. 62, pp. 286–293 [Online]. DOI: 10.1016/j.enbuild.2013.02.057.

Li, X. and Densley Tingley, D. (2021) ‘Solid wall insulation of the Victorian house stock in England: A whole life carbon perspective’, *Building and Environment*, vol. 191, p. 107595 [Online]. DOI: 10.1016/j.buildenv.2021.107595.

Lidelöw, S., Örn, T., Luciani, A. and Rizzo, A. (2019) ‘Energy-efficiency measures for heritage buildings: A literature review’, *Sustainable Cities and Society*, vol. 45, pp. 231–242 [Online]. DOI: 10.1016/j.scs.2018.09.029.

Lin, H., Clavreul, J., Jeandaux, C., Crawley, J. and Butnar, I. (2021) ‘Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers’, *Energy and Buildings*, vol. 240, p. 110865 [Online]. DOI: 10.1016/j.enbuild.2021.110865.

Lipman, C. and Nash, C. (2019) ‘Domestic genealogies: how people relate to those who once lived in their homes’, *cultural geographies*, SAGE Publications Ltd, vol. 26, no. 3, pp. 273–288 [Online]. DOI: 10.1177/1474474019832348.

Litti, G., Audenaert, A. and Lavagna, M. (2018) ‘Life cycle operating energy saving from windows retrofitting in heritage buildings accounting for technical performance decay’, *Journal of Building Engineering*, vol. 17, pp. 135–153 [Online]. DOI: 10.1016/j.jobe.2018.02.006.

Litti, G., Khoshdel, S., Audenaert, A. and Braet, J. (2015) ‘Hygrothermal performance evaluation of traditional brick masonry in historic buildings’, *Energy and Buildings*, vol. 105, pp. 393–411 [Online]. DOI: 10.1016/j.enbuild.2015.07.049.

Llantoy, N., Chàfer, M. and Cabeza, L. F. (2020) ‘A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate’, *Energy and Buildings*, vol. 225, p. 110323 [Online]. DOI: 10.1016/j.enbuild.2020.110323.

Loli, A. and Bertolin, C. (2018) ‘Towards Zero-Emission Refurbishment of Historic Buildings: A Literature Review’, *Buildings*, vol. 8, no. 2, p. 22 [Online]. DOI: 10.3390/buildings8020022.

Lomas, K. J. and Kane, T. (2013) ‘Summertime temperatures and thermal comfort in UK homes’, *Building Research & Information*, Routledge, vol. 41, no. 3, pp. 259–280 [Online]. DOI: 10.1080/09613218.2013.757886.

London Energy Transformation Initiative (LETI) (2020) *LETI Embodied Carbon Primer*, LETI [Online]. Available at https://www.leti.london/ecp (Accessed 2 March 2022).

London Energy Transformation Initiative (LETI) (2021) *Leti Climate Emergency Retrofit Guide*, London, LETI [Online]. Available at https://www.leti.london/retrofit (Accessed 20 November 2021).

López, C. S. P. and Frontini, F. (2014) ‘Energy Efficiency and Renewable Solar Energy Integration in Heritage Historic Buildings’, *Energy Procedia*, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), vol. 48, pp. 1493–1502 [Online]. DOI: 10.1016/j.egypro.2014.02.169.

Maby, C. and Owen, A. (2015) *Installer Power: The key to unlocking low carbon retrofit in private housing*, Glouster, Severn Wye Energy Agency [Online]. Available at https://www.linktoenergy.org.uk/wordpress/wp-content/uploads/2015/11/SWEA-Installer-Power-Executive-Summary.pdf (Accessed 8 July 2020).

MacInnes, J. (2020) 'Secondary Analysis of Quantitative Data', in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J. W., and Williams, R. A. (eds), *Sage Research Methods Foundations*, London, SAGE Publications Ltd [Online]. Available at https://methods.sagepub.com/foundations/secondary-analysis-of-quantitative-data (Accessed 24 March 2022).

Madsen, L. V. (2018) 'Materialities shape practices and notions of comfort in everyday life', *Building Research & Information*, Routledge, vol. 46, no. 1, pp. 71–82 [Online]. DOI: 10.1080/09613218.2017.1326230.

Magrini, A. and Franco, G. (2016) 'The energy performance improvement of historic buildings and their environmental sustainability assessment', *Journal of Cultural Heritage*, vol. 21, pp. 834–841 [Online]. DOI: 10.1016/j.culher.2016.03.012.

Majcen, D., Itard, L. C. M. and Visscher, H. (2013) 'Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications', *Energy Policy*, Decades of Diesel, vol. 54, pp. 125–136 [Online]. DOI: 10.1016/j.enpol.2012.11.008.

Mallaband, B., Haines, V. and Mitchell, V. (2013) 'Barriers to domestic retrofit: Learning from past home improvement experiences', in Swan, W. and Brown, P. (eds), *Retrofitting the Built Environment*, Oxford, John Wiley & Sons, pp. 184–199 [Online]. DOI: 10.1002/9781118273463.ch14 (Accessed 19 March 2021).

Mannay, D. (2014) *Visual Methodologies: Participatory Potential, Practicalities, De-Familiarisation and Dissemination*, 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom, SAGE Publications, Ltd. [Online]. DOI: 10.4135/978144627305013496529 (Accessed 15 March 2022).

Marique, A.-F. and Rossi, B. (2018) 'Cradle-to-grave life-cycle assessment within the built environment: Comparison between the refurbishment and the complete reconstruction of an office building in Belgium', *Journal of Environmental Management*, vol. 224, pp. 396–405 [Online]. DOI: 10.1016/j.jenvman.2018.02.055.

Martínez-Molina, A., Tort-Ausina, I., Cho, S. and Vivancos, J.-L. (2016) 'Energy efficiency and thermal comfort in historic buildings: A review', *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 70–85 [Online]. DOI: 10.1016/j.rser.2016.03.018.

Mason, C. (2013) *Jumpergate - the story that wasn't* [Online]. Available at https://www.bbc.co.uk/news/uk-politics-24586951 (Accessed 14 February 2022).

Mason, R. (2006) 'Theoretical and Practical Arguments for Values-Centered Preservation', *CMR The Journal of Heritage Stewardship*, vol. 3, no. 2, pp. 21–48.

Mason, R. (2008) 'Be Interested and Beware: Joining Economic Valuation and Heritage Conservation', *International Journal of Heritage Studies*, vol. 14, no. 4, pp. 303–318 [Online]. DOI: 10.1080/13527250802155810.

Mates, J. (2021) '"Why so generous?": Inside Italy's scheme offering huge subsidies towards low-carbon eco-homes I ITV News', *ITV News*, Online, 21st October [Online]. Available at https://www.itv.com/news/2021-10-21/italy-offering-to-pay-full-cost-of-upgrading-to-green-homes-plus-a-bonus (Accessed 25 February 2022).

May, N. and Griffiths, N. (2015) *Guide to planning responsible retrofit*, Sustainable Traditional Buildings Alliance [Online]. Available at http://www.sdfoundation.org.uk/downloads/Guide-1-Planning-Responsible-Retrofit-2015-08.pdf (Accessed 5 April 2019).

May, N. and Rye, C. (2012) *Responsible Retrofit of Traditional Buildings: A Report on Existing Research and Guidance with Recommendations.*, London, Sustainable Traditional Buildings Alliance [Online]. Available at http://www.sdfoundation.org.uk/downloads/RESPONSIBLE-RETROFIT_FINAL_20_SEPT_2012.pdf.

Mazzarella, L. (2015) 'Energy retrofit of historic and existing buildings. The legislative and regulatory point of view', *Energy and Buildings*, vol. 95, pp. 23–31 [Online]. DOI: 10.1016/j.enbuild.2014.10.073.

Menzies, G. (2013) *Whole Life Analysis of timber, modified timber and aluminium-clad timber windows: Service Life Planning (SLP), Whole Life Costing (WLC) and Life Cycle Assessment (LCA).*, Edinburgh, Heriott Watt University.

Merlino, K. R. (2014) '[Re]Evaluating Significance: The Environmental and Cultural Value in Older and Historic Buildings', *The Public Historian*, vol. 36, no. 3, pp. 70–85 [Online]. DOI: 10.1525/tph.2014.36.3.70.

Ministry of Housing Communities and Local Government (2019) *National planning policy framework.*,.

Mısırlısoy, D. and Günçe, K. (2016) 'Adaptive reuse strategies for heritage buildings: A holistic approach', *Sustainable Cities and Society*, vol. 26, pp. 91–98 [Online]. DOI: 10.1016/j.scs.2016.05.017.

Moncaster, A. M., Rasmussen, F. N., Malmqvist, T., Houlihan Wiberg, A. and Birgisdottir, H. (2019) 'Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies', *Journal of Cleaner Production*, vol. 235, pp. 378–393 [Online]. DOI: 10.1016/j.jclepro.2019.06.233.

Moncaster, A. M. and Symons, K. E. (2013) 'A method and tool for "cradle to grave" embodied energy and carbon impacts of UK buildings in compliance with the new TC350 standards', *Energy and Buildings*, vol. 66, pp. 514–523.

Morgan, C. (2019) *Sustainable Renovation: improving homes for energy, health and environment*, 2nd edn, Dingwall, The Pebble Trust, vol. 1.

Morgan, D. L. (2014) *Integrating Qualitative and Quantitative Methods: A Pragmatic Approach*, 1 Oliver's Yard, 55 City Road London EC1Y 1SP, SAGE Publications, Inc. [Online]. DOI: 10.4135/9781544304533 (Accessed 22 May 2019).

Morrison Hershfield Limited (2020) *Building Envelope Thermal Bridging Guide*, Version 1.5, British Columbia, Morrison Hershfield [Online]. Available at https://morrisonhershfield.com/bpa_library/building-envelope-thermal-bridging-guide/ (Accessed 1 June 2021).

Munarim, U. and Ghisi, E. (2016) 'Environmental feasibility of heritage buildings rehabilitation', *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 235–249 [Online]. DOI: 10.1016/j.rser.2015.12.334.

NCH Software (2019) 'Express Scribe', [Online]. Available at https://www.nch.com.au/scribe/index.html.

Nicol, F., Bahadur Rijal, H., Imagawa, H. and Thapa, R. (2020) 'The range and shape of thermal comfort and resilience', *Energy and Buildings*, vol. 224, p. 110277 [Online]. DOI: 10.1016/j.enbuild.2020.110277.

Nicol, J. F. and Humphreys, M. A. (1973) 'Thermal comfort as part of a self-regulating system', *Builidng Research and Practice*, vol. 6, pp. 191–197 [Online]. DOI: 10.1080/09613217308550237.

Nicol, S., Roys, M., Ormandy, D. and Ezratty, V. (2015) *The cost of poor housing in the European Union*, Watford, BRE [Online]. Available at https://www.bre.co.uk/healthbriefings.

Nottingham Energy Partnership (2020) *Energy Cost Comparison* [Online]. Available at https://nottenergy.com/resources/energy-cost-comparison/ (Accessed 5 January 2021).

Nowicka, K. (2022) 'The Heritage Given: Cultural Landscape and Heritage of the Vistula Delta Mennonites as Perceived by the Contemporary Residents of the Region', *Sustainability*, Multidisciplinary Digital Publishing Institute, vol. 14, no. 2, p. 915 [Online]. DOI: 10.3390/su14020915.

ODYSSEE-MURE (2021a) *Households energy consumption for EU 28 and UK at normal and European adjusted climates* [Online]. Available at https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/heating-consumption-per-m2.html (Accessed 20 March 2021).

ODYSSEE-MURE (2021b) *United Kingdom Energy Profile 2018*, Country Profiles, ODYSSEE-MURE [Online]. Available at https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/united-kingdom.html#buildings (Accessed 11 January 2021).

Office of Gas and Electricity Markets (Ofgem) (2020) *Decision for Typical Domestic Consumption Values 2020*, Ofgem [Online]. Available at https://www.ofgem.gov.uk/publications-and-updates/decision-typical-domestic-consumption-values-2020 (Accessed 10 November 2020).

Oliver, P. (2006) *Built to meet needs: Cultural Issues in Vernacular Architecture*, 1st edn, Routledge [Online]. Available at https://doi.org/10.4324/9780080476308.

Olsen, W. (2009) 'Non-nested and Nested Cases in a Socioeconomic Village Study', in *The SAGE Handbook of Case-Based Methods*, London, SAGE Publications Ltd, pp. 494–510 [Online]. DOI: 10.4135/9781446249413.n30 (Accessed 14 March 2022).

Olwig, K. R. (2018) 'England's "Lake District" and the "North Atlantic Archipelago": A body of managed land contra a body politic', *Landscape Research*, Routledge, vol. 43, no. 8, pp. 1032–1044 [Online]. DOI: 10.1080/01426397.2018.1503240.

Omar, N. A. M. and Syed-Fadzil, S. F. (2011) 'Assessment of Passive Thermal Performance for a Penang Heritage Shop house', *Procedia Engineering*, 2nd International Building Control Conference, vol. 20, pp. 203–212 [Online]. DOI: 10.1016/j.proeng.2011.11.157.

OneClickLCA (2021) *World's fastest Building Life Cycle Assessment software* [Online]. Available at https://www.oneclicklca.com/ (Accessed 16 March 2022).

Ortiz, M., Itard, L. and Bluyssen, P. M. (2020) 'Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review', *Energy and Buildings*, vol. 221, p. 110102 [Online]. DOI: 10.1016/j.enbuild.2020.110102.

O'Sullivan, K. and Howden-Chapman, P. (2017) 'Mixing methods, maximising results: Use of mixed methods research to investigate policy solutions for fuel poverty and energy vulnerability', *Indoor and Built Environment*, vol. 26, no. 7, pp. 1009–1017 [Online]. DOI: 10.1177/1420326X17707327.

Ozarisoy, B. and Elsharkawy, H. (2019) 'Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK', *Energy and Buildings*, vol. 187, pp. 201–217 [Online]. DOI: 10.1016/j.enbuild.2019.01.030.

Palmer, J. and Cooper, I. (2014) *United Kingdom housing energy fact file 2013*, Housing Energy fact file, Department for Energy and Climate Change [Online]. Available at https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013.

Palmer, P., Gillich, A. and Redmond, S. (2021) 'Enabling local rapid change solutions to the Climate Emergency', *European Council for an Energy Efficient Economy (ECEEE)*, Hyeres, France [Online]. Available at https://openresearch.lsbu.ac.uk/item/8ywv7 (Accessed 25 February 2022).

Pan, S., Li, Z., Loveday, D. and Demian, P. (2018) *'Intelligent furniture': the potential for heated armchairs to deliver thermal comfort with energy savings in the UK residential context*, Loughborough University [Online]. Available at https://repository.lboro.ac.uk/articles/conference_contribution/_Intelligent_furniture_the_potential_for_heated_armchairs_to_deliver_thermal_comfort_with_energy_savings_in_the_UK_residential_context/9438074 (Accessed 1 July 2020).

Parkinson, T., de Dear, R. and Brager, G. (2020) ‘Nudging the adaptive thermal comfort model’, *Energy and Buildings*, vol. 206, p. 109559 [Online]. DOI: 10.1016/j.enbuild.2019.109559.

Pauwels, L. (2020) ‘Visual Elicitation in Interviews’, in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J., W., and Williams, R., A. (eds), *SAGE Research Methods Foundations*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781526421036846496 (Accessed 15 March 2022).

Pender, R. (2021) ‘Personal communication: Heritage building research’,.

Pender, R. and Lemieux, D. J. (2020) ‘The Road Not Taken: Building Physics, and Returning to First Principles in Sustainable Design’, *Atmosphere*, Multidisciplinary Digital Publishing Institute, vol. 11, no. 6, p. 620 [Online]. DOI: 10.3390/atmos11060620.

Pendlebury, J., Hamza, N. and Sharr, A. (2014) ‘Conservation values, conservation-planning and climate change’, *disP - The Planning Review*, vol. 50, no. 3, pp. 43–54 [Online]. DOI: 10.1080/02513625.2014.979042.

Pickles, D. and Cattini, C. (2015) *Energy Efficiency and Historic Buildings: Energy Performance Certificate*, Historic England [Online]. Available at https://historicengland.org.uk/images-books/publications/eehb-energy-performance-certificates/.

Pickles, D. and McCaig, I. (2017) *Energy Efficiency & Historic Buildings: Application of Part L of the Building Regulations to Historic & Traditionally Constructed Buildings*, Historic England [Online]. Available at https://historicengland.org.uk/images-books/publications/energy-efficiency-historic-buildings-ptl/heag014-energy-efficiency-partll/ (Accessed 5 April 2019).

Piddington, J., Nicol, S., Garrett, H. and Custard, M. (2020) *The Housing Stock of the United Kingdom*, Watford, BRE Trust [Online]. Available at https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf.

Pigliautile, I., Casaccia, S., Morresi, N., Arnesano, M., Pisello, A. L. and Revel, G. M. (2020) ‘Assessing occupants’ personal attributes in relation to human perception of environmental comfort: Measurement procedure and data analysis’, *Building and Environment*, vol. 177, p. 106901 [Online]. DOI: 10.1016/j.buildenv.2020.106901.

Pili, S. (2017) ‘Experimentation of a Smart-Planning Approach for the Sustainable Renewal of the Building Heritage of Smaller Sardinian Historic Centers’, *Smart and Sustainable Planning for Cities and Regions*, Springer, Cham, pp. 65–77 [Online]. DOI: 10.1007/978-3-319-75774-2_5 (Accessed 31 October 2018).

Pineda, P., García-Martínez, A. and Castizo-Morales, D. (2017) ‘Environmental and structural analysis of cement-based vs. natural material-based grouting mortars. Results from the assessment of strengthening works’, *Construction and Building Materials*, vol. 138, pp. 528–547 [Online]. DOI: 10.1016/j.conbuildmat.2017.02.013.

Pohoryles, D. A., Maduta, C., Bournas, D. A. and Kouris, L. A. (2020) ‘Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting', *Energy and Buildings*, vol. 223, p. 110024 [Online]. DOI: 10.1016/j.enbuild.2020.110024.

Pomponi, F., Giesekam, J., Hart, J. and D'Amico, B. (2020) *Embodied Carbon: Status quo and suggested roadmap*, Zero Waste Scotland [Online]. Available at https://zerowastescotland.org.uk/sites/default/files/Embodied_carbon_spreads%20final.pdf (Accessed 1 February 2022).

Pomponi, F. and Moncaster, A. (2016) 'Embodied carbon mitigation and reduction in the built environment – What does the evidence say?', *Journal of Environmental Management*, vol. 181, pp. 687–700 [Online]. DOI: 10.1016/j.jenvman.2016.08.036.

Pomponi, F. and Moncaster, A. (2017) 'Circular economy for the built environment: A research framework', *Journal of Cleaner Production*, vol. 143, pp. 710–718 [Online]. DOI: 10.1016/j.jclepro.2016.12.055.

Pracchi, V. (2014) 'Historic Buildings and Energy Efficiency', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 210–225 [Online]. DOI: 10.1179/1756750514Z.00000000052.

Pracchi, V., Rosina, E., L'Erario, A., Monticelli, C., Aliprandi, S. and Zanelli, A. (2017) 'From arazzo to textile based innovative system for energy efficiency of listed buildings', *REHAB 2017 Proceedings of the 3rd International Conference on Preservation, Maintenance and Rehabilitation of Historical Buildings and Structures*, pp. 1093–1103 [Online]. Available at http://hdl.handle.net/11311/1030859.

Psomas, T., Heiselberg, P., Duer, K. and Bjørn, E. (2016) 'Overheating risk barriers to energy renovations of single family houses: Multicriteria analysis and assessment', *Energy and Buildings*, vol. 117, pp. 138–148 [Online]. DOI: 10.1016/j.enbuild.2016.02.031.

QSR International Pty Ltd (2019) 'NVivo 12', QSR International Pty Ltd.

Quidos (2020) 'Conventions (v 11.1) for RdSAP 9.92, 9.93 and 9.94', Quidos.

Rafique, A. and Williams, A. P. (2021) 'Reducing household greenhouse gas emissions from space and water heating through low-carbon technology: Identifying cost-effective approaches', *Energy and Buildings*, vol. 248, p. 111162 [Online]. DOI: 10.1016/j.enbuild.2021.111162.

Rasmussen, T. V., Møller, E. B. and Buch-Hansen, T. C. (2015) 'Extensive Renovation of Heritage Buildings - Reduced Energy Consumption and CO Emissions', *The Open Construction and Building Technology Journal*, vol. 9, no. 1, pp. 58–67 [Online]. DOI: 10.2174/1874836801509010058.

Redden, R. and Crawford, R. H. (2021) 'Valuing the environmental performance of historic buildings', *Australasian Journal of Environmental Management*, vol. 28, no. 1, pp. 59–71 [Online]. DOI: 10.1080/14486563.2020.1772133.

RenOnBill (2021) *On-bill schemes to deliver the Renovation Wave and economic recovery*, Policy briefing, RenOnBill [Online]. Available at https://storage.googleapis.com/renonbill-website.appspot.com/image/multimedia/14_04_2021_12_50/06259%20RenOnBill%20policy%20briefing_70_FINAL.pdf.

Reservoir logs (2021) *Wood Volume vs Weight* [Online]. Available at https://www.reservoirlogs.co.uk/wood-volume-vs-weight/ (Accessed 14 October 2021).

Riley, M. and Holton, M. (2020) *Place based interviewing: creating and conducting walking interviews*, SAGE Research Methods Cases Part 1, London, SAGE Publications Ltd. [Online]. Available at https://dx.doi.org/10.4135/978144627305015595386.

Roberti, F., Oberegger, U. F. and Gasparella, A. (2015) 'Calibrating historic building energy models to hourly indoor air and surface temperatures: Methodology and case study', *Energy and Buildings*, vol. 108, pp. 236–243 [Online]. DOI: 10.1016/j.enbuild.2015.09.010.

Rodrigues, C. and Freire, F. (2017) 'Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis', *Energy and Buildings*, vol. 140, pp. 388–398 [Online]. DOI: 10.1016/j.enbuild.2017.01.084.

Rodriguez-Maribona, I. and Grün, G. (2016) *Energy Efficiency in European Historic Urban Districts: a practical guidance*, Leipzig, Fraunhofer-Center for International Management and Knowledge Economy [Online]. Available at http://www.effesus.eu/wp-content/uploads/2016/06/EFFESUS_Booklet_Final-Version.pdf (Accessed 12 December 2018).

Rosenow, J. and Eyre, N. (2016) 'A post mortem of the Green Deal: Austerity, energy efficiency, and failure in British energy policy', *Energy Research & Social Science*, vol. 21, pp. 141–144 [Online]. DOI: 10.1016/j.erss.2016.07.005.

Rospi, G., Cardinale, N., Negro, E., Rospi, G., Cardinale, N. and Negro, E. (2017) 'Energy Performance and Economic Feasibility Study of Historical Building in the City of Matera, Southern Italy', *Energies*, vol. 10, no. 12, p. 2009 [Online]. DOI: 10.3390/en10122009.

Royal Institution of Chartered Surveyors (RICS) (2017) *Whole Life Carbon Assessment for the Built Environment, 1st edition*, professional standards and guidance, London, RICS [Online]. Available at https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/ (Accessed 4 March 2022).

Royston, S. (2014) 'Dragon-breath and snow-melt: Know-how, experience and heat flows in the home', *Energy Research & Social Science*, vol. 2, pp. 148–158 [Online]. DOI: 10.1016/j.erss.2014.04.016.

Ruel, E., Wagner, W. E. and Gillespie, B. J. (2016) *The Practice of Survey Research: Theory and Applications*, 2455 Teller Road, Thousand Oaks California 91320, SAGE Publications, Inc [Online]. DOI: 10.4135/9781483391700 (Accessed 5 July 2019).

Rupp, R. F., Vásquez, N. G. and Lamberts, R. (2015) 'A review of human thermal comfort in the built environment', *Energy and Buildings*, vol. 105, pp. 178–205 [Online]. DOI: 10.1016/j.enbuild.2015.07.047.

Rye, C. (2015) 'Are traditional buildings really carbon villains? Why it matters when insulating solid walls', *Journal of Building Survey, Appraisal & Valuation*, vol. 4, no. 2, pp. 119–126.

Rye, C. and Scott, C. (2012) *The SPAB research report 1: U-Value report*, Society for the Protection of Ancient Buildings [Online]. Available at https://www.spab.org.uk/sites/default/files/documents/MainSociety/Advice/SPABU-valueReport.Nov2012.v2.pdf (Accessed 24 November 2020).

Rye, C., Scott, C. and Hubbard, D. (2012) *The SPAB Building Performance Survey 2012 Interim Report*, Society for the Protection of Ancient Buildings.

Sadat Korsavi, S., Montazami, A. and Brusey, J. (2018) 'Developing a design framework to facilitate adaptive behaviours', *Energy and Buildings*, vol. 179, pp. 360–373 [Online]. DOI: 10.1016/j.enbuild.2018.09.011.

de Santoli, L. (2015) 'Guidelines on energy efficiency of cultural heritage', *Energy and Buildings*, vol. 86, pp. 534–540 [Online]. DOI: 10.1016/j.enbuild.2014.10.050.

Sapsford, R. (2007) *Survey Research*, 2nd edn, London, SAGE Publications Ltd.

Schaich, H., Bieling, C. and Plieninger, T. (2010) 'Linking Ecosystem Services with Cultural Landscape Research', *GAIA - Ecological Perspectives for Science and Society*, vol. 19, no. 4, pp. 269–277 [Online]. DOI: 10.14512/gaia.19.4.9.

Sedovic, W. and Gotthelf, J. H. (2005) 'What Replacement Windows Can't Replace: The Real Cost of Removing Historic Windows', *Journal of Preservation Technology*, vol. 36, no. 4, p. 5.

Sesana, E., Bertolin, C., Gagnon, A. S. and Hughes, J. J. (2019) 'Mitigating Climate Change in the Cultural Built Heritage Sector', *Climate*, Multidisciplinary Digital Publishing Institute, vol. 7, no. 7, p. 90 [Online]. DOI: 10.3390/cli7070090.

Shove, E. (2018) 'What is wrong with energy efficiency?', *Building Research & Information*, vol. 46, no. 7, pp. 779–789 [Online]. DOI: 10.1080/09613218.2017.1361746.

Shrubsole, C., Macmillan, A., Davies, M. and May, N. (2014) '100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock':, *Indoor and Built Environment*, vol. 23, no. 3, pp. 340–352 [Online]. DOI: 10.1177/1420326X14524586.

Simpson, B. (2018) 'Pragmatism: A Philosophy of Practice', in *The SAGE Handbook of Qualitative Business and Management Research Methods: History and Traditions*, London, SAGE Publications Ltd, pp. 54–68 [Online]. DOI: 10.4135/9781526430212.n4 (Accessed 22 May 2019).

Simpson, K., Murtagh, N. and Owen, A. (2021) 'Domestic retrofit: understanding capabilities of micro-enterprise building practitioners', *Buildings and Cities*, vol. 2, no. 1, pp. 449–466 [Online]. DOI: 10.5334/bc.106.

Slater, A. and Garrett, H. (2019) 'English Housing Survey Chapter 3 figures and annex tables, annex 3 (figure 3.7)', MHCLG [Online]. Available at https://www.gov.uk/government/statistics/english-housing-survey-2017-to-2018-energy.

Smith, L. (2006) *Use of heritage*, Abingdon, Routledge.

Smith, M., Apperley, J., Couling, A., Dillon, M., Forth, A. and MacDonald, P. (2021) *Built for the environment: Addressing the climate and biodiversity emergency with a fair and sustainable built environment*, RIBA [Online]. Available at https://www.architecture.com/knowledge-and-resources/resources-landing-page/built-for-the-environment-report.

Smith, O. (2014) 'Balancing Heritage and Environmental Policies for Sustainable Refurbishment of Historic Buildings: The Case of New Court, Trinity College, Cambridge', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 116–131 [Online]. DOI: 10.1179/1756750514Z.00000000050.

Soini, K., Vaarala, H. and Pouta, E. (2012) 'Residents' sense of place and landscape perceptions at the rural–urban interface', *Landscape and Urban Planning*, vol. 104, no. 1, pp. 124–134 [Online]. DOI: 10.1016/j.landurbplan.2011.10.002.

Sorrell, S., Dimitropoulos, J. and Sommerville, M. (2009) 'Empirical estimates of the direct rebound effect: A review', *Energy Policy*, vol. 37, no. 4, pp. 1356–1371 [Online]. DOI: 10.1016/j.enpol.2008.11.026.

Sorrell, S., Gatersleben, B. and Druckman, A. (2018) *Energy sufficiency and rebound effects*, Energy Sufficiency [Online]. Available at https://www.energysufficiency.org/static/media/uploads/site-8/library/papers/sufficiency-rebound-final_formatted_181118.pdf.

Stuart, C. M. (2014) 'Managing or Driving Change? Establishing Consensus of Opinion on Improving the Energy Efficiency of Historic Buildings', *The Historic Environment: Policy & Practice*, vol. 5, no. 2, pp. 182–195 [Online]. DOI: 10.1179/1756750514Z.00000000048.

Summerfield, A. J., Oreszczyn, T., Palmer, J., Hamilton, I. G., Li, F. G. N., Crawley, J. and Lowe, R. J. (2019) 'What do empirical findings reveal about modelled energy demand and energy ratings? Comparisons of gas consumption across the English residential sector', *Energy Policy*, vol. 129, pp. 997–1007 [Online]. DOI: 10.1016/j.enpol.2019.02.033.

Summerfield, A. J., Oreszczyn, T., Palmer, J., Hamilton, I. G. and Lowe, R. J. (2015) 'Comparison of empirical and modelled energy performance across age-bands of three-bedroom dwellings in the UK', *Energy and Buildings*, vol. 109, pp. 328–333 [Online]. DOI: 10.1016/j.enbuild.2015.09.050.

Sunikka-Blank, M. and Galvin, R. (2012) 'Introducing the prebound effect: the gap between performance and actual energy consumption', *Building Research &*

Information, vol. 40, no. 3, pp. 260–273 [Online]. DOI: 10.1080/09613218.2012.690952.

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

Sustainable Traditional Buildings Alliance (2020) *STBA Guidance Wheel* [Online]. Available at https://stbauk.org/guidance-wheel/ (Accessed 16 November 2020).

Teekaram, A. (2013) *Potential Energy and CO2 savings carried out for the Chimney Balloon Company*, Bracknell, BSRIA Limited.

Teli, D., Gauthier, S., Aragon, V., Bourikas, L., James, P. and Bahaj, A. (2016) 'Thermal adaptation to high indoor temperatures during winter in two UK social housing tower blocks', *Proceedings of The 9th Windsor Conference: Making Comfort Relevant*, The Windsor Conference [Online]. Available at https://eprints.soton.ac.uk/392663/ (Accessed 1 July 2020).

The Energy Saving Trust (2021) *A comprehensive guide to solar panels* [Online]. Available at https://energysavingtrust.org.uk/advice/solar-panels/ (Accessed 2 February 2022).

The National Archives (n.d.) *Open Government Licence version 3* [Online]. Available at http://nationalarchives.gov.uk/doc/open-government-licence/version/3/ (Accessed 7 April 2022).

Theirbach, C., Hergesell, J. and Baur, N. (2020) 'Mixed Methods Research', in Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J., W., and Williams, R., A. (eds), *SAGE Research Methods Foundations*, London, SAGE Publications Ltd [Online]. DOI: 10.4135/9781526421036932545 (Accessed 14 March 2022).

Thornton, B. J. (2011) 'The Greenest Building (is the one that you don't build!): Effective Techniques for Sustainable Adaptive Reuse/Renovation', *Journal of Green Building*, vol. 6, no. 1, pp. 1–7 [Online]. DOI: 10.3992/jgb.6.1.1.

Tokede, O., Udawatta, N. and Luther, M. (2017) 'Retrofitting heritage office buildings in the UK: a case study', *Built Environment Project and Asset Management*, vol. 8, no. 1, pp. 39–50 [Online]. DOI: 10.1108/BEPAM-11-2016-0068.

Tüysüz, F. and Sözer, H. (2020) 'Calibrating the building energy model with the short term monitored data: A case study of a large-scale residential building', *Energy and Buildings*, vol. 224, p. 110207 [Online]. DOI: 10.1016/j.enbuild.2020.110207.

Tweed, C. and Sutherland, M. (2007) 'Built cultural heritage and sustainable urban development', *Landscape and Urban Planning*, vol. 83, no. 1, pp. 62–69 [Online]. DOI: 10.1016/j.landurbplan.2007.05.008.

Vakhitova, T. V. (2015) 'Rethinking conservation: managing cultural heritage as an inhabited cultural landscape', *Built Environment Project and Asset Management*, vol. 5, no. 2, pp. 217–228 [Online]. DOI: 10.1108/BEPAM-12-2013-0069.

Vernacular Architecture Group (2022) *Vernacular Architecture Group* [Online]. Available at https://www.vag.org.uk/ (Accessed 16 February 2022).

Viessmann (2018) '1805 Vitosol Technical Guide', Viessmann.

Vilches, A., Garcia-Martinez, A. and Sanchez-Montañes, B. (2017) 'Life cycle assessment (LCA) of building refurbishment: A literature review', *Energy and Buildings*, vol. 135, pp. 286–301 [Online]. DOI: 10.1016/j.enbuild.2016.11.042.

Vlami, V., Danek, J., Zogaris, S., Gallou, E., Kokkoris, I. P., Kehayias, G. and Dimopoulos, P. (2020) 'Residents' Views on Landscape and Ecosystem Services during a Wind Farm Proposal in an Island Protected Area', *Sustainability*, vol. 12, no. 6, p. 2442 [Online]. DOI: 10.3390/su12062442.

Wade, F. and Visscher, H. (2021) 'Retrofit at scale: accelerating capabilities for domestic building stocks', *Buildings and Cities*, Ubiquity Press, vol. 2, no. 1, pp. 800–811 [Online]. DOI: 10.5334/bc.158.

Webb, A. L. (2017) 'Energy retrofits in historic and traditional buildings: A review of problems and methods', *Renewable and Sustainable Energy Reviews*, vol. 77, pp. 748–759 [Online]. DOI: 10.1016/j.rser.2017.01.145.

Weiler, V., Harter, H. and Eicker, U. (2017) 'Life cycle assessment of buildings and city quarters comparing demolition and reconstruction with refurbishment', *Energy and Buildings*, vol. 134, pp. 319–328 [Online]. DOI: 10.1016/j.enbuild.2016.11.004.

Welsh Government (2021) *All new schools and colleges in Wales to be net zero carbon* [Online]. Available at https://gov.wales/all-new-schools-and-colleges-wales-be-net-zero-carbon (Accessed 4 March 2022).

Whitman, C. J., Prizeman, O., Walker, P. and Gwilliam, J. A. (2019) 'Heritage retrofit and cultural empathy; a discussion of challenges regarding the energy performance of historic UK timber-framed dwellings', *International Journal of Building Pathology and Adaptation*, Emerald Publishing Limited, vol. 38, no. 2, pp. 386–404 [Online]. DOI: 10.1108/IJBPA-02-2019-0023.

Wight Heat (2021) *Wight Heat Briquettes: Calorific values of fuel* [Online]. Available at https://www.wightheat.co.uk/calorific.php (Accessed 14 October 2021).

Wilkinson, S. J. and Remoy, H. (2017) 'Adaptive reuse of Sydney offices and sustainability', *Sustainable Buildings*, vol. 2, no. 6, pp. 1–10 [Online]. DOI: 10.1051/sbuild/2017002.

Wilson, C., Crane, L. and Chryssochoidis, G. (2015) 'Why do homeowners renovate energy efficiently? Contrasting perspectives and implications for policy', *Energy Research & Social Science*, vol. 7, pp. 12–22 [Online]. DOI: 10.1016/j.erss.2015.03.002.

Wintour, P. (2013) 'No 10 says people should consider wearing jumpers to keep fuel bills down', *The Guardian*, Online, 18th October [Online]. Available at https://www.theguardian.com/money/2013/oct/18/no-10-jumpers-fuel-bills (Accessed 14 February 2022).

Wise, F., Jones, D. and Moncaster, A. (2021) ‘Reducing carbon from heritage buildings: the importance of residents’ views, values and behaviours’, *Journal of Architectural Conservation*, vol. 27, no. 1–2, pp. 117–146 [Online]. DOI: 10.1080/13556207.2021.1933342.

Wise, F., Moncaster, A. and Jones, D. (2021) ‘Rethinking retrofit of residential heritage buildings’, *Buildings and Cities*, vol. 2, no. 1, p. 495 [Online]. DOI: 10.5334/bc.94.

Wise, F., Moncaster, A. and Jones, D. (2022) ‘Is it all about the windows? Residents’ values in residential heritage buildings’, *Central Europe towards Sustainable Buildings 2022*, Prague, Forthcoming.

Wise, F., Moncaster, A., Jones, D. and Dewberry, E. (2019) ‘Considering embodied energy and carbon in heritage buildings – a review’, *from Policy to Practice*, p. 10.

Wise, F., Moncaster, A., Jones, D. and Dewberry, E. (2022) ‘Low carbon heritage: residents’ views from Cumbria and the English Lake District World Heritage Site’, *EEHB2022 proceedings*, Benediktbeuern Monastery, Forthcoming.

Wood, C., Bordass, B. and Baker, P. (2009) *Research into the thermal performance of traditional windows: timber sash windows*, Research Report, English Heritage [Online]. Available at https://historicengland.org.uk/research/results/reports/109-2009.

Woodcock, S. (2010) ‘Fitted Press Cupboards and Built-in Wall Cupboards of the Lake District’, *Regional Furniture*, vol. 24, pp. 17–39.

Yang, H., Cao, B. and Zhu, Y. (2018) ‘Study on the effects of chair heating in cold indoor environments from the perspective of local thermal sensation’, *Energy and Buildings*, vol. 180, pp. 16–28 [Online]. DOI: 10.1016/j.enbuild.2018.09.003.

Yin, R. (2009) ‘How to do Better Case Studies: (With Illustrations from 20 Exemplary Case Studies)’, in *The SAGE Handbook of Applied Social Research Methods*, Thousand Oaks, SAGE Publications, Inc., pp. 254–282 [Online]. DOI: 10.4135/9781483348858.n8 (Accessed 14 March 2022).

Yin, R. K. (2014) *Case study research: design and methods*, 5th edn, Los Angeles, SAGE.

Yung, E. H. K. and Chan, E. H. W. (2012) ‘Implementation challenges to the adaptive reuse of heritage buildings: Towards the goals of sustainable, low carbon cities’, *Habitat International*, vol. 36, no. 3, pp. 352–361 [Online]. DOI: 10.1016/j.habitatint.2011.11.001.

Zagorskas, J., Zavadskas, E. K., Turskis, Z., Burinskienė, M., Blumberga, A. and Blumberga, D. (2014) ‘Thermal insulation alternatives of historic brick buildings in Baltic Sea Region’, *Energy and Buildings*, vol. 78, pp. 35–42 [Online]. DOI: 10.1016/j.enbuild.2014.04.010.

Zeng, R. and Chini, A. (2017) ‘A review of research on embodied energy of buildings using bibliometric analysis’, *Energy and Buildings*, vol. 155, pp. 172–184 [Online]. DOI: 10.1016/j.enbuild.2017.09.025.

Zhang, X. and Wang, F. (2017) ‘Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China’, *Energy and Buildings*, vol. 155, pp. 404–413 [Online]. DOI: 10.1016/j.enbuild.2017.09.049.

Appendices

Appendix A) Details for pre-survey scoping interviews with local conservation and sustainability experts

A.1) Scoping interview Information sheet

Research study participant information sheet

Reducing Whole Life Energy and CO2 Emissions in Cumbrian Heritage Buildings

Principal Researcher: Freya Wise

If you have any queries, in the first instance please contact Freya Wise at:
Email: freya.wise@open.ac.uk
Telephone: 01539 732918
Address: Department of Engineering and Innovation
The Open University
Walton Hall
Milton Keynes
MK7 6AA

If you wish to speak to someone else about this project please contact Alice Moncaster at:
Alice.moncaster@open.ac.uk

Invitation paragraph
You are being asked to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information fully. You have been asked to participate because you have some knowledge of heritage or sustainability or because you live in a heritage building.

General information about the research study and collected research data
The wider purpose of this research is to look at ways of reducing energy and CO2 emissions from heritage buildings. There are a number of key research areas that we hoping to investigate.
These areas are:

1. How people who live in heritage buildings feel about their heritage buildings in terms of the buildings' heritage value, their energy performance and indoor environment?
2. What is users' energy behaviour within their heritage buildings and how does this effect energy use?
3. What is the whole life carbon impact of different retrofit options and how acceptable are different options to residents and planners?

As someone from Cumbria with knowledge about/interest in heritage/sustainability your opinion would be valuable in a number of ways:

- Do you think that the research gaps we have identified are relevant to Cumbria?
- What key issues do you think heritage buildings are facing in a Cumbrian context?
- What sort of changes do you think would be acceptable reduce carbon from heritage buildings?

Your participation would take the form of an informal interview with the researcher to discuss some of these issues and your opinion would be really useful to help us develop our project.

This research forms part the researcher's PhD project with The Open University, it is being funded by the Design Star Centre for Doctoral Training: https://www.designstar.org.uk
The project has been registered with and approved by the Open University's Human Research Ethics Committee and the ethics reference number is: HREC/3182/Wise.

What will I be asked to do if I agree to take part?
If you choose to take part in this research project you would be invited to meet the researcher at a time convenient to you for an informal interview of approximately one hour to one and a half hours duration. This interview would involve a discussion about the issues above and your broader opinions on heritage buildings and sustainability in Cumbria. With your permission the interview would be audio recorded so that we would have an accurate record of the discussion which could then be transcribed.

This study should be beneficial to our understanding of how to make heritage buildings more sustainable while preserving their heritage values. Your participation will help shape the research so that it is of practical and local relevance. It is hoped that some Cumbrian specific guidance for heritage building owners and other stakeholders such as sustainability organisations and local policy groups will be produced once the research project is completed. If this is something that interests you we are happy to share our findings with you once we have completed our analysis.

Participation is entirely voluntary and it is up to you if you wish to take part or not. If you do decide to participate you will be given a copy of this information sheet to keep and asked to sign a consent form. If you decide to participate then later change your mind you can decide to withdraw at any point without giving a reason.

How will the data I provide be used?
The audio recording of the interview will be transcribed and as soon as this is completed the audio recording will be securely deleted. Transcripts and other data that you provide us with will be stored securely on an encrypted and password protected laptop and on a secure server in line with The Open University's Data Protection Policies. We will require your name and signature on our consent form. If you would like to be contacted with the research findings there will be an option for you to give us your email address. Consent forms will be transferred to a secure electronic format and physical copies will be securely destroyed. The data you provide us with and its analysis will be used to inform our research project, and will form a part of the researcher's PhD thesis. It may also be used by the researcher in other publications such as research journals, research reports and conference presentations.

It would be useful for our project if we could attribute quotes from you in our research outputs. This does however mean that you would be identifiable and any comments you made would be linked to you in any research publications. It would be clearly understood that any views expressed were that of the individual not the organisation. If you would like to take part in the research but not wish to be identified that is perfectly alright and the data and any quotes can be anonymised. Heritage and sustainability is not deemed to be a sensitive topic in the UK and there shouldn't be any risks to having your comments attributed but it is completely up to you. If you wish you may ask for any sections of the interview to be deleted or any section or the whole interview to be anonymised. You may also withdraw your consent up to two months after the date of your interview in which case your data will be securely destroyed and not used in any research publications. A copy of the transcript can be sent to you after the interview if you wish to review it.

There is an obligation of researchers to make their data available alongside their research publications, this includes research journals, publications etc during and after the project. After the project's conclusion your data (the interview transcripts) will placed in the Open University's Institutional Depository, ORDO where it will remain for ten years in line with the Open University's data retention schedule. Before the data is be shared it will be anonymised. Data will not be stored outside the EU.

Your right to withdraw from the study

- You have the right to withdraw from the study at any time before the interview by emailing the researcher, you do not have to give a reason.
- You have the right to withdraw from the study at any time during your participation by asking for the recording to stopped and leaving the interview, you do not have to give a reason.
- You have the right to ask for your data to be deleted after your participation in the study by contacting the researcher on the email address provided, up until two months after the interview, when the data will have been used to inform the development of the survey.

How do I agree to take part?
If you do decide to take part please email the researcher and we will arrange an appropriate date and location for the interview where you will be asked to sign the attached consent form before proceeding with the interview.

Thank you
Thank you for taking the time to read this information sheet and considering whether you would be interested in taking part in this research.

Data Protection
The Open university is the Data Controller for the personal information that you provide. The lawful basis for processing your data will be that conducting academic research is part of the Open University's public task. (the consent we request from you relates to ethical considerations).

We may share the information (ie interview transcripts) that you give us with other researchers alongside research publications as part of our commitment to making research data open. This data will be anonymised as described above before being made available.

You have a number of rights as a data subject:

- To request a copy of the personal data we have about you
- To rectify any personal data which is inaccurate or incomplete
- To restrict the processing of your data
- To receive a copy of your data in an easily transferrable format (if relevant)
- To erase your data
- To object to us processing your data

If you are concerned about the way we have processed your personal information, you can contact the Information Commissioner's Office (ICO). Please visit the ICO's website for further details.

http://www.open.ac.uk/research/ethics/

A.2) Scoping interview consent form

Informed Consent for Reducing Whole Life Energy and CO2 Emissions in Cumbrian Heritage Buildings

Freya Wise
Postgraduate Research Student
Department of Engineering and Innovation

The Open University

Please tick the appropriate boxes — Yes / No

1. Taking part in the study

	Yes	No
I have read and understood the study information dated 11/04/2019, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time up until two months after the date of my interview (when the data will have been analysed) without having to give a reason.	☐	☐
I understand that taking part in the study involves an informal, audio recorded interview.	☐	☐
I agree to the interview being audio recorded and transcribed.	☐	☐

2. Use of the information in the study

I understand that information I provide will be used to help develop the research project and will form part of the researcher's PhD thesis. As well as potentially being used in research publications such as journal articles, conference papers and research reports.

I understand that personal information collected about me that can identify me, such as my name or my address, will not be shared beyond the study team unless I explicitly give permission for my opinion to be attributed to me and be shared in research outputs.

I understand that my data will be stored securely in electronic format on an encrypted, password protected laptop and on a secure server and that the physical copy of this form will be stored securely under lock and key for the duration of the research project (estimated 3 years). After which it will be anonymised and stored securely in an institutional depository for ten years in line with funder requirements.

	Yes	No
• I agree that my information can be quoted in research outputs in an anonymised format.	☐	☐
• I agree that my name, and organisation (if applicable), can be used in quotes in research outputs	☐	☐

3. Future use and reuse of the information by others

I give permission for anonymised transcripts of the interview that I attend to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning. The data will be de-identified by providing an anonymised attribution i.e. 'Cumbrian Sustainability Professional' or 'Cumbrian Heritage Building Owner.' An appropriate creative commons licence will be placed on the data. After the project is complete this consent form will be digitised and securely stored for as long as the research data is retained. The original consent form will be securely destroyed by means of shredding.

	Yes	No
• I would like to be contacted with the results of the research and agree to my email being used for this purpose.	☐	☐

4. Signatures

____________________ ____________________ ____________________

Name of participant [IN CAPITALS]   Signature   Date

This research project on: Reducing Whole Life Energy and CO2 Emissions in Heritage Buildings has been reviewed by, and received a favourable opinion, from the OU Human Research Ethics Committee - HREC/3182/Wise
http://www.open.ac.uk/research/ethics/

A.3) Scoping interview schedule

Section 1

Could you describe to me what you think a heritage building is?

What is your involvement with heritage buildings?

What is your opinion of heritage buildings in a Cumbrian context, what, if anything do you think they add to the area?

Section 2

What key issues do you think heritage buildings might be facing in Cumbria?

Do you think that the research gaps that we have identified are relevant to Cumbria?

Can you identify any other gaps that might be more relevant?

Did you know the Lake District National Park is now a World Heritage Site and if so do you have a strong opinion on this?

What effect do you think this might have on heritage buildings in the park?

Section 3

What sort of questions do you think it would be useful for us to ask in our survey?

Do you have any thoughts about how we might get this survey to reach a good selection of people?

Do you have any thoughts about stakeholders who it would be useful for us to engage with?

Appendix B) Full copy of survey questions

Heritage values and energy use in older Cumbrian buildings

Page 1: Introduction and permissions page

Heritage values and energy use in older Cumbrian buildings

Invitation paragraph

You are being invited to take part in an online survey for a research project. Before you decide whether to take part please read the following information so that you understand why the research is being done and what it will involve.

We would like to invite you to take part if your home was built before 1940 and is situated in Cumbria.

General information about the research study and collected research data

This research is part of a project looking at how to reduce energy and carbon emissions from older buildings in Cumbria without damaging their heritage value. The part of the research that you are being invited to take part in today is an anonymous online survey investigating:

- What people value about their buildings
- How they use energy in their buildings
- What changes they might consider making to reduce their building's energy use and carbon emissions.

The data from this survey will be really useful to help develop our understanding of these issues in a Cumbrian context. It will help inform the development of several in depth case studies which will form the next stage of the project.

This research forms part of the researcher's PhD project with The Open University. It is being funded by the Design Star Centre for Doctoral Training: https://www.designstar.org.uk.
The project has been registered with and approved by the Open University's Human Research Ethics Committee and the ethics reference number is: HREC/3233/Wise.

What will I be asked to do if I agree to take part?

If you choose to take part you will be asked to fill in an online survey about your experience of living in your home, how you use energy for heating and lighting and what sort of alterations you might consider making to reduce your building's energy use. The survey should take you around 10-15 minutes to complete.

Your participation will really help to increase our understanding of these areas and particularly in the context of Cumbria. One of the outputs from this project will be some Cumbrian specific guidance.

Your right to withdraw

Participation is entirely voluntary. If you do decide to take part you will be asked to tick the consent boxes at the bottom of this page. If you participate you are still free to withdraw from the survey at any time and without giving a reason by closing the webpage. At the end of the survey you will be asked to confirm that you are still happy for your answers to be included in our analysis.

Data Protection

Your answers to the survey questions will be completely anonymous and we will not be able to trace them back to you as an individual. No personally identifying information will be collected. All the survey data will be kept securely in an electronic format. This survey uses the JISC Online Surveys tool; JISC do not collect cookies or IP addresses when administering the survey.

Data from the survey will be aggregated and analysed. Results from the analysis will be included in research publications, such as journal articles, conference papers and other publications. Upon completion of the project the anonymous, aggregated survey data will be stored in the OU's data repository in line with the aim of making research open.

Contact Details
Principal researcher: Freya Wise

If you have any queries, in the first instance please contact Freya Wise

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Milton Keynes
MK7 6AA

Website: http://www.open.ac.uk/people/fw939

If you wish to speak to someone else about this project please contact Alice Moncaster at: Alice.moncaster@open.ac.uk

How do I agree to take part?

If you want to take part click the consent buttons to confirm that you have read this information sheet and are happy to take part, then click next to start the survey.

Thank you for taking the time to read this information!

Having read the information above are you happy to take part in this survey? ✱
Required

- ○ I have read and understood the information and am happy to take part
- ○ I do not wish to take part

Having read the information above are you happy for data (such as anonymous quotes) from the survey to be used in research publications and presentations?

- ☐ Yes in publications and presentations
- ☐ No
- ☐ Only in publications
- ☐ Only in presentations

Page 2: The Basics

This sections asks some basic questions about your building and your household

In what district of Cumbria is your building located?

What type of building is it?

- Detached
- Semi-detached
- Terraced
- End of terrace
- Flat

Can you characterise it?

- Farmhouse
- Cottage
- Barn conversion
- Suburban house
- Stately home
- Castle
- Peel tower
- Other

If you selected Other, please specify:

Where is your building located?

- Rural
- Village
- Town
- City

Is your building any of the following? (tick all that apply)

- Grade I listed
- Grade II* listed
- Grade II listed
- In a conservation area
- In the Lake District National Park
- In the Yorkshire Dales National Park
- None/unprotected
- Other

If you selected Other, please specify:

Do you own your home or is it rented?

- Owned (including with a mortgage)
- Rented

How old is your building to the nearest decade? If developed over time please give the date for the **largest** existing part of the building. *(Please give in date format, ie 1820s rather than 200 years old).*

If developed over time how old is the **oldest** still existing part of the building to the nearest decade?

Page 3: Heritage

This section asks some questions about what you value about your building.

Heritage value can include things like historic value, uniqueness, aesthetic values, values for the local community (i.e. a local landmark), forming part of a distinctive landscape etc although this is not exhaustive.

Do you consider your building to have heritage value?

○ Yes ○ No

What is most important to you about your building and its locality?

Please don't select more than 1 answer(s) per row.

	Very important	Important	Slightly important	Not important	N/A
Age	☐	☐	☐	☐	☐
Architecture	☐	☐	☐	☐	☐
History of type of building (eg victorian terrace)	☐	☐	☐	☐	☐
History of specific building (eg events relating to this building)	☐	☐	☐	☐	☐
Local community	☐	☐	☐	☐	☐
Inherited	☐	☐	☐	☐	☐
Local services	☐	☐	☐	☐	☐
Price	☐	☐	☐	☐	☐

Views	☐	☐	☐	☐	☐
Specific location	☐	☐	☐	☐	☐
Family home	☐	☐	☐	☐	☐
Heritage value	☐	☐	☐	☐	☐
Character in the landscape	☐	☐	☐	☐	☐
Original historic features (please detail in 'other' box)	☐	☐	☐	☐	☐
The particular materials (please detail in 'other' box)	☐	☐	☐	☐	☐
Specific features (please detail in 'other' box)	☐	☐	☐	☐	☐
Size of building	☐	☐	☐	☐	☐
Traditional construction	☐	☐	☐	☐	☐

Other

Are there any specific heritage aspects to your building, either physical or to do with its history, that you value but that other people might not notice or know about?

Page 4: Energy

This section asks some questions about your thoughts on reducing energy and carbon emissions in heritage buildings

The government has recently committed to the UK achieving net zero carbon emissions by 2050 to help mitigate climate change. What level of responsibility do you think different groups have for reducing energy use and carbon emissions from heritage buildings as part of these broader efforts?

Please don't select more than 1 answer(s) per row.

	No responsibility	Little responsibility	Some responsibility	Lots of responsibility	Full responsibility
Building professionals	☐	☐	☐	☐	☐
Energy companies	☐	☐	☐	☐	☐
English Heritage	☐	☐	☐	☐	☐
Governments	☐	☐	☐	☐	☐
Homeowners	☐	☐	☐	☐	☐
Local authorities	☐	☐	☐	☐	☐

Do you think it is more difficult to reduce energy and carbon emissions from heritage buildings than from more modern buildings?

	Much easier	Slightly easier	About the same	Slightly harder	Much harder
Tick one	☐	☐	☐	☐	☐

Would you like to reduce your building's energy use?

	No, not really	Maybe	Yes	Yes, definitely
Tick one	☐	☐	☐	☐

What do you currently do, and what might you be willing to do, to reduce your energy use in your building?

Please don't select more than 1 answer(s) per row.

	Currently do	Might do	Wouldn't do	Not applicable
Making sure lights are turned off when room is not in use	☐	☐	☐	☐
Only heating parts of the building that are actively in use	☐	☐	☐	☐
Reducing the number of machines left on standby	☐	☐	☐	☐
Reducing hot water use	☐	☐	☐	☐
Turning heating off when away	☐	☐	☐	☐
Turning the heating temperature down	☐	☐	☐	☐
Wearing extra clothes when it's cold ie jumpers, slippers, dressing gowns etc.	☐	☐	☐	☐
No heated Bedrooms	☐	☐	☐	☐
Using 'smart home' technology	☐	☐	☐	☐
Other (please detail)	☐	☐	☐	☐

If you ticked other please give details

Page 5: Energy Systems and Behaviour

This section asks some questions about how you heat your home.

If you have central heating what fuel does it use?

- ○ Gas central heating
- ○ Oil central heating
- ○ Electric central heating
- ○ Biomass central heating
- ○ No central heating
- ○ Other

If you selected Other, please specify:

[ ]

What types of heating/cooling do you use in your building? *(Question 24 asks about renewable energy technologies*).

Please don't select more than 1 answer(s) per row.

	Normally	Often	Sometimes	Rarely	Never use	Do not have
Air conditioning	☐	☐	☐	☐	☐	☐
Coal fires	☐	☐	☐	☐	☐	☐
Electric fires	☐	☐	☐	☐	☐	☐
Wood fires	☐	☐	☐	☐	☐	☐
Wood stove	☐	☐	☐	☐	☐	☐
Gas fires	☐	☐	☐	☐	☐	☐

Radiators	☐	☐	☐	☐	☐	☐
Solid fuel range (eg Aga or similar)	☐	☐	☐	☐	☐	☐
Storage heaters	☐	☐	☐	☐	☐	☐
Underfloor heating	☐	☐	☐	☐	☐	☐
Ceiling fans	☐	☐	☐	☐	☐	☐
Portable fans	☐	☐	☐	☐	☐	☐
Portable heaters	☐	☐	☐	☐	☐	☐
Hot water bottles	☐	☐	☐	☐	☐	☐
Other (please detail)	☐	☐	☐	☐	☐	☐

Other:

What heating controls do you have? (tick all that apply)

- ☐ One thermostat
- ☐ Room thermostat
- ☐ Radiator thermostats
- ☐ Computer controlled system
- ☐ Other

If you selected Other, please specify:

At what temperature do you generally have your main living space?

If you selected Other, please specify:

When your heating is on, how long is it generally on for?

- ◌ Once a day
- ◌ Twice a day
- ◌ Intermittently
- ◌ All day
- ◌ All day and all night

In **an average year** which months do you generally heat your building for? (tick all that apply)

☐ January	☐ February	☐ March
☐ April	☐ May	☐ June
☐ July	☐ August	☐ September
☐ October	☐ November	☐ December

☐ Unknown

Page 6: Comfort

This section asks some questions about how comfortable your building is to live in.

How do you use your windows for comfort in Summer?

	Always	Often	Sometimes	Rarely	Never
All windows are open	☐	☐	☐	☐	☐
Some windows are open	☐	☐	☐	☐	☐
A few windows are open	☐	☐	☐	☐	☐

How do you use your windows for comfort in Winter?

	Always	Often	Sometimes	Rarely	Never
All windows are open	☐	☐	☐	☐	☐
Some windows are open	☐	☐	☐	☐	☐
A few windows are open	☐	☐	☐	☐	☐

Overall how satisfied are you with living in your building?

	Very unsatisfied	Unsatisfied	Fairly unsatisfied	Fairly satisfied	Satisfied	Very satisfied
Please tick one	☐	☐	☐	☐	☐	☐

Please use the following scales to indicate how comfortable your building is to live in.

Thermal

Do you feel hot/cold in your building in:

	Very hot	Hot	Warm	Neutral	Cool	Cold	Very Cold
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

Would you like it to be warmer/cooler?

	Much warmer	Warmer	As now	Cooler	Much cooler
In summer	☐	☐	☐	☐	☐
In winter	☐	☐	☐	☐	☐

Ventilation

Do you find your building draughty/stuffy in:

	Very draughty	Draughty	Slightly draughty	Neutral	Slightly stuffy	Stuffy	Very Stuffy
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

Would you like there to be more/less ventilation:

	Much less	Less	As now	More	Much more
In summer	☐	☐	☐	☐	☐
In winter	☐	☐	☐	☐	☐

Air quality

Are you satisfied with the air quality in your building in:

	Very unsatisfied	Unsatisfied	Fairly unsatisfied	Fairly satisfied	Satisfied	Very satisfied
Summer	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐

Does your building feel damp/dry in:

	Very damp	Damp	Slightly damp	Neutral	Slightly dry	Dry	Very dry
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

Luminosity

Do you find it dim/bright in your building in:

	Very dim	Dim	Slightly dim	Neutral	Slightly bright	Bright	Very bright
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

Would you like it to be dimmer/brighter?

	Much dimmer	Dimmer	As now	Brighter	Much brighter
In summer	☐	☐	☐	☐	☐
In winter	☐	☐	☐	☐	☐

Noise levels

Do you find it noisy/quiet in your building?

	Very noisy	Noisy	Slightly noisy	Neutral	Slightly quiet	Quiet	Vey quiet

External noise levels	☐	☐	☐	☐	☐	☐	☐
Internal noise levels	☐	☐	☐	☐	☐	☐	☐

Would you like it to be noisier/quieter?

	Much noisier	Noisier	As now	Quieter	Much quieter
External noise levels	☐	☐	☐	☐	☐
Internal noise levels	☐	☐	☐	☐	☐

Is there anything in particular that influences your comfort in your building that you would like to tell us about? (Are there any issues such as age, health conditions or fuel poverty that might influence your comfort in your building or mean that you have to take particular actions? This could include things like having the heating on all year for example).

Page 7: Solutions

This penultimate section asks about different types of solutions that you might be willing to undertake to reduce your energy use and carbon emissions and what any barriers might be.

Thinking about the impact on your building's heritage values and assuming that money and planning permission were no issue, which of these options would you be willing to take to reduce energy use and carbon emmisions?

Please don't select more than 1 answer(s) per row.

	Already have	Would be willing to take now	Might look at in the future	No, wouldn't do	Not applicable
Loft insulation	☐	☐	☐	☐	☐
Floor insulation	☐	☐	☐	☐	☐
Interior wall insulation	☐	☐	☐	☐	☐
Exterior wall insulation	☐	☐	☐	☐	☐
Energy efficient lighting	☐	☐	☐	☐	☐
Draught proofing	☐	☐	☐	☐	☐
Chimney balloons	☐	☐	☐	☐	☐
Energy efficient appliances/devices	☐	☐	☐	☐	☐
Upgrade boiler	☐	☐	☐	☐	☐
New windows (wood frame)	☐	☐	☐	☐	☐
New windows (UVPC frame)	☐	☐	☐	☐	☐

New windows (metal frame)	☐	☐	☐	☐	☐
Secondary glazing	☐	☐	☐	☐	☐
Thermal curtains	☐	☐	☐	☐	☐
Exterior shutters	☐	☐	☐	☐	☐
Interior shutters	☐	☐	☐	☐	☐
Thick wall hangings	☐	☐	☐	☐	☐
Photovoltaic solar panels (electric)	☐	☐	☐	☐	☐
Solar thermal panels	☐	☐	☐	☐	☐
Biomass boiler	☐	☐	☐	☐	☐
Air source heat pump	☐	☐	☐	☐	☐
Ground source heat pump	☐	☐	☐	☐	☐
Any other suggestions (please detail)	☐	☐	☐	☐	☐

Any other suggestions:

What do you feel are the barriers to reducing your building's energy use and carbon emissions and how important are they? *(please rate against the scale)*

	Very important	Quite important	Important	Slightly important	Not important	N/A

Cost	☐	☐	☐	☐	☐	☐
Knowledge of suitable options	☐	☐	☐	☐	☐	☐
Planning restrictions	☐	☐	☐	☐	☐	☐
Time commitment	☐	☐	☐	☐	☐	☐
Disruption	☐	☐	☐	☐	☐	☐
Availability of tradespeople	☐	☐	☐	☐	☐	☐
Feel that we have done everything possible	☐	☐	☐	☐	☐	☐
Concern about impacting heritage values	☐	☐	☐	☐	☐	☐
Other (please detail in box below)	☐	☐	☐	☐	☐	☐

If you selected other please detail:

How motivated do you feel to reduce your building's energy use and carbon emissions?

	Not at all motivated	A little bit motivated	Quite motivated	Very motivated	Extremely motivated
Please tick one	☐	☐	☐	☐	☐

What do you think the potential might be to reduce your building's energy use and carbon emmisions?

	Very limited	Limited	Moderate	Substantial	Very Substantial
Tick one:	☐	☐	☐	☐	☐

Where would you go to find out about how to reduce your building's energy use and carbon emissions?

	I've been here and was satisfied	I've been here and was unsatisfied	I would go here	I wouldn't go here	I don't know what they could offer
Local authority planning department	☐	☐	☐	☐	☐
Local authority building control	☐	☐	☐	☐	☐
Other local authority department	☐	☐	☐	☐	☐
Friends/neighbours/relatives	☐	☐	☐	☐	☐
Builder	☐	☐	☐	☐	☐
Architect	☐	☐	☐	☐	☐
Energy consultant	☐	☐	☐	☐	☐
Heritage organisation	☐	☐	☐	☐	☐
Energy Saving Trust website	☐	☐	☐	☐	☐
Cumbria Action for Sustainability	☐	☐	☐	☐	☐
The internet	☐	☐	☐	☐	☐
Other heritage building owners/users	☐	☐	☐	☐	☐
Other (please detail)	☐	☐	☐	☐	☐

Other please detail:

Page 8: Policy

This final section has some questions about your feelings about planning policy relating to heritage buildings in your district.

Do you think that planning regulations for heritage buildings in your district are:

	Much too relaxed	A bit too relaxed	About right	A bit too restrictive	Much too restrictive
Please tick one:	☐	☐	☐	☐	☐

Do you feel that planning regulations are consistently interpreted/applied in relation to heritage buildings in your district?

	Very inconsistent	Fairly inconsistent	Inconsistent	Fairly consistent	Very consistent
Please tick one:	☐	☐	☐	☐	☐

If you feel that planning regulations **are** applied/interpreted inconsistently could you provide any brief examples?

Page 9: Further Research

After analysing the results of this survey we are hoping to conduct further research with a small number of case study buildings. This would involve a researcher visiting your building a few times, conducting some interviews with you about your heritage values and energy use and examining any energy data you have (such as energy bills).

Would you be willing for your building to be a case study?

- ◌ Yes
- ◌ No

If you would be willing for your building to be a case study please email the research team at: freya.wise@open.ac.uk

We will then provide you with more information about what your building being a case study would involve so that you can make an informed decision on whether you wish to take part. We will also ask some questions to check that your building would be suitable for the study.

26 / 28

Page 10: Submit Survey Results

Please tick below to confirm that you are happy to submit your answers * *Required*

- ◌ I am happy for my responses to be used for the research.
- ◌ I want to withdraw my response

27 / 28

Page 11: Final page

Thank you very much for taking the time to fill out this survey and thereby contribute to the research!

Key for selection options

2 - In what district of Cumbria is your building located?

- Allerdale
- Barrow and Furness
- Carlisle
- Copeland
- Eden
- South Lakes
- Not in Cumbria

17 - At what temperature do you generally have your main living space?

- 14ºC
- 15ºC
- 16ºC
- 17ºC
- 18ºC
- 19ºC
- 20ºC
- 21ºC
- 22ºC
- 23ºC
- 24ºC
- 25ºC
- Other

Appendix C) Ethical details for nested case studies

C.1) Nested case study information sheet

Reducing carbon emissions from Cumbrian residential heritage buildings while retaining their heritage values.

The Open University

What the case study will involve

Each case study will involve three elements. It would be our hope that all these elements could be completed on one visit to your building but depending on time requirements a follow up visit might be required.

The first element would be an informal interview between you and myself, as lead researcher, to explore some of the areas from the survey in more detail. This would include questions on:

- Anything you know about the history of your building (including any documentary information you may have, plans, deeds etc).
- What you value about your building.
- What sort of changes to it you might find acceptable in order to reduce energy use, and any barriers there might be for you.
- How comfortable you find your building as a place to live.
- What sort of things you do which use/save energy in your building.

With your permission we would audio record this interview so that we have a detailed record to analyse. You don't need to do any preparation for this discussion apart from potentially getting out any documents you may have about the history of your building.

For the second element I would ask you if you could take me on a walk through your building to get a sense of its form and history and to look at any particular historic and energy features that your building may have, for example, historic cornices, particular materials, door lintels, chimneys, type of boiler, thermostat controls, window details etc.

With your permission I would audio record the walk through and take a number of, narrow angle, photographs of specific features of interest. This would follow on from any details that you've mentioned in the interview.

For the third element we would like to create a simplified energy model of your building based on Energy Performance Certificate (EPC) type data. This will then allow us to conduct analysis of the carbon impact of a range of retrofit options. The information that we would need to do this would involve:

- Taking some measurements of both the interior and exterior dimensions of your building
- Taking some photographs of some interior and exterior features of your building
- Examining your heating system and controls
- Examining your windows and lighting
- Asking about any renewable energy technologies you may have

- Asking about any insulation that you may have, especially in the loft
- Examining any energy data that you may have (i.e. energy bills). It would be useful if you could get these out ready for the visit and if you would allow me to take a copy (either by taking photos of a paper version or by emailing an electronic version).

It would be best to do this after the building walk though rather than at the same time as taking specific measurements will take longer and have a different focus than looking at heritage features.

Time commitment

It is likely that the interview and building walk through will take between 1-2 hours of your time. The energy survey is likely to take another 1-2hours.

Your time commitment is therefore likely to be approximately half a day. This can be arranged at a time convenient to you. If it would work better for you, I could make two visits, one for the interview and walk through and another for the energy survey. It is probable that less time may be required than described but we have included the highest estimate so that you definitely know what you are signing up for!

What happens after the visit?

I will go away and we will analyse the data that you have provided.

We will use the energy model to explore the carbon savings of a range of retrofit options. We will then compare this with data which we will be gathering on the carbon footprint of these options, that is, the carbon cost required to make, transport and construct the retrofit. This will enable us to get a picture of the whole life carbon impact of each of the retrofit options we are examining.

Using the information you have provided us with on the heritage values of your building we will then consider which options might be most suitable in terms of their carbon savings and heritage sensitivity. We will also be looking at the local planning context of your building to see what might be appropriate from this point of view.

Results

Once we have conducted the analysis we are happy to share the results with you and would be interested to know if the carbon saving information affects your thoughts about what changes you might consider making to your building. We would be happy to visit you again to discuss the results and your reaction to them or just to share the results via email.

We do have to emphasise however that this is a theoretical research project. Our energy model will provide an approximate idea of the carbon savings of the different retrofits but it will not be completely accurate, especially given that heritage buildings are challenging to model appropriately (in fact this is one of the things we will be exploring). We don't suggest that you base any home alterations on these results without seeking specific advice from a qualified professional energy expert or other qualified professional.[1]

Timescale

We would like to undertake the visit to your home from the beginning of February onwards. We can liaise with you to find a convenient time for this, to take place on any weekday, either during the day or in the evening whichever is best for you, or if you really can't do during the week a Saturday may also be possible.

We will hopefully be able to share the initial results with you by the end of 2020.

All research projects that The Open University run must achieve approval from our ethical research and data protection panels. If you are still interested, we will send you the consent forms and further information (about GDPR etc) for this purpose in the New Year.

Extra (bonus!) research element

In addition to the data outlined above we would be very interested in gathering some more information on the energy behaviour of people within Cumbrian heritage buildings. Would you be prepared to fill in an energy diary for approximately one week in the winter and one week in the summer?

We are still developing this idea but just wanted to gauge whether it is something you might be prepared to do or not? If you thought you might be willing to do this, we would provide you with more details once we have finalised them.

This would involve writing a few comments each day into a format we would provide. These comments would include things like:

- Temperature setting of your heating
- Other heating (put the log burner on in the evening)
- Which rooms you were in and how long for (roughly!)
- What activities you did in the house that day (cooked two meals, read books, was out at work all day etc)
- What level of clothing you were wearing at different times

Finally, if you were interested in this would you prefer a paper version or an online version of the energy diary?

Thank you!

Thank you very much for taking the time to read this information. Whether you are still interested or not it would be great if you could get back to us and let us know either way. If you don't reply we will send you a follow up email in early January just to check that this one didn't get lost in Christmas busy-ness.

[1] The researchers on this project and/or The Open University can take no responsibility for any damage or challenges to your property that might result from you basing any home alteration decisions on the results of our research. We urge you to seek proper advice before undertaking any form of alteration to you building.

C.2) Nested case study physical site visit consent form

Informed Consent for Reducing carbon emissions from residential heritage buildings in Cumbria while retaining their heritage values. Pilot case study

Freya Wise
Postgraduate Researcher
Engineering and Innovation
The Open University

Please tick the appropriate boxes	Yes	No
1. Taking part in the study		
I have read and understood the study information sheet or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time (up until the 31st of September 2020, when the data will have been analysed) without having to give a reason.	☐	☐
I understand that taking part in the study involves a visit to my building by the researcher; an informal, audio recorded interview, an audio recorded walk through of my building with the researcher to identify any heritage and energy features, an energy use survey of my building and an energy diary.	☐	☐
I understand that, while the results of the study will be shared with me, I should not base any energy use or building alteration decisions on these results, as the energy model used is theoretical rather than highly detailed and accurate.	☐	☐
I agree to limited photos being taken during the building walk through	☐	☐
I agree to the interview and walk through being audio recorded	☐	☐
I agree to measurements and energy data about my building be collected and photographs being taken to enable the creation of an energy model.	☐	☐
I agree to filling out an energy diary over two, one week, periods and that this information can be used in the research.	☐	☐

2. Use of the information in the study

I understand that information I provide will be used for the research and will be used in research outputs such as reports, publications, research presentations and the researcher's thesis.

I understand that personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the study team.

I understand that my data will be stored in a secure electronic format for the duration of the study. After which it will be completely anonymised and stored in The Open University's Online Data Repository, ORDO for a period of ten years in line with the University's data retention schedule, after which it will be securely destroyed.

	Yes	No
I agree that my information can be quoted in research outputs in an anonymous format	☐	☐
I agree that non-identifiable photos may be used in research outputs.	☐	☐
I agree that an energy model may be created for my building and that anonymous output of this may be included in research outputs	☐	☐

3. Future use and reuse of the information by others

I give permission for the interview transcript that I provide to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning.

I give permission for the limited photographs that I provide to be deposited in a specialist data centre after they have been anonymised, so they can be used for future research and learning.

I give permission for the energy model of my building to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning.

I give permission for information from the energy diary that I fill in to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning.

The data will be de-identified by providing an anonymised attribution and generalising any specific location information. Any photographs will be checked to ensure that they do not enable your building to be identified. An appropriate creative commons licence will be placed on the data. After the project is complete this consent form will be digitised and securely stored for as long as the research data is retained. The original consent form will be securely destroyed by means of shredding.

4. Signatures

Name of participant [IN CAPITALS]	] Signature	Date

This research project, reducing carbon emissions from residential heritage buildings in Cumbria while retaining their heritage values, has been reviewed by, and received a favourable opinion, from the OU Human Research Ethics Committee - HREC reference number: HREC/3233/Wise

http://www.open.ac.uk/research/ethics/

C.3) Nested case study virtual visit consent form

Informed Consent for Reducing carbon emissions from residential heritage buildings in Cumbria while retaining their heritage values. Pilot case study

Freya Wise
Postgraduate Researcher
Engineering and Innovation
The Open University

Please tick the appropriate boxes — Yes / No

1. Taking part in the study

	Yes	No
I have read and understood the study information sheet or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time (up until the 30th of May 2021, when the data will have been analysed) without having to give a reason.	☐	☐
I understand that taking part in the study involves 1-2 virtual meetings with the researcher; a recorded interview, a recorded walkthrough of my building to identify heritage and energy features, and an energy diary.	☐	☐
I understand that, while the results of the study will be shared with me, I should not base any energy use or building alteration decisions on these results, as the energy model used is theoretical rather than highly detailed and accurate.	☐	☐
I agree to the interview and building walk through being recorded.	☐	☐
I agree that limited photos may be extracted from the recording	☐	☐
I agree to energy data about my building be collected.	☐	☐
I agree to filling out an energy diary over two, one week, periods and that this information can be used in the research.	☐	☐

2. Use of the information in the study

I understand that information I provide will be used for the research and will be used in research outputs such as reports, publications, research presentations and the researcher's thesis.

I understand that personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the study team.

I understand that my data will be stored in a secure electronic format for the duration of the study. After which it will be completely anonymised and stored in The Open University's Online Data Repository, ORDO for a period of ten years in line with the University's data retention schedule, after which it will be securely destroyed.

	Yes	No
I agree that my information can be quoted in research outputs in an anonymous format	☐	☐
I agree that non-identifiable photos may be used in research outputs.	☐	☐

3. Future use and reuse of the information by others

I give permission for the interview transcript that I provide to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning.

I give permission for the limited photographs that I provide to be deposited in a specialist data centre after they have been anonymised, so they can be used for future research and learning.

I give permission for information from the energy diary that I fill in to be deposited in a specialist data centre after it has been anonymised, so it can be used for future research and learning.

The data will be de-identified by providing an anonymised attribution and generalising any specific location information. Any photographs will be checked to ensure that they do not enable your building to be identified. An appropriate creative commons licence will be placed on the data. After the project is complete this consent form will be digitised and securely stored for as long as the research data is retained. The original consent form will be securely destroyed by means of shredding.

4. Signatures

Name of participant [IN CAPITALS]	] Signature	Date

This research project, reducing carbon emissions from residential heritage buildings in Cumbria while retaining their heritage values, has been reviewed by, and received a favourable opinion, from the OU Human Research Ethics Committee - HREC reference number: HREC/3233/Wise

http://www.open.ac.uk/research/ethics/

Appendix D) Nested case site visit paperwork

D.1) Nested case interview schedule and building tour checklist

1 Introduction
How long have you lived in this building?

Why did you decide to live in this building?

What do you like and what don't you like about living in this building?

What is important to you about this building?

2 Heritage Values
Would you describe your building as a heritage building?

What do you think of your building's heritage values?

Are you generally interested in history?

What do you know about your building's history? When was it built etc?

Do you think your building has an impact on the local area? If so in what way?

Do you think smaller older buildings add anything to the area or is it just tourist attraction heritage buildings?

Do you think the vernacular building landscape contributes to the local economy?

If you could replace your building with a modern new build would you?

If you could replace your building with a new high spec 'green' building would you? Why either way?
Would you if it meant this building was destroyed?

3. Environmental attitude
What are your thoughts about climate change?

What are your thoughts about reducing carbon emissions?

Who do you think has the most responsibility for reducing UK CO^2?

Have you done anything to try to reduce energy and carbon from your building?

Have you heard of embodied carbon and if so do you understand what it means?

Do you think of yourself as generally environmentally friendly?

4. Acceptability of changes
Here's the list of the adaption options from the survey plus another couple that we've added. Are there other adaptions you'd like to add to the list?

How much do you know about the planning context for your building and what you can or can't do?

How easy do you think it would be to get planning permission for some of these changes?

Do you have an opinion on the local planning policies and how they're applied?

What would you say are the main barriers to reducing your building's carbon emissions?

Comfort and energy behaviour
How comfortable do you find your building as a place to live?

Is there anything in particular that influences your comfort, or that you would change if you could?

What sort of things do you do to maintain comfort?

How much time do you spend in your building?

Which spaces in your building do you and your family spend most of your time in?

Are there any spaces that are rarely used by anyone? Or are used differently at different times of year?

If you were relaxing in your building on a cold winter's evening what would you be doing and what would you be wearing?

How would this differ in the summer months?

Where do you source your energy from?

Are you on any kind of green tariff?

Do you have any renewable energy technologies or low energy technologies?
Do you know how much energy you use each year?

House walk through
Historic Features Checklist

- Unusual or interesting layouts
  - Former (or current) use of building
  - Corner and end of row buildings
  - Obvious extensions or adaptions (good or bad!)
  - Feature buildings
- Original fixtures and fittings (or include 'old')
  - Doors, windows
  - Fireplace or other heating system/product (range; wood burner; back boiler; etc.)
  - Staircase fittings and woodwork
- External details
  - Interesting (or unusual?) materials (e.g. dressed stone; formed or carved stone or timber; timber cladding;)
  - Roof: Eaves, verge and ridge details (e.g. profiled timber; fancy chimney; corbelled brick or stone; gable stones)
  - Garden and surroundings: location; garden; boundary treatment; outbuildings; gates and/or metalwork)
  - Solid wall, any insulation etc?

Checklist of things to note:
General condition:

- Temperature: warm / cold? Note outside temperature too if you measure
- Feel/smell damp? Stale? High levels of moisture in air? (Is moisture ever a problem?)
- Interior decoration state (simple: good/average/bad)

Windows:

- Window unit
  - Case Type (fixed, casement, sash and case, modern/replacement)
  - Glazing (single old or new; double; triple; secondary)
  - Material (timber; metal; uPVC)
  - Condition (paint; condensation (pane or cill); fogging)
  - Ventilator at head (position)
- Covering:
  - Curtains (and height)
  - Blinds
  - Pelmet
  - Shutters
  - Exterior shutter
- Behaviour
  - Open/close windows (open close curtains/shutters)
  - Ventilation
  - Cold? Draughts? Location of seats/furniture
- External doors
  - Type
  - Integral and frame seals
  - External seals or coverings (curtain; draught excluder; etc)

Heating and energy

- System:
  - Fuel
  - Boiler
  - Distribution (radiators/vent/direct etc)
- Controls
  - Timer
  - Room/panel thermostat(s)
- Behaviours
  - Temperature preference (living rooms; bedrooms)
  - Do you know how to work your controls?
  - How often do you use the fire / wood burner?
- Lights
  - Types (fixed and/or lamps; bulb types)
  - Habits and use
- Water
  - Number of bathrooms and/or fittings (i.e. sinks; WCs; showers; baths)
  - Habits and water use (especially hot water)
- Electrical
  - Lots of gadgets
  - Habits and use
- Ventilation
  - Kitchen and bathrooms

D.2) Nested case blank retrofit matrix

Participants were asked to place a tick, cross, or question mark in each box to indicate whether heritage/aesthetics for example would be an issue for them with that retrofit measure or not. They were also asked to state, in summary, whether each measure would be something that they would consider or not. Participants were asked to talk through their reasoning for each option.

Retrofit Option	**Heritage/ aesthetics**	**Planning**	**Cost**	**Practical implications**	**In summary**
Loft Insulation					
Floor insulation					
Internal wall insulation					
External wall insulation					
Energy efficient lighting					
Draught proofing					
Chimney ballons					
Upgrade boiler					
New windows (wood frame)					
New windows (UVPC frame)					
New windows (aluminium frame)					
Secondary glazing					
Thermal curtains					
Exterior shutters					
Interior shutters					
Wind Turbine					
Photovoltaic (electric) solar panels					
Solar thermal panels					

Retrofit Option	Heritage/ aesthetics	Planning	Cost	Practical implications	In summary
Biomass boiler					
Air source heat pump					
Ground source heat pump					
Water source heat pump					
Hydropower turbine					
Energy efficient appliances/devices	N/A	N/A			
Improve heating/ hot water controls	N/A	N/A			
Thick wall hangings					
Lower heating temperature		N/A	N/A		
Turn heating off when away		N/A	N/A		
No heated bedrooms		N/A	N/A		
Only heat parts of house actively in use		N/A	N/A		

For the things that you have done have they made a useful difference do you think?

If you have any renewals technologies are you happy with their performance?

D.3) Nested case blank reflection sheet

A printed reflection sheet was completed by the researcher directly after each site visit to note down initial impressions on the case and on how the visit had gone. These were reviewed during later analysis.

Case study .... Reflection sheet	
Describe the Building?	
Describe the People?	
Heritage values?	
Environmental attitude?	

Energy behaviours?	
Any special features?	
Anything extra to note?	
How did the interview/ walkthrough go?	
How did the energy survey go?	
Anything to follow up?	
Overall impression	

Appendix E) Energy diary sample

The first and last pages of the energy diary and a sample day are shown, all other days are the same as the sample day.

Energy Use Diary

Part Two: Summer

The Open University

Energy Use Diary
Summer

Hello!
Thank you for agreeing to fill out this energy diary! It will really help us to understand how people use energy in heritage buildings. We would like you to fill this diary out twice a day (morning and evening) for five days. If you've already filled in the winter diary for us, that's great, thank you! If not we'll ask you to fill in another very similar diary around October.
If possible we'd like you to fill the diary in from Thursday to Monday, or Friday to Tuesday. This is so it covers a couple of weekdays and a weekend because people often do different things at weekends compared to weekdays.

As part of the diary we will, if you agree, provide you with two digital thermometers. We will ask you to place one of these outside your building and one in your main living space and then ask you to check them once per day and note down their recordings.

This diary is designed to be filled in by one person for the household but different people can fill in different bits if necessary. It would be great if you can fill in this dairy during a fairly 'normal' week for you, so not when you are going away for seven days or if you have guests to stay (unless that is an every-week occurrence for you of course!). Although we do appreciate that 'normal' at the moment may be rather different to pre-coronavirus normal.

We hope that its fairly self explanatory but we would encourage you to have a look through the diary and get in touch if you have any questions on elements you might not be clear on: freya.wise@open.ac.uk We will now ask for some initial information from you before you start the diary (we do need this again please even if you have already completed an energy diary as the heating settings and windows are likely to be different!).

Initial information

At the start of the diary there are a couple details that we will ask you to fill in now so that you don't have to enter them each day.

What is your name? ____________________

Could you tell us roughly how old everyone in your household is? *To the nearest decade is fine, EG two under tens, one 30-40 year old, one 40-50 year old.*

____

How many people are currently living in your household?

____

If you have central heating can you tell us:
When and how long it is on for each day if at all? (*Eg: twice a day 6am-8am and 5pm-9pm*)

What temperature the main thermostat is set to? ______________________________

If you have radiator controls (or other form of temperature zoning) could you tell us what the radiators in the main living space, the kitchen and the bedrooms in use are set to?

Main living space: __________ Kitchen: __________ Bedroom 1: __________

Bedroom 2: __________ Bedroom 3: __________ Bedroom 4: __________

If you don't have central heating but have some other form of heating system that is used to a regular pattern could you briefly describe it?
If your only heating system is used intermittently then we'll just ask you to mention its use each on each day that you make recordings.

Eg, wood burning stove in living room, used for a couple of hours each evening.

Could you tell us approximately how many openable windows your property has? If you have a conservatory please provide a separate number for this.

____

At the start of the diary period could you tell us how many of these windows are open? (again providing a separate number for any conservatory)

Completely closed?_______________ Open a crack? _______________

Open a bit? _______________ Wide open? _______________

Could you tell us if you have any form of mechanical ventilation and if so what it is and which room it's in?

Eg, 1 Extractor fan in kitchen, 1 in each of the two bathrooms.

Thank you very much for this initial information! As part of the diary we will just ask you to note if any of these things change rather than getting you to repeat it in great detail!

When you are ready please turn over and start your energy diary!

<u>Day one! Please add the date:</u>

Morning: *(When you get up till 11am)* ____________________

Approximately what time did you get up? __________

Good Morning! Please could you tell us what the weather is like today? *Please circle as many of the below as are applicable and briefly describe.*

Windy | Rainy | Sunny | Snowy | Frosty

Eg, windy and cloudy today but dry and not too cold

Stormy | Cold | Mild | Humid | Hot

Could you check your inside and outside thermometer?
Please note the time you checked them? ______________________________

For the outside thermometer:
Curent temperature: ____________

Maximum temperature: ____________

Minimum temperature: ____________

Press reset! Done! ☐

For the inside thermometer:
Current temperature: ____________

Maximum temperature: ____________

Minimum temperature: ____________

Press reset! Done! ☐

How many people were in the house over this period? *If it varied go with highest number*

____

Did you use any auxiliary heating this morning? *If yes please briefly describe what and for how long, otherwise leave blank.*

Eg. Put the log burner on for a few hours

Did you open or close any windows/external doors or use any extractor fans? *If so please briefly describe otherwise leave blank*

Eg. Opened kitchen window a bit while cooking then closed half an hour later .

Did you have any lights on this morning? *If so how roughly how many? (For more than 5 mins!).* 0 ☐ 1-2 ☐ 3-5 ☐ 6-10 ☐ 11-15 ☐ More ☐

What were you doing and where did you do it? *We just want a general idea of what you did and roughly when and where. It doesn't need to be accurate to the minute! There is some information about the different sections below.*

Activities: Just a rough guide is great although it is helpful to distinguish some activities such as cooked or cold meals which use different amounts of energy. Here are some examples we thought up but they are by no means exclusive.

Had a shower	Put on dishwasher	Read books
Had a bath (how long?)	Put on washing machine.	Watched TV
Had a cooked meal	Vacuumed	Used computer
Had a cold meal	Went out	Did DIY (power-tools Y/N)

Location: What part of the house were you in? Living room, bedroom, kitchen, study etc and a rough percentage or time of how long for.

Clothing: It is really helpful to know what level of clothing you had on at different times. We've defined the levels of clothing as below. It would also be helpful to know if you are wearing any slippers or shoes and if you're using any other 'personal insulation' such as lap rugs, throws etc.

Light clothing (ie shirtsleeves/t-shirt)
Medium Clothing (ie shirt and jumper)
Heavy clothing (ie shirt, jumper and body-warmer/coat)

Morning -11am *(if there are two of you in the household you could divide the boxes in two, fill them in for both of you and ignore the 'others box' at the bottom*

What activities did you do?	*Eg: got up at 7am, had a cooked breakfast. Read books for 2 hours then went out. 10am-3pm*
What rooms were you in and for roughly how long?	*Bedroom 10%, Kitchen 20%, Living room 70%*
What level of clothing were you wearing?	*Medium clothing, plus slippers.*
What did others do and where?	*Person 3, worked in office all morning, 8am-11am. Person 4 got up, had cold breakfast, went to school 9am*

Day one!

Midday/afternoon (*11.00am-4.00pm*)
If everyone is out please tick, then skip this section and go straight to the evening. ☐

How many people were in the house over this period? *If it varied go with highest number*

Did you use any auxiliary heating this afternoon?

Did you open or close any windows/doors or use any extractor fans this afternoon?

Did you have any lights on this afternoon? 0 ☐ 1-2 ☐ 3-5 ☐ More ☐

Midday/Afternoon 11am -4pm

What activities did you do?	
What rooms were you in and for roughly how long?	
What level of clothing were you wearing?	
What did others do and where?	

<u>Day One!!</u>

Evening (*4.00pm-bedtime*)

How many people were in the house over this period? *If it varied go with the highest number*

Did you use any auxiliary heating this evening?

Did you open or close any windows/doors or use any extractor fans this evening?

Evening 4pm -Bedtime

What activities did you do?	
What rooms were you in and for roughly how long?	
What level of clothing were you wearing?	
What did others do and where?	

Any changes to the central heating settings today? *If yes please briefly describe otherwise leave blank.*

Eg, heating on for an extra two hours this mor ning 9am-11am because it was a bit cold!

If you spent the evening at home could you hazar d a guess at how many lights wer e on for any length of time? *So not just five minutes for the bathr oom light.*

0 ☐ 1-2 ☐ 3-5 ☐ 6-10 ☐ 11-15 ☐ More ☐

If you are taking meter readings have you remembered to check it today? *Please pop the readings on the page at the back of the book!*

I checked the meters! ☐

Roughly what time did you go to bed? ____________________ zZZ

Anything else that you think might have used a significant amount of ener gy over the day?

Eg: Computer, Radio/TV, Baking, Electric blanket, Nightlight, Security lights, fans etc.

If you have any questions or challenges with the diary please contact: freya.wise@open.ac.uk

Thank you for filling in day one of your ener gy diary!
(only four days to go!)

Meter readings: if possible it would be great if you could take meter readings of your electricity use and gas use (if applicable), so we can compare energy usage with energy behaviours. We appreciate that some people's meters may not be in accessible places so if you don't feel that it is possible or can't get it as it's at the back of a packed garage that's fine! If it was possible though, it would be very helpful! It's not vital, but it would also be helpful if you could try to check the meter at roughly the same time each day and please note the time you checked it!

If you use other types of fuel and have a way of recording this easily that would also be great!

Fuel type	**Electricity: This should be in kWh.** *(but if not please list the units, which should be shown on your meter)*	**Gas:** *Depends on the meter, might be in kWh but could be in other units please say which (should be shown on your meter)*	**Other fuel types.** *Please use appropriate units and say what it is. I.E five logs or three briquettes or 1 x 10kg bag of wood pellets*
Day 1: Time checked:			
Day 2: Time checked:			
Day 3: Time checked:			
Day 4: Time checked:			
Day 5: Time checked:			

Comments on Coronavirus and the impacts of social distancing.

We appreciate that coronavirus may have effected your daily routine during the time you have spent filling out the diary. If you wouldn't mind it would be really helpful if you could indicate how different this period has been compared with your usual activities.

If you could just note any significant changes to do with occupancy patter ns, heating behaviours or energy use that would be great and will help us to understand how what you have recorded may differ from your normal activities.

For example:

- *Are there more of you in the house than normal?*
- *Have you changed your heating behaviours because you'r e at home more?*
- *Would you usually be out walking on the fells for most of each day or away every weekend?*
- *Are you working from home and have a lot more electronic equipment in the house than usual?*

If you have any other comments on the experience of filling in the energy diary, other things you would like to have mentioned but didn't have space for, or any other comments that you'd like to share with us please pop them down here.

Thank you again for your time and efforts in filling in this diary! If, when you're finished, you could drop us an email that would be great and we'll arrange to come and pick up the diary and thermometers.

Any other comments: *For example do you always do your washing on a Wednesday and therefore this wasn't picked up the diary because of the days you did it?*

This diary is a piece of research for the project: Reducing carbon emissions from Cumbrian residential heritage buildings while retaining their heritage values.

The Open University

Appendix F) Photo elicitation information sheet

Photo elicitation

As part of the research we are trying to understand the range of different things that people like about their older buildings and everyone knows that a picture is worth a thousand words. So we would like to ask you to take one-three photos of heritage features of your building that you and/or other members of your household particularly like and send them to us with a couple of sentences to a paragraph for each photo about what you like about the thing it shows. (if you want to share with other household members and they have different opinions, if there are more than three of you then you can have one photo each!)

This could be anything you like; so it could be a view out of your window because what you really like is the location or conversely it could be a view of your house from the outside because your favourite aspect is how it fits in its landscape. Equally it could be the lintel of a fireplace, an original door/window or the proportions of a room, it's entirely up to you.

If you were happy then we might like to use your photos and parts of their description in our research publications and presentation but if you would prefer that we didn't share them then that is also fine but it would still be great to see them. With careful cropping it shouldn't generally be possible to identify your building from one photo, but if it should contain any identifying features (for example if it was a photo of a distinctive front facade) then we could just provide a written description instead of a photo to ensure anonymity. We're very happy to discuss individual photos on a case by case basis, if you are happy for us to use some but not others, so let us know if you have any concerns.

If you don't want to take part that's perfectly fine but we thought it might be a bit of fun. If you need any more information let us know!

Appendix G) SBEM Retrofit modelling results

SBEM models were created for CS1, CS5 and CS14 and, where there was uncertainty, assumptions were adjusted to get modelled energy demand as close to actual energy demand as possible. A subset of ten retrofit measures were modelled for each of the three cases and a package combining the retrofit measures was modelled for each of the cases (Table G.1).

Full details of the assumptions and data entry for the SBEM models can be seen at: https://figshare.com/s/9cd9f051ba8b21a3d7e3

Table G.1 List of retrofit measures in SBEM Modelling

Description of Measure	Variations
Baseline	CS1 0.2% less energy than actual, CS5 2.3% more energy than actual, CS14 12% more energy than actual.
Thermal Curtains for all windows	
Interior Shutters for all windows	
Secondary glazing for single glazed windows	
Secondary glazing (where not already) and curtains	
Floor insulation for any suspended floors	
Wall hangings to one external wall in each reception room	
No heating for bedrooms	Modelled for CS5 and CS14 only. CS1 currently do not heat their bedrooms.
Retrofitting of external doors with 10mm aerogel blanket	
Double glazing for all windows to current building regulations	
Replace old boiler with efficient modern one.	Modelled for CS1, who have an old, inefficient boiler, only. CS5 and CS14 already have efficient modern boilers.
Additional loft insulation	CS1 currently have 100mm and CS5 and CS14 150mm, this was increased to 250mm in all cases
Combination of measures: Interior shutters to all windows; Floor insulation; wall hangings; door retrofitted; additional loft insulation; and air infiltration improvement	The retrofit package included an improved boiler for CS1 and no heated bedrooms for CS5 and CS14. Air infiltration improvement was considered a result of the combined measures.

The percentage energy saving for each of the retrofits, for each case study can be seen in Figure G.1, while the energy and carbon savings from the combined package can be seen in Figure G.2

Figure G.1: Percentage energy reduction from each of the SBEM modelled measures

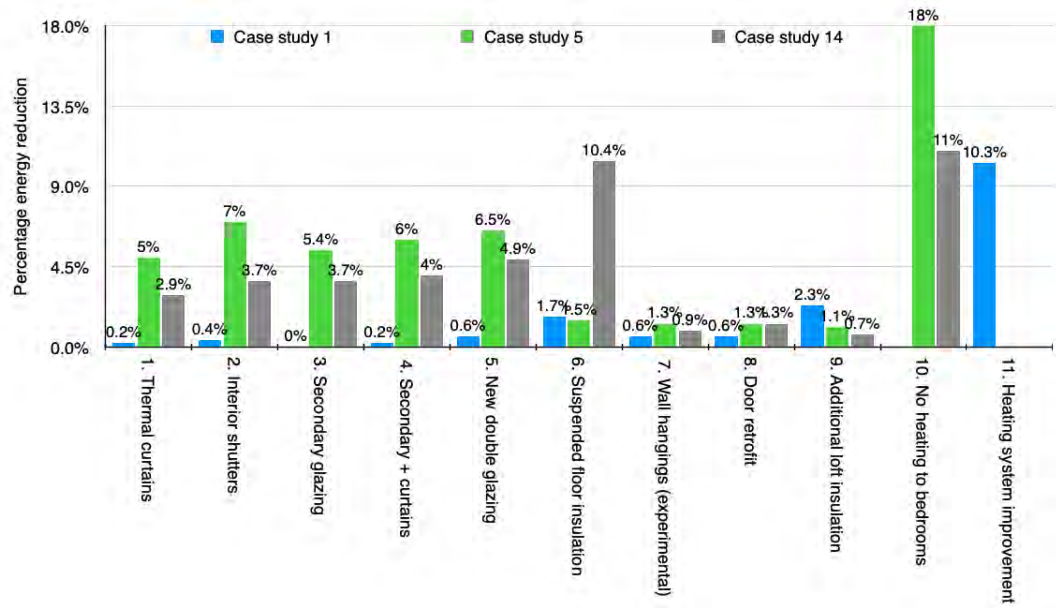
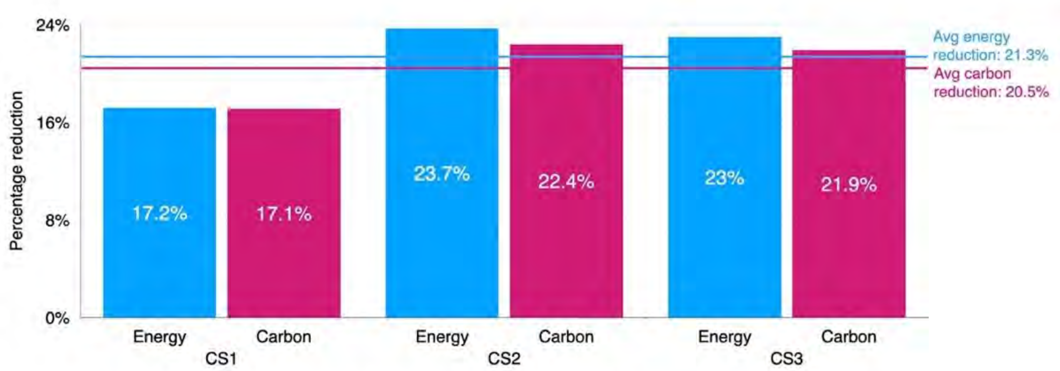


Figure G.2 Percentage savings for energy and carbon from SBEM combination package for each of the three case studies.



If option 10 (the behavioural change) is not included in the package for CS5 and CS14, then the reductions, including the rebound effect, would be: CS5, energy 12.5%, carbon 11.8%; CS14 energy 16.4%, carbon 15.6%.

These results are discussed in more detail in Wise, Moncaster, et al., (2021).

Appendix H) Design Builder baseline modelling and calibration

The Design Builder baseline models were created using data derived from the case study site visits. The technical survey included the collection of internal dimensions in all accessible rooms, internal and external wall thicknesses, and dimensions of external openings, which enabled the creation of detailed floor plans. A visual inspection of construction elements was undertaken, and participants were asked if they knew about the details of any construction build-ups as a result of previous work such as redecorating or similar. Details of heating and hot water systems were noted.

These details, together with information from the interviews, building tours and energy diaries enabled models to be created based on the building, and operating characteristics for each of the case studies.

The details of each construction build-up (walls, roofs, floors, and openings) and their individual and combined thermal properties, for each case study building, are available at: https://figshare.com/s/9d096fe06d62a6877330

H.1) Baseline Assumptions

A number of assumptions were nonetheless necessary in the creation of the energy models, for details that were not possible to determine through the actual data collection.

If no specific information about the build-up of a construction element was available a standard assumption was made based on the research team's experience of the construction of older buildings. This assumption was applied across the case studies. The main areas where assumptions were made was in the thickness of render (20mm), lathe and plaster (18mm) plaster (13mm), and/or plasterboard (12.5mm) for walls, and in the construction assemblies of floors, as most participants had never lifted their floors and therefore could not provide any build-ups details.

Construction elements are created by defining the build-up, thickness, and material of individual layers within the construction, the software then automatically calculates the thermal performance of the construction element. Construction material layers were mainly based on materials selected from the Design Builder component library which uses data from reputable sources such as the CIBSE Guide, the ASHRAE handbook and ISO 10456 (ASHRAE, 2021; ISO, 2017; CIBSE, 2016). A small number of additional materials, such as a specific wood fibre insulation product for CS12 were defined from manufacturer data.

Glass u-values for single glazed windows, single glazing with shutters, and single glazing with secondary glazing, were taken from research by Historic England (Wood et al., 2009). Values for double and triple glazing were taken from the software's glazing library. Total solar transmission and light transmission values were taken from the glazing library. U-values for shuttered windows are calculated with shutters closed. Most extant double or triple glazing in the cases was assumed to be argon filled. However double glazing for CS15 and some double glazing for CS9 was identified as very old or poor quality and was therefore considered to be air filled.

It is not possible to model shutters or curtains in Design Builder. The Historic England U-value for single glazing with shutters assumes that shutters are closed. Shutters were assumed to be closed approximately 50% of the time and therefore an average U-value between the un-shuttered and shuttered values is used. While shutters may be closed for less time than this, they are also more likely to be closed at night when temperatures are cooler and will therefore have a disproportionate effect on reducing heat loss. For the same reason the solar transmittance and light transmittance values were not altered as it was assumed that shutters would generally be used as night. The UK calculation methodology gives a formula for calculating the effect of curtains on the u-values of any window (BRE and DECC, 2014, p. 15).

$$\mathrm{U_{w,effective}} = \frac{1}{\frac{1}{\mathrm{U_W}} + 0.04}$$

This formula was used to calculate the u-values of applicable windows, where U_w is the window U-value calculated or measured without curtains.

The influence of both linear and repeat thermal bridging has been identified as a significant factor in the performance of buildings (Morrison Hershfield Limited, 2020). The building survey was not detailed enough to calculate specific linear thermal bridges. The default values from the UK's national calculation methodology were therefore used (BRE, 2018). These values have been degraded by the greater of 0.04W/mK or 50% (Table H.2). This is standard practice when specific values are not available and was considered appropriate for older buildings where it is unlikely that attention was given to mitigating linear thermal bridges during construction (BRE, 2018).

Table H.2: Psi values used for linear thermal bridging

Linear thermal bridges	Psi value
Roof-wall	0.18W/mK
Wall-ground floor	0.24W/mK
Wall-wall (corners)	0.14W/mK
Wall-floor internal (not ground floor)	0.11W/mK
Wall-floor external (not ground floor)	0.24W/mK
Lintel above window or door	0.45W/mK
Sill below window	0.08W/mK
Jamb at window or door	0.09W/mK

A total linear bridging transmittance is automatically calculated for each zone by taking the length of each category i.e. walls (calculated from the model geometry), multiplying by the appropriate Psi value, and then summing all the categories (DesignBuilder Software Ltd, 2020a). The total bridging is calculated on outer dimensions for each zone and gives the conductance of the total linear bridging for each zone. This is included in the model using a single surface per zone which has no film resistance and is located below the building to avoid interfering with shading calculations. The area of these fictitious surfaces is calculated to provide the sum of the linear bridges for each zone, for inclusion in the model. The effect of linear bridging is therefore accounted for.

Energy Plus/Design Builder, like most energy simulation tools, simulates materials in one dimension as homogenous layers (Morrison Hershfield Limited, 2020). This presents challenges for repeat thermal bridging, such as studwork in partitions, mortar joints in walls or joists in roofs and floors. These thermal bridges cannot be included directly in the simulation and must be included via some form of proxy. There is an option within the software to calculate the effect of thermal bridging on u-values if the percentage of bridging is known (DesignBuilder Software Ltd, 2020b). This follows the calculation procedure set out in BS EN ISO 6946 (BSI, 2020). The combined method used is suitable for most bridging (except metal through an insulation layer which is unlikely to be extant for the case studies) so the combined method is considered acceptable for this project ([Anderson, B] and Kosmina, 2019). This involves calculating the upper and lower limit of the thermal resistance of a material based on the heat flow paths through it, the mean of the two values is then assumed to be the value of the bridged construction (British Standards Institute, 2020). The location and distribution of common repeat thermal bridges for each of the buildings is assumed based on knowledge of traditional construction processes.

Once this calculation is complete, Design Builder suggests adjusting the bridged layer's thickness to achieve the u-value with bridging. However, this can affect the thermal mass of the construction, something which is particularly significant for traditionally constructed buildings such as the case studies. An alternative method, following that of (Pohoryles et al., 2020) is therefore used, whereby the thickness is maintained and the thermal conductivity of the bridged layer is adjusted instead. Repeat thermal bridging is considered for studwork in partition walls or drylining, for joists in solid, suspended, or intermediate floors and for joists and rafters in roofs. It is also considered for mortar in solid stone walls as research has identified that one of the reasons that standard models underestimate the performance of traditional construction is because the percentage of mortar is often much higher in reality than assumed by models (Li et al., 2015; Hulme and Doran, 2014; Baker, 2011). Based on the literature a value of 40% mortar has been assumed for this modelling (Li et al., 2015).

Occupancy, heating, hot water, lighting, cooking and electrical equipment energy demand and use patterns were initially based on standard domestic room profiles from the UK National Calculation Methodology (BRE, 2018). These parameters were then adjusted to reflect actual occupant behaviour based on the energy diary, site visit and interview data.

An area of particular uncertainty was the rate of air infiltration for each property, because the project budget precluded air tightness testing and none of the cases had had this undertaken previously. A range of values between 10-15$m^3h^{-1}m^2$ at 50 pascals was identified as a reasonable assumption for older buildings (Rye et al., 2012; Hubbard, 2011). A value within this range was therefore chosen for each case study based on residents' feedback and researcher observation of building air tightness. The only exception to this was CS14 where a slightly higher infiltration level of 17$m^3h^{-1}m^2$ at 50 pascals was selected due to the very high levels of air infiltration within their building. These infiltration assumptions were checked with a Cumbrian air tightness expert who confirmed that they were likely to be reasonable (Table H.3).

Table H.3 Air infiltration values assumed for each case study building

Case	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
M^3/h-m^2 @ 50 Pa	11	14	15	14	14	13	14	13	15	14	10	17	14

It is only possible to define electric direct heating in Design Builder, other heating fuels must use water or blown air as a heat transfer medium. It was therefore not possible to model wood stoves or open fires within the model. These were used as regular secondary heating by nine of the 16 case studies although only three cases were able to provide any data on the amount of wood that they used. The use of this secondary heating was therefore not included in the energy modelling or the actual energy figures.

However, CS11 uses a wood stove in their living room as their only heating source and do have data on how much wood they use each year. It was impossible to model this heating system accurately, instead an electric radiant heater was modelled and adjusted to a higher radiant factor and a lower efficiency to approximate the behaviour of the actual stove. The heating demand for this system has been referred to and treated as 'wood' throughout the rest of this thesis.

The exclusion of wood burning stoves from those cases that make regular use of it (CS1, CS2, CS5, CS7, CS9, CS12, CS14) may reduce demand on the main heating system if the two are running at concurrent times in the same rooms. This is likely to be true for CS1, CS5 and CS9, while the other cases use their wood burning stoves to replace, rather than to supplement, their main heating. Therefore, for CS1, CS5, and CS9 the model may slightly overestimate the main heating fuel demand because the effect of the stoves is not accounted for. This limitation therefore adds an additional element of uncertainty into the modelling.

During the modelling process the standard way that the model considers the heat exchange between neighbouring properties was found to lead to a significant underestimation of energy demand. This applied to CS8, CS9, CS11, CS12 and CS13 which are all terraced and also to a lesser degree to CS1, CS3, CS14 and CS15 which are semi-detached. Adjacent properties were modelled as adiabatic and therefore did not allow any heat transfer between the adjacent property and the case study. In several cases however (CS8, CS9, CS11, and CS12) neighbouring properties are holiday or second homes and are therefore irregularly heated and occupied. Neighbouring properties were therefore defined as 'semi-conditioned' spaces rather adiabatic spaces to allow heat exchange to take place. This significantly improved closeness of the model to actual heating demand.

H.2) Actual energy assumptions

The granularity of the energy data provided by the case studies was varied. Most participants provided yearly figures for gas/oil and for electricity for several years based on fuel bills or own meter reads. A mean yearly value was calculated for both fuel types to reduce usage variations and the impact of annual weather variations. Where participants had more that 6 years of data only the most recent were used. For participants using oil where use was measured in litres, a value of 9.8kWh/l was used (Nottingham Energy Partnership, 2020). For CS1 who uses propane for cooking an energy value of 7.07kWh/l was used (Nottingham Energy Partnership, 2020).

As described above CS11 uses a wood burning stove as their main heating system. They use an average of 960kg of briquettes and 1 cubic meter of logs each year. A value of 4.9kWh/kg was used for briquettes giving 4,704kWh per year (Wight Heat, 2021). The weight of a cubic meter of logs is dependent on the type of wood and how tightly they are stacked, 360kg is considered reasonable for a stacked cubic meter (Reservoir logs, 2021; Wight Heat, 2021). However logs are more likely to be delivered as a loose cubic meter which is likely to be at least a third air (Reservoir logs, 2021) so it is assumed that a cubic meter in this case equates to 238kg. Using an energy value of 4.2kWh/kg (Nottingham Energy Partnership, 2020), this gives 999kWh for logs and a total heating fuel use of 5,704kWh a year. CS11 was able to provide energy data on their electricity use.

Assessing the energy demand for CS2 and CS15 was problematic because only partial data was available. CS2 uses electricity for all their energy needs. They have on-site hydroelectricity which covers some of their energy use, but the exact amount generated and used was unclear. Based on residents' estimates of the on-site generation and how much of this was used in their property, 6,000kWh of hydro-generation was assumed to be used on site and added to metered electricity use to give a total of 15,158kWh per year. This calculation was undertaken before the energy simulation was developed and modelled energy was calibrated to this figure.

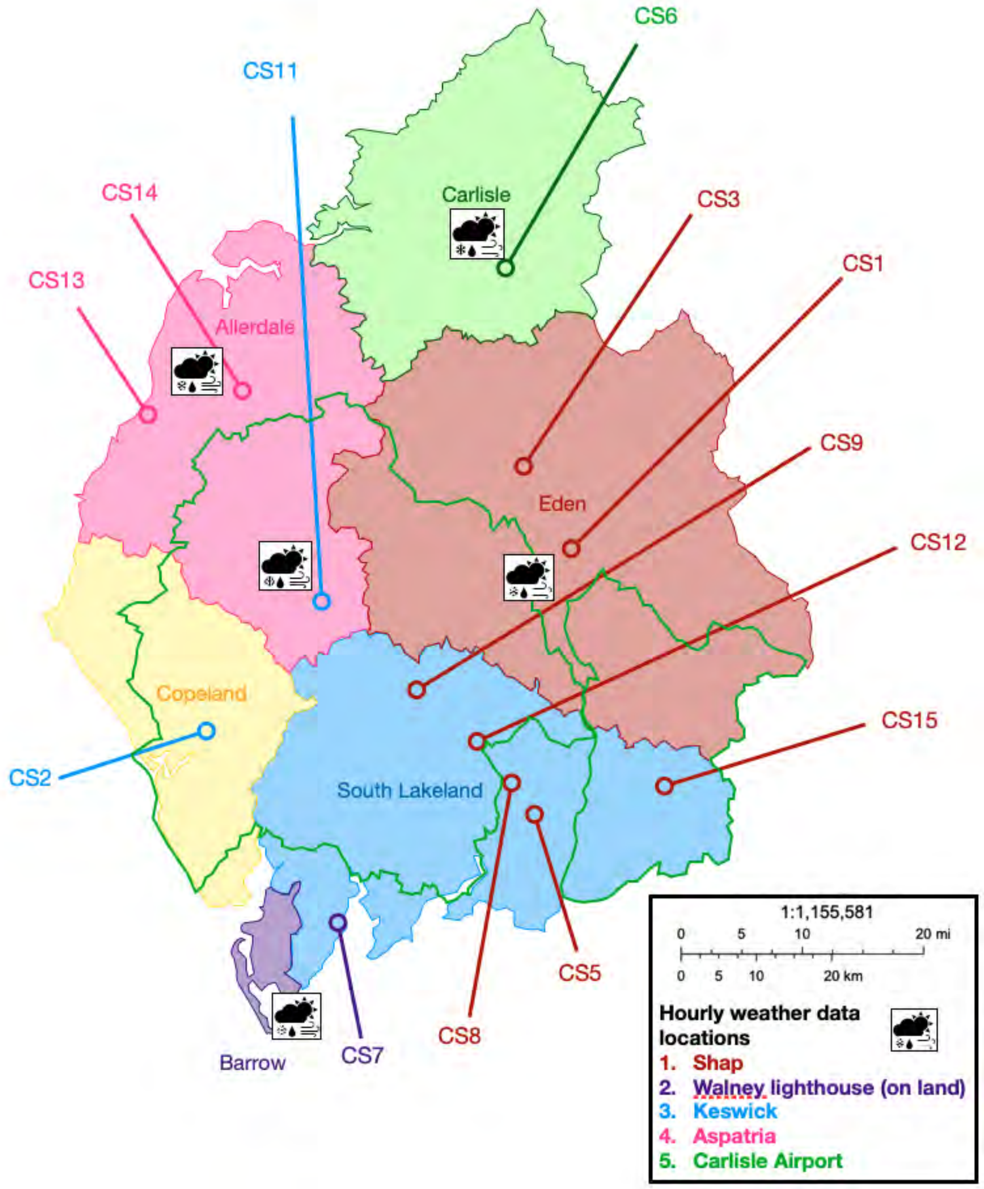
Finally, CS15 provided actual meter readings but was only able to provide six months of data from early March to mid-August, this data was multiplied by two and the resulting figure for gas use was then increased by 30% to approximate increased heating demand in winter, this gave a figure of 13,197kWh. CS15's annual gas usage is therefore an assumed rather than actual figure.

H.3) Calibration

Calibration of the models was a stepwise process where one change was made at a time and its effect noted before further adjustments were made. Changes were made to parameters where there was uncertainty and were varied within what were considered reasonable ranges. Infiltration levels, for example, were varied within the range of 10-15$m^3h^{-1}m^2$ at 50 pascals that had been identified as reasonable. CS2, CS8, CS9 and CS13 had stated that there was insulation in their lofts, which were not accessible during the visit, but they were unsure how much insulation was present, the insulation thickness was therefore varied by up to 100mm during the calibration process. For some cases there was also uncertainty about how long certain rooms such as studies were heated for, these values were therefore also adjusted by a few hours either way. The calibration process additionally gave the opportunity to examine all the input data in detail and a number of errors in data entry were found which were corrected as part of the calibration. An overview of the calibration adjustments made for each case can be seen below (Table H.5).

The use of appropriate weather data is an important element for energy simulations. The closest pre-loaded hourly weather data in Design Builder was for Aughton near Liverpool and this was used initially. However freely downloadable weather data in the correct format for seven locations within Cumbrian was found later in the modelling process. This data consisted of hourly weather data from 2004-2018 interpolated to create a typical meteorological year (Climate.OneBuilding, 2021). This has a good time match with the actual average yearly energy data used for the majority of the case studies. The most appropriate dataset, informed by both meteorology and topology was chosen for each of the case studies (Figure H.3). The use of this more local weather data significantly increased the closeness of the modelled data to the actual data, although site specific data would of course be preferable for future studies.

Figure H.3: Weather data for each case study



Modelled totals for each fuel used were bought as close as possible to the actual data, with the aim to be within +/- 5% of the actual data. This is known as the Mean Bias Error (MBE) (As described in: Tüysüz and Sözer, 2020; Federal Energy Management Program, 2015). Some of the case studies provided energy data broken down into months (CS6 and CS9) or quarters (CS3 and CS12). This enabled a measurement of the variation between actual and modelled energy across the year, through the calculation of the coefficient of variation for the root mean square error (C_vRMSE) (Federal Energy Management Program, 2015). The RMSE formula is shown below:

$$RSME_{Period} = \sqrt{\sum \frac{(S-M)_{interval}{}^{2}}{N_{Interval}}}$$

The actual energy use data is subtracted from the modelled data for each time period to obtain the difference. Each difference is then squared, and the squares are summed. The resulting figure is divided by the number of periods and the square root then provides the RMSE. The coefficient variant is then found by dividing the RMSE by the mean value of all periods across the year. The final figure should be 15% or less for the model to be considered calibrated.

The C_vRMSE was calculated for the four cases with sub-annual data. CS6 and CS9 were within the recommended range and CS3 and CS12 were only slightly out for gas (Table H.4). Electricity was within tolerance for all except CS12. Some variation from the actual values was expected given the uncertainties inherent in the model creation and the fact that the weather data is based on a fifteen-year average from the closest weather station rather that the same year and location as the actual data.

Table H.4: Calculated C_VRMSE and MBE for case studies with sub-annual data

Case	Gas C_v(RMSE)	Gas MBE	Electricity C_v(RMSE)	Electricity MBE
CS3	16.6%	1%	7.5%	-0.02%
CS6	9.9%	-1.5%	14.8%	-1.1%
CS9	12.7%	-1.2%	11.3%	-0.2%
CS12	16.7%	-5.1%	35%	-3%
C_v(RMSE) should be within 15% and MBE +/-5% to be considered calibrated				

It is therefore suggested that the models are likely to be reasonably representative of the actual building performance.

Table H.5: Overview of calibration adjustments process for each case study

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Adjust -ment 1	Increase kitchen electric equipment	Increase assumed holidays	Increase assumed holidays	Weather data changed to more local station	Error in ground modelling corrected	Reduce electric equipment in unused spaces	Increase study electric equipment	Error in ground modelling corrected	Adjust hot water use	Error in insulation definition corrected	Reduce loft (games room) electric equipment	Increase front room electric equipment	Error in ground modelling corrected
Adjust -ment 2	Error in loft insulation corrected	Reduce kitchen electric equipment	Increase assumed cooking gas	Infiltration reduced	Error in kitchen roof insulation corrected	Adjust heating schedules in unused spaces	Error in lightbulb type corrected in 4 rooms	Heating set point in Bathroom increased	Reduce kitchen equipment electricity	Error in dining room floor definition corrected	Reduce infiltration	Adjust heating pattern in line with new information from participants	Increase infiltration
Adjust -ment 3	Reduce toilet and increase bathroom water consumpti on	Weather data changed to more local station	Increase infiltration	Guest bedroom assumed heating adjusted	Infiltration increased	Increase office electric equipment	Increase kitchen electric equipment	Increase kitchen electric equipment	Adjust heating temperature set point in main room	Additional hour heating period in middle of day based on energy diary	Reduce kitchen electric equipment	Increase hot water use in bathroom	Increase hot water use in bathroom
Adjust -ment 4	Internal window added between conservat ory and house	Infiltration reduced	Adjust office heating and equipment schedule	Infiltration increased	Temperatur e set point increase (new info from homeowner)	Error in kitchen heating schedule corrected	Increase infiltration	Error in PSI values corrected	Reduce heater efficiency	Increase infiltration	Error in lightbulb type corrected in one rooms	Increase infiltration	Error in lightbulb type in two rooms corrected
Adjust -ment 5	Error in light bulb type corrected in two rooms	Error in ground floor assumption corrected	Increase kitchen electric equipment	Increase kitchen electric equipment, reduce office electric equipment	Increase heating schedule length (as above)	Error in loft construction corrected	Error in guest bedroom heating corrected on analysis of second energy diary data	Increase study electric equipment	Increase infiltration	Heating set point increased based on energy diary	Reduce hot water use	Increase dining room (home office) electric equipment	Adjust occupancy schedules based on energy diary

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Adjust-ment 6	Reduce assumed heating temperature in master bedroom	Error in application of heating schedule corrected	Reduce equipment radiant fraction	Error in floor definition corrected	Increase set point temperature in guest bedroom	Curtains added to appropriate windows	Error in kitchen roof construction corrected	Adjust office heating and equipment schedule	Reduce heater efficiency	Increase natural ventilation rate in hot weather	Reduce infiltration	Increase landing (gaming space) electric equipment	Increase lounge electric equipment
Adjust-ment 7	Reduce electric equipment in reception rooms	Infiltration reduced	Set point temperature in living room increased	Hot water use in kitchen increased	Increase hot water demand in kitchen and bathroom	Heating schedule for toilet adjusted	Hot water use in bathrooms and kitchen increased	Adjust insulation thickness in extension wall	Reduce living room electric equipment	Error in hot water system corrected	Adjust heating pattern in dining room (work space) for occupancy	Task lighting included in living room and dining room	Error in party wall definition corrected
Adjust-ment 8	Error in ground floor construction corrected	Loft insulation increased	Roof insulation thickness adjusted	Guest bedroom assumed heating adjusted	Increase infiltration		Error in cooking gas corrected	Adjust holiday set back temperature	Reduce hot water use	Specific insulation material for loft applied	Adjust heating pattern in craft room for occupancy	Increase utility electric equipment	Error in lightbulb type in two rooms corrected
Adjust-ment 9	Error in reception room heating schedule corrected	Holiday heating schedule adjusted	Curtains added to appropriate windows	Curtains added to appropriate windows	Increase assumed cooking gas		Error in main roof construction corrected	Infiltration increased	Increase radiant fraction for heater	Updated weather data	Error in living room floor corrected	Increase infiltration	Adjust guest bedroom heating settings
Adjust-ment 10	Error in partition wall definition corrected	Hot water in kitchen and bathroom increased	Hot water in bathrooms and kitchen increased	Infiltration increased	Error in lightbulb type in one room corrected		Curtains added to appropriate windows	Increase hot water	Error in floor construction corrected	New insulation info allowed correction of error for Master Bedroom roof	Curtains added to appropriate windows	Increase hot water use in kitchen and bathroom	Increase infiltration
Adjust-ment 11	Assumed infiltration reduced	Error in master bedroom temperature set point corrected	Heating period increased by one hour		Error in cellar floor construction corrected			Error in roof construction corrected	Error in roof construction corrected	Increase kitchen electric equipment		Increase landing electric equipment	Error in double glazing construction corrected

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Adjust-ment 12	Hot water use reduced in guest bedrooms	Infiltration increased			Increase kitchen electric equipment			Curtains added to appropriate windows	Error in wall render material corrected	Increase kitchen hot water use		Increase hot water use in kitchen	Error in roof construction corrected
Adjust-ment 13	Error in ceiling construction corrected	Error in intermediate floor construction corrected			Reduce bathroom hot water demand				Increase radiant fraction for heater	Error to master bedroom wall insulation corrected		Increase infiltration	Curtains added to appropriate windows
Adjust-ment 14	Curtains added to appropriate windows	Curtains added to appropriate windows			Increase heating set point temperature in guest bedroom				Curtains added to appropriate windows	Error in ground floor construction corrected		Error in dining room floor construction corrected	
Adjust-ment 15		Infiltration increased			Error in ceiling construction corrected					Error in internal wall construction corrected		Error in living room window construction corrected	
Adjust-ment 16										Curtains added to appropriate windows		Curtains added to appropriate windows	
Adjust-ment 17										Hot water use in bathroom increased			
Adjust-ment 18										Infiltration increased			

Appendix I) Operational Retrofit modelling details

The operational impact of 40 individual retrofit measures were modelled for each of the case studies in Design Builder. A number of specific details on how individual measures were modelled is provided below.

I.1) Insulation

Thermal bridging was accounted for as applicable, following the method outlined in Appendix H.1.

Loft insulation was applied between and above joist in cold roofs. An appropriate thickness of insulation was applied above existing insulation to create a total thickness of 300mm (Table I.6).

Table I.6: Thickness of loft insulation added for each case study

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Thickness (mm)	180	50	150	150	150	100	50	50	N/A	N/A	100	150	N/A

Ceiling insulation was applied between rafters in warm roofs and was only applied to those cases that did not currently have any ceiling insulation (CS5, CS8, CS9, CS11, CS14). This is because the addition of further ceiling insulation would substantially reduce headroom and hide rafters that residents identified as heritage features. For CS5, CS8, and CS14 sloped ceiling insulation was applied in kitchens with sloping ceilings, for CS9 it was applied to a bay window and for CS11 to their main roof. Insulation materials were applied in standard thicknesses. For open ceilings (CS11 and parts of CS14) insulation was only applied between rafters, as these were often identified as heritage features by residents. For ceilings where the rafters were already covered, insulation was applied between and below rafters to reduce thermal bridging. An air gap for ventilation above the insulation was maintained in all cases.

Internal wall insulation (IWI) was applied to all case studies in standard thicknesses. Lower thicknesses of insulation were used to reduce the risk to the moisture balance and to reduce space loss. IWI was not applied to the modern extension or cellar for CS9 or the dining room extension for CS12 as these were already well insulated. IWI was not applied to the master bedroom for CS12 or the bathroom for CS6 as both of these already have IWI. IWI was modelled as being applied directly against the stonework in line with manufacturers' directions. The current wall finish, whether plaster or plasterboard was reapplied over the insulation.

External wall insulation (EWI) was applied to all case studies in standard thicknesses. EWI was not applied to the cellar or modern extension for CS9 or to the dining room extension for CS12 as these were already well insulated. EWI was not applied to cellars (CS6, CS8, CS9, CS14, CS15). EWI was applied directly to the stonework and 20mm of lime render was applied over it.

Solid floor insulation was applied to solid ground floors in all case studies except CS15 who only has a solid ground floor in their unheated cellar. For Geocell (natural product) insulation, a new floor build-up with 300mm geocell and a limecrete floor was laid. Kingspan (standard) insulation was applied under the existing floor covering which was then re-laid. Aerogel (technical) insulation was bonded to chipboard and applied under the existing floor covering which was then re-laid.

Suspended floor insulation was applied to all suspended ground floors, either suspended above the ground (CS1 and CS5) or above a cellar (CS6, CS8, CS9, CS14, CS15). Suspended floor insulation was applied between joists, maintaining a 10mm air gap for ventilation. The thicknesses and material qualities of the insulation materials are shown below (Table I.7).

Table I.7: Insulation material characteristics

Insulation type	Product name	Thickness (mm)	Thermal conductivity (W/m-K)	Specific heat (J/ kg-K)	Density (kg/m³)
		Loft Insulation			
Natural	Cosywool	Case specific	0.039	1800	12
Standard	Supersoft	Case specific	0.040	1000	12
Technical	Ultrawool	Case specific	0.035	1800	12
		Ceiling insulation			
Natural	Gutex thermoflex	150	0.036	2100	50
Standard	Knauf Rocksilk	150	0.037	1000	33
Technical	Spaceloft aerogel	20	0.015	1000	150
Heritage	Daithonite	50	0.045	1000	360
		Internal wall insulation			
Natural	Gutex thermoroom	50	0.039	2100	130
Standard	Knauf omnifit	50	0.035	1000	24
Technical	Spaceloft aerogel	20	As above	As above	As above
Heritage	Diathonite	50	As above	As above	As above
		External wall insulation			
Natural	Gutex multitherm	100	0.040	2100	140
Standard	Knauf EWI Rocksilk	100	0.036	1000	105
Technical	Isohemp	120	0.071	1500	340
		Solid floor insulation			
Natural	Geocell	300	0.08	1000	140
Standard	Kingspan kooltherm	60	0.018	1000	12.8
Technical	Spaceloft aerogel	10	As above	As above	As above
		Suspended floor insulation			
Natural	Thermofloc	140	0.038	1000	33.4
Standard	Knauf omnifit	140	As above	As above	As above
Technical	Spaceloft aerogel	20	As above	As above	As above

I.2) Window replacements and additions

Window replacements included double and triple glazed low-e glazing with hardwood or UPVC frames. Replacement triple glazing was applied to all windows except CS12's sitting room window, which was already the equivalent of triple glazed. Replacement double glazing was applied to all windows that were not already good quality double glazed wood. Double and triple glazing was defined from the Design Builder database (Table I.8). Current curtains were retained and their effect on u-values was calculated accordingly.

Table I.8: Replacement window u-values

Window	Description	Glass u-value (W/m²K)	Frame u-value (W/m²K)
Double glazed wood	Two panes of 6mm low E glass, argon filled	1.493	2.97
Double glazed UPVC	Two panes of 6mm low E glass, argon filled	1.493	3.476
Triple glazed wood	Three panes of 3mm glass, middle pane clear glass outer panes low E glass, argon filled	0.78	2.97
Triple glazed UPVC	Three panes of 3mm glass, middle pane clear glass outer panes low E glass, argon filled	0.78	3.476

Curtains and shutters were applied to all windows that did not already have them. Secondary glazing was applied to all single glazed windows. It was also applied to CS15's UPVC double glazed windows as these were very poor quality and secondary glazing was something that they had expressed an interest in. The thermal characteristics of the window additions were calculated as described in section H.1.

I.3) Renewable energy technologies

Solar PV panels were sized according to the London Energy Transformation Initiative (LETI) retrofit guide which suggests that solar PV should cover 40% of a building's roof surface to be consistent with deep retrofit (LETI, 2021). Panels were sized in full 1m^2 which in some cases equated to slightly less that the full 40%, reductions were also sometimes necessary for roof lights etc. Roofs were angled between 21° and 32° and panels were sited on south facing roofs where possible. CS3, CS11 and CS12 were modelled with panels on west facing roofs and CS8 and CS14 were modelled with panels on east facing roofs. Where there was a choice of east or west facing roofs both options were tested and the more effective was taken forward. Solar PV generation potential was sense checked using an alternative spreadsheet developed for an Open University course.

Solar thermal panels were sized to cover 60% of the hot water demand for each case study based on manufacturer guidance (Viessmann, 2018). The rest of the hot water demand is met by an electric immersion heater and a new thermal storage hot water tank is included in the modelled system.

Panels are available at 1.5m^2 and combinations are used as required. Most panels had an area between 3-6m^2. The largest panel area was 10.5m^2 on CS3's west facing roof and 9m^2 on CS8's east facing roof.

Ground source heat pumps (GSHP) were modelled with underfloor heating on the ground floor and radiators on the upper floors, Domestic hot water (DHW) is modelled as a separate system. It only appeared possible to model borehole collectors for GSHP's in Design Builder. GSHPs used a pre-loaded system template after attempts to convert and upload specific manufacturer data in the correct format failed. There were three system sizes that could be used, 12.6kW, 15kW and 24kW. Peak heat load was calculated using a simulation option in Design Builder and the closest size of heat pump was used for each case (Table I.9). For CS5, CS6 and CS7 the peak heat demand was slightly more than the size of heat pump. This was only slightly higher for CS5 and CS6. The difference was 4kW for CS7, but their large house is very rarely operated to full capacity, so it was not considered unreasonable to use the slightly lower size of heat pump.

Table I.9 Case study peak heat demand and size of peak heat output chosen for GSHP in kW

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Peak heat	14	7.6	14	16.1	16.2	28.1	11.1	9.7	7.3	5.6	11.4	12.5	8.2
GSHP size	15	12.6	15	15	15	24	12.6	12.6	12.6	12.6	12.6	12.6	12.6

Air source heat pumps (ASHP) were modelled as a high temperature system with radiators. The high temperature ASHP Design Builder system template was used. The auto size function was used to provide appropriate radiator sizes, this meant that the system would perform relatively efficiently without other retrofits, however in reality the size of radiators required might prove impractical. Other retrofits which improve the buildings fabric efficiency are likely to be required to enable the heat pumps to work effectively with reasonable radiator sizes. The ASHP was considered to provide 90% of the heating load with a back-up boiler providing the remaining 10% and boosting temperatures for the DHW. A coefficient of performance (CoP) of 2.8 is used for the ASHP. Most of the back-up boilers saw very little use as peak heat demand was rarely reached in any of the cases.

Current boilers were assumed to be replaced with an 87.3% efficient biomass pellet boiler. The model used was chosen from the UK Product Characteristic Database (BRE, 2020b) and was a Biotech, PZ 8 RL with an index number of 700120. The rest of the heating system remained the same except for CS2 and CS11 where a hot water-based heating system was modelled in place of the existing storage heaters and wood burning stove respectively.

For case studies with a current boiler efficiency below 89% (CS1, CS6, CS7, CS12 and CS14) a more efficient version of their current boiler was modelled (Table I.10).

Table I.10: Replacement boiler efficiency and model

Case	CS1	CS6	CS7	CS12	CS14
Current boiler efficiency	65%	88.7%	85.3%	88.8%	85.5%
Current boiler fuel	Oil	Gas	Oil	Gas	Gas
New boiler efficiency	92%	90.1%	92%	90.1%	90.1%
New boiler fuel	Oil	Gas	Oil	Gas	Gas
New boiler model	Eurocal efficiency kitchen boiler	Ravenheat HE System A T	Eurocal efficiency kitchen boiler	Ravenheat HE System A T	Ravenheat HE System A T
New boiler index number	15482	9762	15482	9762	9762

I.4) Other retrofit measures

Energy efficiency lighting was modelled as replacing all current non-LED bulbs with LEDs, based on LED lighting from the Design Builder component library that had a power output of 2.5W/m^2. If not already utilised, all lights were also assumed to have linear control added meaning that they would be considered to be switched off if the model detected that there was enough daylight to meet a room’s lighting needs.

Wall hangings were modelled as 20mm of woollen carpet. They were modelled to cover most of one wall, either external or to an unheated space, in the main living spaces of each case study. CS1, CS5, CS6, CS13, and CS14 have more than one main living space so wall hangings are modelled in both. For CS3 and CS8 wall hangings were also modelled in studies.

Two levels of draught proofing were modelled by reducing the overall infiltration rate by 20% and 30% respectively (Table I.11), based on findings in the literature (Gillott et al., 2016; Teekaram, 2013; Rye and Scott, 2012).

Table I.11: Level of infiltration reduction modelled for each case

	CS1	CS2	CS3	CS5	CS6	CS7	CS8	CS9	CS11	CS12	CS13	CS14	CS15
Current (m^3/h-m^2 @50 pascals)	11	14	15	14	14	13	14	13	15	14	10	17	14
20% reduction	8.8	11.2	12	11.2	11.2	10.4	11.2	10.4	12	11.2	8	13.6	11.2
30% reduction	7.7	9.8	10.5	9.8	9.8	9.1	9.8	9.1	10.5	9.8	7	11.9	9.8

For the ‘no bedroom heating’ measure, bedrooms were modelled as unheated. For the no holiday heating, heating was scheduled as off during the specific period that was considered holiday for each case study. The holiday days were distributed throughout the year by taking the UK school and bank holidays pre-loaded into the system as the basis for holiday dates.

Temperature reduction was modelled by reducing all temperature set points for each case study up to a maximum of 2°C in 0.5°C increments. This meant that four simulations were performed for each case to model the full 2°C reduction.

Finally smart heating was modelled by providing individual temperature set points for each room in a case study building. The set points used were chosen based on information in the energy diaries about the levels that thermostatic radiator valves were set to, and on interview and building tour information on room use and heating patterns.

Appendix J) LCA Retrofit modelling

The LCA involved the analysis of 52 individual materials because of the need for additional materials in the installation of some of the retrofit measures, such as new lime plaster for wall insulation or additional radiators for ASHPs. A hierarchy was used for considering the embodied carbon of products. EPDs for specific products were used where possible (25 materials), if this was not possible EPDs for a similar product was used (13). If this was not possible then generic data for that product family was used (11). Finally, if none of the above was possible proxy data was used (6).

Most of the EPDs are based on the EN15084+A1 (42), however 10 of the most recent EPDs are based on the more recently updated EN15084+A2. There is a small difference in how the environmental impacts are calculated and this creates an average difference of around 3.5% (Anderson, 2022b), using both EPD types is therefore considered acceptable. Some EPDs do not report biogenic carbon separately. In this case the values for biogenic carbon calculated by the OneClickLCA software has been used (OneClickLCA, 2021).

J.1) Transport emissions

Stage A4 transport from manufacturer to site were calculated by considering the weight of the materials transported and UK government figures for CO_2e emissions per tonne per kilometre for an average laden HGV (BEIS, 2021b). This transport was assumed from the manufacturer to a common distribution point in Cumbria, considered to be either Penrith or Carlisle depending on the material. Final transport emissions to each of the case studies were modelled as an average diesel van up to 3.5tonnes, this transport was also used as the transport mechanism for waste disposal. If the weight of materials was more than 3.5tonnes then final distribution by HGV was modelled. All transport emissions were based on data from BEIS (2021b). The vast majority of transport was assumed to be by road, although solar PV panels and aerogel insulation also required transport by sea.

Specific transport distances were used where manufacturer location information was available (32 materials). If specific data was not available (20) an assumed transport distance of 1000km was used as most products were sources from Europe. A different process was followed for two products. Aerogel where the values assumed in the EPD of 100km transport in USA followed by 5,600km by sea to Europe, followed by 400km by truck within Europe, were considered reasonable, with 400km similar to the distance from the port of Bristol to Penrith in Cumbria. Solar PV panels also assumed 8,800km sea travel from Mexico and then road transport from the European distributor.

J.2) Stage 5 Construction/installation

For the construction and installation stage, additional materials, such as putty for windows or metalwork for shutters, were included as a stage 5 impact rather than as a full extra product, based on the EPD. These impacts have been included where applicable.

Information on the impacts of package disposal was included for 16 of the materials and this has been included in the assessment where applicable. The EPDs for most measures stated that their installation would require no additional emissions, although some included no installation details.

General wastage of 2% has been included for all materials. For floor insulation options existing floor coverings were assumed to be lifted and then reinstalled after the insulation had been put in place. Floor coverings for 15% of the floor area were considered to be wastage and replaced with new floor coverings of the same type (i.e., carpet, timber floor, slate tiles), as part of the installation of the retrofit.

J.3) Stage B1 Use, Stage B2 Maintenance and stage B3 Repair

The use stage, where the use of a measure creates additional carbon, was only applicable for three measures. The use of smart heating controls was modelled as the use of Wi-Fi controlled individual room thermostats. The use of these thermostats required electricity, and this was included in the LCA as it had not been included in the operational energy modelling. Taking grid decarbonisation into account, this resulted in a figure of 285kgCO_2e over 50 years for each smart thermostat unit. The other retrofit measure with a stage B1 impact were the heat pumps, which use a refrigerant as part of the heat exchanger mechanism. These refrigerants often have very high equivalent carbon emissions (Hamot et al., 2020) and may be subject to leakage. A common heat pump refrigerant, R32 and a 2% lifetime leakage rate were assumed based on averaged EPD data.

Maintenance (B2) was included for products where data was available. This included the replacement floor coverings referred to above, the annual cleaning of wall hangings, repainting of wooden window frames every five years, a yearly maintenance visit for EE and biomass boilers and maintenance visits every two years for heat pumps. Most of the insulation materials stated that maintenance was unnecessary during the life of the product.

The repair stage (B3) includes the partial replacement of a measure (De Wolf et al., 2017). This was included where applicable. For external wall insulation for example, a basecoat and topcoat of lime render were applied over the insulation. The topcoat was considered to be replaced in the 30th year in accordance with manufacturer data, while the basecoat and insulation itself lasted the whole of the assessment period. For GSHPs the heat pump was considered to be replaced at 20 and 40 years based on average GSHP data, but the external ground pipework was considered to last for the whole assessment period so was not replaced. The repair stage was applied to other measures as applicable.

J.4) Stage C, End of life emissions

Where this data was included in the EPD, waste disposal emissions were calculated based on these figures. However, transport to waste disposal sites was calculated specifically from each case study to the nearest municipal waste disposal location. If specific data on disposal emissions were not available, average disposal emissions for the most appropriate material category from UK official data was used, considering either landfill or open loop recycling (BEIS, 2021b). The disposal of any material that had to be removed prior to the installation of the retrofit was also treated in this manner.

J.5) Overview of LCA materials and data availability

Retrofit measures and supporting materials	Specific product	Similar product	Proxy product	Average product	Specific transport	Average transport	EN15084 +A1 GWP total	EN15084+ A2 GWP fossil	Installation additional products	Installation packaging disposal included	No installation information
Loft insulation natural: Cosywool	X				X			X			X
Loft insulation standard: Supersoft	X				X			X			X
Loft insulation technical: Ultrawool	X				X			X			X
Ceiling insulation natural: Gutex thermoflex	X				X		X			X	
Ceiling insulation standard: Knauf rocksilk	X				X			X		X	
Ceiling insulation technical: Aerogel	X					X	X				X
Ceiling insulation heritage: Diathonite	X				X			X			X
Ceiling insulation: Lime plaster		X			X			X			X
Ceiling insulation: Gyproc Plasterboard	X				X		X			X	
IWI natural: Gutex thermoroom	X				X		X			X	
IWI standard: Knauf omnifit	X				X		X			X	
IWI technical: Aerogel	X					X	X				X
IWI heritage: Diathonite	X				X			X			X
IWI: Lime plaster (as above)											
IWI: Gyproc plasterboard (as above)											
IWI: Wooden studwork for plasterboard		X				X	X			X	
EWI natural: Gutex multitherm	X				X		X			X	
EWI standard: Knauf rocksilk	X				X			X		X	
EWI technical: Isohemp blocks	X				X		X		X		
EWI: Lime render		X				X	X				X

Retrofit measures and supporting materials	Specific product	Similar product	Proxy product	Average product	Specific transport	Average transport	EN15084 +A1 GWP total	EN15084+ A2 GWP fossil	Installation additional products	Installation packaging disposal included	No installation information
Solid floor insulation natural: Geocell foamglass	X				X		X				X
Solid Floor insulation standard: Kingspan Kooltherm	X				X		X			X	
Solid Floor insulation technical: aerogel bonded chipboard	X					X	X				X
Solid floor insulation chipboard		X			X		X				X
Solid floor: Lime floor screed				X	X		X				X
Solid floor: Carpet		X			X		X			X	
Solid floor: Slate tiles		X			X		X			X	
Solid floor: Timber floor		X			X		X			X	
Suspended floor insulation natural: Thermofloc		X			X		X				X
Suspended floor insulation standard: Knauf omnifit	X				X		X			X	
Suspended floor insulation technical: Aerogel bonded to chipboard	X					X	X				X
Suspended floor: chipboard (as above)											
Suspended floor: Carpet (as above)											
Suspended floor: Slate tiles (as above)											
Suspended floor: Timber floor (as above)											
Window replacement: Low e double glazed, hardwood frames, Munster Joinery	X				X		X		X		

Retrofit measures and supporting materials	Specific product	Similar product	Proxy product	Average product	Specific transport	Average transport	EN15084 +A1 GWP total	EN15084+ A2 GWP fossil	Installation additional products	Installation packaging disposal included	No installation information
Window replacement: Low e double glazed, UPVC frames Munster Joinery	X				X		X		X		
Window replacement: Low e triple glazed, hardwood frames Munster Joinery	X				X		X		X		
Window replacement: Low e triple glazed, UPVC frames Munster Joinery	X				X		X		X		
Window alterations: Curtains			X		X			X			X
Window alterations: curtain pole		X			X		X			X	
Window alterations: Interior shutters			X		X		X		X		
Window alterations: Secondary glazing			X			X	X				X
EE lighting: LED bulbs		X			X		X				X
Thick wall hangings			X		X		X			X	
Thick hangings: pole (as above)											
EE bioler				X			X				X
Biomass pellet boiler				X			X				X
EE/Bio boiler: radiator				X		X	X			X	
EE/Bio boiler: hot water pipework				X		X	X				X
Solar PV: Maxeon 3 black	X					X	X				X
Solar PV: Inverter				X		X	X				X
Solar thermal: evacuated tubes				X		X	X				X
Solar thermal: hot water tank				X		X	X				X

Retrofit measures and supporting materials	Specific product	Similar product	Proxy product	Average product	Specific transport	Average transport	EN15084 +A1 GWP total	EN15084+ A2 GWP fossil	Installation additional products	Installation packaging disposal included	No installation information
GSHP: flat or borehole collector with underfloor heating				X							X
GSHP underfloor heating				X		X	X				X
ASHP: high temperature with radiators				X		X	X				X
ASHP: radiator (as above)											
Smart heating controls: wifi controlled room thermostat			X			X	X				X
Draught proofing: window foam sealing strips		X				X	X				X
Draught proofing: base of door seals		X				X	X				X
Draught proofing: airtightness tape		X				X	X				X
Draught proofing: Door curtains			X			X		X			X
Draught proofing: curtain pole (as above)											

J.6) LCA key assumptions and data link for each material

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
Loft insulation natural: Cosywool	https://portal.environdec.com/api/api/v1/EPDLibrary/Files/78be8497-87dd-4c92-3a66-08d99c9745fc/Data	Loft insulation is installed manually in accessible lofts on top of current loft insulation products. Therefore no removal of material is required, no additional materials are required and there are no emissions associated with the installation. The product has as lifespan of greater than 50years therefore no replacement is required in the time period of the assessment.
Loft insulation standard: Supersoft	https://portal.environdec.com/api/api/v1/EPDLibrary/Files/2e216133-92fb-4185-3a65-08d99c9745fc/Data	
Loft insulation technical: Ultrawool	https://portal.environdec.com/api/api/v1/EPDLibrary/Files/78be8497-87dd-4c92-3a66-08d99c9745fc/Data	
Ceiling insulation natural: Gutex thermoflex	https://www.ecologicalbuildingsystems.com/product/thermoflex	Ceiling insulation is installed manually and there are therefore no emissions associated with the installation. Removal of current plasterboard/lime plaster is required and new plasterboard/lime plaster is installed on top of the new insulation. The insulation has a lifespan greater than fifty years therefore no replacement is required in the time period of the assessment.
Ceiling insulation standard: Knauf rocksilk	https://www.knaufinsulation.co.uk/products/rocksilk-flexible-slab	
Ceiling insulation technical: Aerogel	https://environdec.com/library/epd725	
Ceiling insulation heritage: Diathonite	https://environdec.com/library/epd3516	
Ceiling insulation: Lime plaster	https://environdec.com/library/epd4457	
Ceiling insulation: Gyproc Plasterboard	https://environdec.com/library/epd506	
IWI natural: Gutex thermoroom	https://www.ecologicalbuildingsystems.com/product/thermoroom	Internal wall insulation is installed manually and there are therefore no emissions associated with the installation. Current lime plaster is left in place as a base layer but plasterboard and studwork is removed and disposed of. New lime plaster/plasterboard and studwork is considered to be applied over the new insulation (except diathonite where only lime plaster is considered). The insulation has a lifespan greater than fifty years therefore no replacement is required in the time period of the assessment.
IWI standard: Knauf omnifit	https://pim.knaufinsulation.com/files/download/en-epd-0061_gmw_ecose_034-035_5a8af3b32a2fc.pdf	
IWI technical: Aerogel	As above	
IWI heritage: Diathonite	As above	
IWI: Lime plaster (as above)	As above	
IWI: Gyproc plasterboard (as above)	As above	
IWI: Wooden studwork for plasterboard	https://database.insideinside.nl/published-product/view?id=140	
EWI natural: Gutex multitherm	https://www.ecologicalbuildingsystems.com/product/multitherm	External wall insulation is installed manually and there are therefore no emissions associated with the installation. Scaffolding will be required but this has not been accounted for in the
EWI standard: Knauf rocksilk	https://pim.knaufinsulation.com/files/download/knauf_insulation_rocksilk_ewi_slab_epd_s-p-04008_uk-en.pdf	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
EWI technical: Isohemp blocks	https://www.isohemp.com/sites/default/files/fichiers/lca-isohemp-2020.pdf	assessment. Current lime render is left in place as a base layer but cement render is considered removed. New lime render is applied on top of the new insulation once installed. A base coat and a top coat is considered applied and the top coat is assumed to be replaced after thirty years in line with the manufacturer's lifespan. The insulation itself has a lifespan greater than fifty years therefore no replacement is required in the time period of the assessment.
EWI: Lime render	https://environdec.com/library/epd1642	
Solid floor insulation natural: Geocell foamglass	https://www.baubook.at/vlbg/?URL_R=https%3A%2F%2Fwww.baubook.at%2Fm%2FPHP%2FInfo.php%3FSI%3D2142699086%26SW%3D2&SW=2	Solid floor insulation is installed manually and there are therefore no emissions associated with the installation. For Geocell foamglass current cast concrete and soil build ups are removed and disposed of. For Kingspan and aerogel insulation current floor screed is removed where applicable (i.e. for those cases with slate floors). For Geocell, a lime floor is applied on top of the insulation. For Kingspan and Aerogel new lime floor screed is applied where applicable. The current floor covering (sandstone/slate tiles, carpet or timber flooring) is lifted to install the insulation and a 15% wastage and replacement rate is assumed and included. Cleaning maintenance for this floor area is also included. The insulation itself has a lifespan greater than fifty years therefore no replacement is required in the time period of the assessment.
Solid Floor insulation standard: Kingspan Kooltherm	https://www.greenbooklive.com/pdfdocs/en15804epd/BREGENEPD000320.pdf	
Solid Floor insulation technical: aerogel bonded chipboard	As above	
Solid floor insulation chipboard	OneClickLCA database	
Solid floor: Lime floor screed	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=bcsNHLBasedScreed&profileId=MinieraSanRomedio2020	
Solid floor: Carpet	https://portal.environdec.com/api/api/v1/EPDLibrary/Files/c76d7ad3-e33b-41bc-b75e-e3902a75626c/Data	
Solid floor: Slate tiles	https://environdec.com/library/epd1156	
Solid floor: Timber floor	https://environdec.com/library/epd1509	
Suspended floor insulation natural: Thermofloc	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibuThermoflocFCelluloseInsulation&profileId=PeterSeppele2021	Suspended floor insulation is installed manually and there are therefore no emissions are associated with the installation. No removal of material is considered necessary however the current floor covering (timber flooring or timber flooring and carpet) is lifted to install the insulation and a 15% wastage and replacement rate is assumed and included. Cleaning maintenance for this floor area is also included. The insulation itself has a lifespan greater than fifty years therefore no replacement is required in the time period of the assessment.
Suspended floor insulation standard: Knauf omnifit	https://pim.knaufinsulation.com/files/download/en-epd-0061_gmw_ecose_034-035_5a8af3b32a2fc.pdf	
Suspended floor insulation technical: Aerogel bonded to chipboard	As above	
Suspended floor: chipboard (as above)	As above	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
Suspended floor: Carpet (as above)	As above	
Suspended floor: Slate tiles (as above)	As above	
Suspended floor: Timber floor (as above)	As above	
Window replacement: Low e double glazed, hardwood frames, Munster Joinery	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ireepdHardwoodTripleGlazedWindow_2147&profileId=MunsterJoinery2021	Replacement windows are installed manually and there are therefore no emissions associated with the installation although a certain amount of mastic for the window insulation has been included as per the manufacturers data. Current windows and any shutters or secondary glazing are removed and disposed of in appropriate amounts for each case study. According to the manufacturer the windows have a lifespan of greater than 50 years therefore no replacement is required in the time period of the assessment. For double and triple wooden framed windows there will be some biogenic storage however no data was available on this aspect.
Window replacement: Low e double glazed, UPVC frames Munster Joinery	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ireepdPassivPVCDoubleGlazedWindow_2149&profileId=MunsterJoinery2021	
Window replacement: Low e triple glazed, hardwood frames Munster Joinery	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ireepdHardwoodTripleGlazedWindow_2147&profileId=MunsterJoinery2021	
Window replacement: Low e triple glazed, UPVC frames Munster Joinery	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ireepdHardwoodTripleGlazedWindow_2147&profileId=MunsterJoinery2021	
Window alterations: Curtains	https://environdec.com/library/epd1703	Window alterations are installed manually and there are therefore no emissions associated with the installation. No removal of material is required. Curtains are considered to have a lifespan of 20 years and therefore are replaced twice during the assessment period. Disposal and replacement emissions are included. Secondary glazing is considered to have a
Window alterations: curtain pole	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=breKilnDriedMachinedSawnStructTimber&profileId=WoodForGood2017	
Window alterations: Interior shutters	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=envdecBrimstoneAsh&profileId=VasternTimber2019	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
Window alterations: Secondary glazing	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=envdecAluminiumFramedPartitionSystemSinglem2&profileId=Optima2017	Secondary glazing is considered to have a lifespan of 30 years and is therefore replaced once during the assessment period. Disposal and replacement emissions are included. Shutters are considered to have a lifespan greater than 50 years, therefore no replacement is required in the time period of the assessment. Curtain material is modelled by proxying a thick workwear fabric as this was the closest that could be found. Shutters are a proxied by treated wood with metal work fittings, secondary glazing is proxied with a single layer of glass with a aluminium frame.
EE lighting: LED bulbs	https://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management	EE Lighting LED bulbs are installed manually and there are therefore no emissions associated with the installation. Removal and disposal of the current bulbs is considered. The LED bulbs are considered to last for an average of ten years and 4 replacements throughout the assessment period are therefore required. Disposal and replacement is included.
Thick wall hangings	https://portal.environdec.com/api/api/v1/EPDLibrary/Files/c76d7ad3-e33b-41bc-b75e-e3902a75626c/Data	Wallhangings are installed manually and there are therefore no emissions associated with the installation. No material is required to be removed. Cleaning maintenance for wallhanging is included in the assessment. Wallhangings are considered to last for 25 years and one replacement in the assessment period is therefore required. Disposal and replacement are included. Wallhangings are proxied using the carpet material identified above.
Thick hangings: pole (as above)	As above	
EE boiler: Gas condensing boiler less than 20kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=8acef115-85c0-45f8-9999-9d3b87692fa7&version=20.19.120&stock=OBD_2021_II	Energy efficient and pellet boilers are installed manually and there are therefore no emissions associated with the installation. Current boilers are removed and disposed of. CS2 and CS11 currently do not have wet central heating systems. The disposal of CS2's storage heaters and replacement with radiators and the associated piping is included. For CS11 their
EE boiler: Oil condensing boiler less than 20kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=122fbf6d-8c32-4efa-ac93-aae1c56e0c4a&version=20.19.120&stock=OBD_2021_II	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
Biomass pellet boiler less than 20kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=0e03a1c1-0aa9-4e94-bbc5-653d967b0d8d&version=20.19.120&stock=OBD_2021_II	current wood burning stove is retained, but the addition of radiators and associated pipework is included. Both EE and biomass boilers are considered to last for 20 years meaning that two replacements are required in the assessment period. Disposal and replacement is included in the assessment.
Biomass pellet boiler 20-120kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=49660117-13cd-4475-a66b-a13801723a37&version=20.19.120&stock=OBD_2021_II	
EE/Bio boiler: radiator	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=CHAP-00002-V01-01-FR&profileId=PEP2019	
EE/Bio boiler: hot water pipework	OneClickLCA database	
Solar PV: Maxeon 3 black	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=SPWR-20201-V01_02-FR&profileId=PEP2020	Solar PV and Solar Thermal panels are installed manually and there are therefore no emissions associated with the installation. Scaffolding is likely to be required but this has not been included in the assessment. No current material requires disposal. For solar PV panels an electric inverter is also required and included in the assessment. Both panels and inverter are considered to last for 25 years meaning that one disposal and replacement is required in the assessment period and are included. For solar thermal panels an additional hot water tank is considered necessary and is included in the assessment. For CS13 and CS14 two storage tanks are considered because they currently have tankless hot water systems. The solar thermal panels and hot water tanks are considered to last for 20 years meaning that two replacements are required in the assessment period. Disposal and replacement is included in the assessment.
Solar PV: Inverter	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=inies5616&profileId=INIES	
Solar thermal: evacuated tubes	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=aa6822f9-a10e-45c9-a164-f08ebc994379&version=20.19.120&stock=OBD_2021_II	
Solar thermal: hot water tank	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d3f58b23-9526-43be-8a32-fb583dfebfaa&version=20.19.120&stock=OBD_2021_II	
GSHP: 10kW flat collector	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=3bf7183e-741e-4fb7-a32e-574e76e3e747&version=20.19.120&stock=OBD_2021_II	There will be emissions associated with the groundworks for the installation of the GSHP but these have not been considered in the assessment. For GSHP the current downstairs radiators are considered to be removed and replaced with underfloor heating which is included in the assessment. The external
GSHP: 20kW flat collector	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=063cabc8-b90e-4629-b514-a39dc10f0552&version=20.19.120&stock=OBD_2021_II	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
GSHP: 10kW borehole collector	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=0959c210-3af7-43df-9a7b-0f5ac19656ea&version=20.19.120&stock=OBD_2021_II	included in the assessment. The external pipework for the GSHP is also included. The GSHP heat pump itself is considered to have a 20 year lifespan and is replaced twice, the underfloor heating is considered to have a 30 year lifespan and is replaced once. The external pipework is considered to last for the whole of the assessment period. Disposal and replacement is included in the assessment. The appropriate size and type of heat pump (dependant on outdoor space and access) was modelled for each case study. There is a linear size relationship for the heat pump sizes so a heat pump with a larger output was modelled for CS7.
GSHP: 20kW borehole collector	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=2af8a919-15c5-4709-bc6c-276d1e0951d5&version=20.19.120&stock=OBD_2021_II	
GSHP 10kW flat collector pipes	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=1a27c109-1e99-45e7-b198-7c79f926b996&version=20.19.120&stock=OBD_2021_II	
GSHP 20kW flat collector pipes	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=3d3873a9-16dd-4771-82be-f7b79bbd3f53&version=20.19.120&stock=OBD_2021_II	
GSHP 10kW borehole collector pipes	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d775709c-1411-4aeb-9d20-36e1e8def5e2&version=20.19.120&stock=OBD_2021_II	
GSHP 20kW borehole collector pipes	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=79002203-de3f-4da6-9a72-b689615b9963&version=20.19.120&stock=OBD_2021_II	
GSHP underfloor heating	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=99bbfb89-cbca-448d-a991-7cc302a97d4a&version=20.19.120&stock=OBD_2021_II	
ASHP: 7kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=efa279e8-0ac1-4883-b87c-0cb11e17d265&version=20.19.120&stock=OBD_2021_II	ASHP is considered to be installed manually. For the ASHP additional radiators in in the main living space are included in the assessment. The ASHP is considered to have a 20 year lifespan and is replaced twice. The additional radiators and pipework are considered to have a 25 year lifespan and are replaced once. Disposal and replacement is included in the assessment. The most appropriate size of heat pump was modelled for each case, there is a linear relationship in sizing so larger heat pumps were modelled as appropriate.
ASHP: 10kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=7c0455a7-fc89-4c3c-8225-d528e4375662&version=20.19.120&stock=OBD_2021_II	
ASHP: 14kW	https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=4a08f220-1c52-453c-bf8f-f209586e96c8&version=20.19.120&stock=OBD_2021_II	
ASHP: radiator (as above)	As above	

Retrofit measures and supporting materials	Link to EPD or similar data	Assumptions for category of measures
Smart heating controls: wifi controlled room thermostat	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=CHTX-00004-V01-00-FR&profileId=PEP2020	The smart heating thermostatic room controls are considered to be installed manually and have no emissions associated with them. No removal of material is considered to be required. The controls are considered to last 10 years and four replacements are therefore required in the assessment period. Disposal and replacement is included. In addition the smart controls used electricity during the use phase. This included in the assessment because the operational modelling does not take this electricity demand into account (grid decarbonisation is taken into account).
Draught proofing: window foam sealing strips	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=INIES_CMOU20180529_143852_fixedFeb2021&profileId=INIES	Draught proofing is installed manually and no emissions are required. No removal of current material is required. All draught proofing materials except the door curtains are considered to last 30 years and are therefore replaced once in the assessment period. Door curtains are considered to last 20 years and are therefore replaced once in the assessment period. Disposal and replacement are included.
Draught proofing: base of door seals	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=iftSealsForDoorsPlanet&profileId=Planet2020	
Draught proofing: airtightness tape	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=iftSealsForDoorsPlanet&profileId=Planet2020	
Draught proofing: Door curtains	As curtains above	
Draught proofing: curtain pole (as above)	As above	
No heated bedrooms	No embodied emissions are associated with this measure	
No holiday heating	No embodied emissions are associated with this measure	
Temperature reduction	No embodied emissions are associated with this measure	

Appendix K) Response data for survey

The distribution of survey responses across Cumbria (Figure K.4), the types of buildings that the responses came from compared with Cumbria census data (Figure K.5), buildings' rural/urban location (Figure K.6), building ownership (Figure K.7), and the reported ages of respondents' buildings (Figure K.8) can be seen below and show a wide range of responses from different building types across Cumbria.

Figure K.4: Number and percentage of survey responses from each district across Cumbria

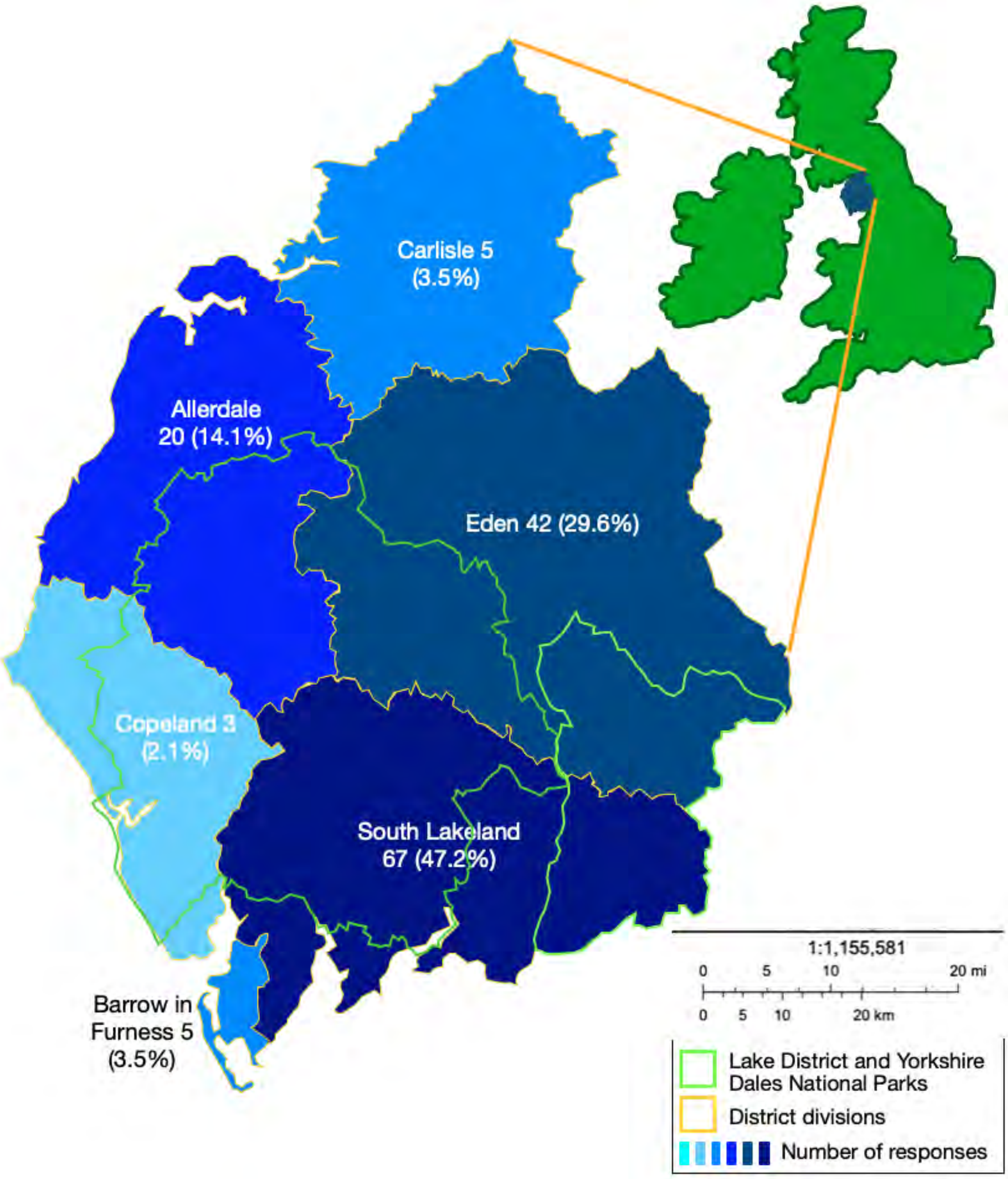
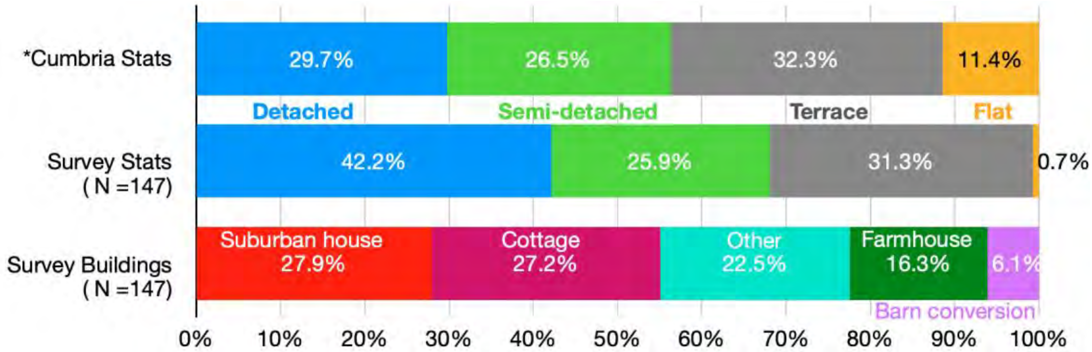


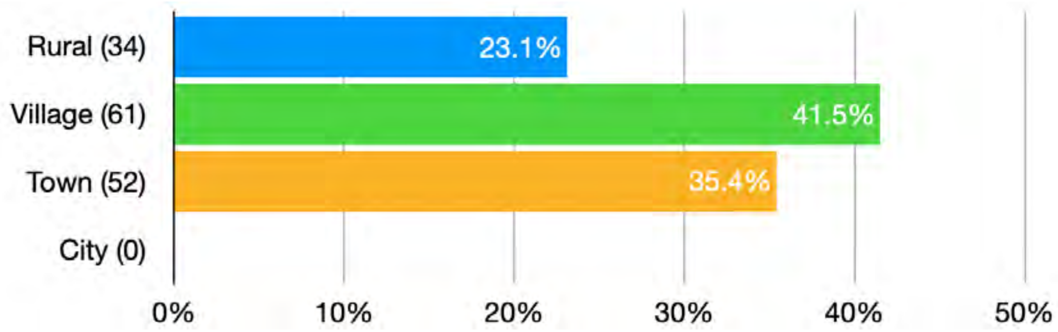
Figure K.5: Survey building types and descriptors, compared with Cumbrian data



Note: Cumbria statistics from Cumbria Intelligence Observatory (2020b).

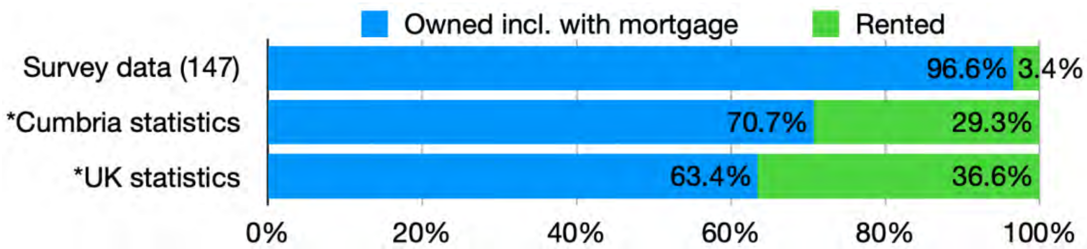
There are more detached houses and less flats in the survey sample, but this is consistent with the age of the surveyed buildings.

Figure K.6: Rural/urban location of survey respondents' buildings (N = 147)



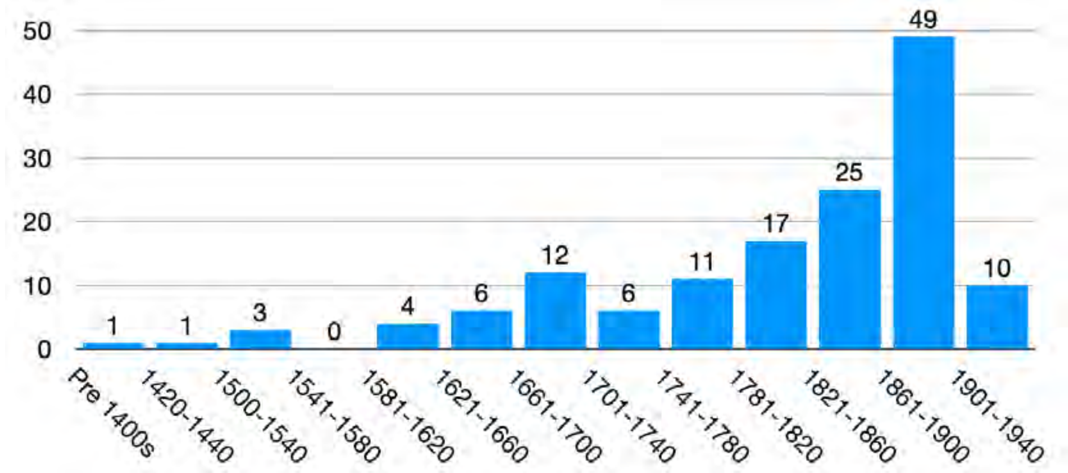
56.3% of the Cumbrian population is rural, 75.1% is rural and hub town and 24.9% can be considered urban (Cumbria Intelligence Observatory, 2020a)

Figure K.7: Survey respondents' building ownership compared with Cumbria and UK data



Note: Cumbria and UK statistics come from Cumbria Intelligence Observatory (2020b)

Figure K.8: Reported age of survey respondents' buildings in 40-year intervals (N =147)



Appendix L) Statistical test results for survey

Differences and statistical test results for the survey data, considering respondents who do and who do not invest heritage values in their homes, is shown below. This is a copy of the supplementary data from Wise, Jones, et al (2021).

L.1) Building details for respondents who do not consider their homes to have heritage value.

Building details are shown for respondents who do not consider their buildings to have heritage value, showing that these cover a range of building types (Figure 1 and Figure 2), locations (Figure 3), designations (Figure 4) and ages (Figure 5).

Figure 1: Percentage of respondents not perceiving their buildings to have heritage value within each general building type.

	Percentage within category that isn't considered to have heritage value	Number within category
Detached	9.8%	6 out of 61
Semi-detached	34.4%	11 out of 32
Terraced	17.5%	7 out of 40
End of terrace	27.3%	3 out of 11
Flat	100%	1 out of 1

Figure 2: Percentage of respondents not perceiving their buildings to have heritage value within each specific building type

	Percentage within category that isn't considered to have heritage value	Number within category
Farmhouse	21.7%	5 out of 23
Cottage	17.5%	7 out of 40
Barn conversion	11.1%	1 out of 9
Suburban house	25%	10 out of 40
Stately home	100%	1 out of 1
Peel tower	0%	0 out of 1
Other	12.9%	4 out of 31

Figure 3: Percentage of respondents not perceiving their buildings to have heritage value within each location and ownership type

	Percentage within category that isn't considered to have heritage value	Number within category
Rural	17.6%	6 out of 34
Village	18.3%	11 out of 60
Town	21.6%	11 out of 51
Owned	17.9%	25 out of 140
Rented	60%	3 out of 5

Figure 4: Percentage of respondents not perceiving their buildings to have heritage value within each building designation

	Percentage within category that isn't considered to have heritage value	Number within category
Grade I	0%	0 out of 1
Grade II*	0%	0 out of 3
Grade II	7.1%	1 out of 14
Conservation area	25%	8 out of 32
Lake District National Park	9.1%	3 out of 33
Yorkshire Dales National Park	30%	3 out of 10
Undesignated	25.5%	13 out of 51

Figure 5: Percentage of respondents not perceiving their buildings to have heritage value within each 40-year age band

	Percentage within category that isn't considered to have heritage value	Number within category
Pre 1400s	0%	0 out of 1
1420-1440	0%	0 out of 1
1500-1540	0%	0 out of 3
1541-1580	0%	0 out of 0
1581-1620	0%	0 out of 4
1621-1660	16.7%	1 out of 6
1661-1700	8.3%	1 out of 12
1701-1740	33.3%	2 out of 6
1741-1780	9.1%	1 out of 11
1781-1820	11.8%	2 out of 17
1821-1860	20%	5 out of 25
1861-1900	26.5%	13 out of 49
1901-1940	20%	2 out of 10

L.2) Statistical tests for comparison of respondents, who do and who do not invest heritage values in their homes

There is significant debate amongst researchers as to whether Likert scale data should be assessed using parametric or non-parametric statistics [1]. A study by De Winter and Dodou found little difference between the power and error percentage of the parametric T-test and the non-parametric Mann-Whitney U test for most data distributions.

For completeness both tests were performed on all the Likert data that had similarly distributed points on the scale. (i.e. 'very unsatisfied' through to 'very satisfied', but not 'already have', 'would do', 'would not do', 'not applicable'). Very few differences were found between the results of the two tests so where results did not agree differences were not considered to be statistically significant.

The results for the different questions are displayed in the following tables.

Table 1: Independent T-Test and Mann-Whitney U test results for valued aspects of buildings. Comparing respondents who perceive heritage value in their buildings with those who do not. Statistically significant results are in bold

	Mean value	Standard deviation	T value, T=	Degrees of freedom	Two tailed significance (significant p < .05)	One tailed significance p =	Mann Whitney U U =	Two tailed significance p =	One tailed significance p =
Age Heritage yes (HY)	2.28	0.871	-5.823	142	**p < .001**	**p < .001**	658	**p < .001**	**p < .001**
Heritage no (HN)	3.32	0.772							
Architecture (HY)	2.11	0.938	-4.840	139	**p < .001**	**p < .001**	738	**p < .001**	**p < .001**
(HN)	3.07	0.874							
Historic type (HY)	2.19	0.917	-5.123	141	**p < .001**	**p < .001**	755	**p < .001**	**p < .001**
(HN)	3.18	0.905							
History of specific building (HY)	2.70	1.116	-4.650	139	**p < .001**	**p < .001**	701	**p < .001**	**p < .001**
(HN)	3.81	0.981							
Local community (HY)	2.25	0.907	-2.89	35	0.775	0.388	1599.5	0.960	0.484
(HN)	2.32	1.188							
Inherited (HY)	4.28	1.089	-1.916	68.78	0.06	**0.03**	1311	0.321	0.161
(HN)	4.59	0.636							
Local services (HY)	2.74	1.232	-0.188	136	0.851	0.426	1514.5	0.890	0.445
(HN)	2.79	1.287							
Price (HY)	2.82	1.161	0.749	136	0.455	0.228	1305.5	0.282	0.141
(HN)	2.63	1.275							
Views (HY)	2.09	0.947	0.073	142	0.942	0.471	1586.5	0.841	0.422
(HN)	2.07	1.016							
Specific location (HY)	2.03	0.912	0.504	141	0.615	0.308	1497.5	0.548	0.275
(HN)	1.93	0.940							
Family home (HY)	2.33	1.309	-1.703	140	0.091	**0.046**	1248	0.101	0.051
(HN)	2.81	1.415							
Heritage value (HY)	2.32	0.800	-9.975	43.086	**p < .001**	**p < .001**	254	**p < .001**	**p < .001**
(HN)	3.85	0.675							
Character in the landscape (HY)	2.10	0.873	-2.890	136	**0.004**	**0.002**	1051.5	**0.010**	**0.006**
(HN)	2.67	1.074							
Original historic features (HY)	2.44	1.138	-6.870	56.943	**p < .001**	**p < .001**	569.5	**p < .001**	**p < .001**
(HN)	3.70	0.775							
Materials (HY)	2.35	1.059	-5.439	137	**p < .001**	**p < .001**	664.5	**p < .001**	**p < .001**
(HN)	3.57	1.069							
Specific features (HY)	2.81	1.299	-4.954	53.288	**p < .001**	**p < .001**	653	**p < .001**	**p < .001**
(HN)	3.92	0.935							
Size (HY)	2.47	1.010	-1.272	138	0.206	0.103	1240	0.108	0.055
(HN)	2.74	0.944							
Traditional construction (HY)	2.10	1.017	-2.681	141	**0.008**	**0.004**	1114	**0.008**	**0.004**
(HN)	2.68	1.090							

In table 1 ‘family home’ and ‘inherited’ value aspects were shown to be statistically significant by the T-test but not by the Mann-Whitney U test, they were therefore not reported as statistically significant.

Table 2: Independent T-Test and Mann-Whitney U test results for use of heating systems. Comparing respondents who perceive heritage value in their buildings with those who do not. Statistically significant results are in bold

	Mean	Standard variation	T value, T=	Degrees of freedom	Two tailed significance (significant p < .05)	One tailed significance p =	Mann Whitney U U =	Two tailed significance p =	One tailed significance p =
Air conditioning heritage yes (HY)	5.95	0.226	0.582	23.194	0.566	0.283	1278	1.000	0.659
Heritage No (HN)	5.87	0.626							
Coal fires (HY)	4.85	1.616	1.185	137	0.238	0.119	1294	0.297	0.149
(HN)	4.42	1.815							
Electric fires (HY)	5.22	1.202	2.051	28.969	**0.049**	**0.025**	1072.5	**0.042**	**0.024**
(HN)	4.44	1.805							
Wood fires (HY)	4.86	1.710	-0.920	129	0.359	0.176	1085.5	0.273	0.135
(HN)	5.22	1.565							
Wood stove (HY)	3.42	2.082	-0.016	137	0.987	0.494	1449.5	0.915	0.460
(HN)	3.42	2.062							
Gas fire (HY)	5.24	1.409	0.339	132	0.735	0.368	1264.5	0.918	0.447
(HN)	5.13	1.660							
Radiator (HY)	2.03	1.661	-0.146	136	0.884	0.442	1323.5	0.583	0.290
(HN)	2.08	1.631							
Solid fuel range (HY)	5.48	1.385	0.131	130	0.896	0.448	1240	0.963	0.532
(HN)	5.43	1.532							
Storage heaters (HY)	5.44	1.427	-2.308	76.105	**0.024**	**0.001**	1158	0.142	0.073
(HN)	5.87	0.626							
Underfloor heating (HY)	4.91	1.860	-2.439	46.777	**0.019**	**0.010**	1048	0.051	**0.022**
(HN)	5.65	1.191							
Ceiling fans (HY)	5.92	0.427	0.469	133	0.640	0.32	1288	1.000	0.729
(HN)	5.87	0.626							
Portable fans (HY)	5.53	0.936	0.723	133	0.471	0.236	1178	0.304	0.641
(HN)	5.36	1.255							
Portable heaters (HY)	4.79	1.325	1.066	136	0.288	0.144	1324.5	0.446	0.222
(HN)	4.46	1.679							
Hot water bottles (HY)	3.93	1.513	1.394	1136	0.166	0.083	1154	0.145	0.073
(HN)	4.33	1.758							
Other (HY)	3.76	2.271	-2.796	15.786	**0.013**	**0.007**	87.5	**0.045**	**0.024**
(HN)	5.50	1.414							

In table 2 differences in the 'Storage heaters' and 'underfloor heating' categories were shown to be statistically significant by the T-test but not by the Mann-Whitney U test, they were therefore not reported as statistically significant.

Table 3: Independent T-Test and Mann-Whitney U test results for overall satisfaction with building comfort. Comparing respondents who perceive heritage value in their buildings with those who do not. Statistically significant results are in bold

	Mean	Standard variation	T value, T=	Degrees of freedom	Two tailed significance (significant p < .05)	One tailed significance p =	Mann Whitney U U =	Two tailed significance p =	One tailed significance p =
Overall satisfaction with building comfort heritage yes	**5.15**	**1.088**	1.276	143	0.204	0.102	1361.5	0.139	0.071
Heritage No	**4.86**	**1.177**							

Table 4: Independent T-Test and Mann-Whitney U test results responsibility to reduce carbon emissions. Comparing respondents who perceive heritage value in their buildings with those who do not. Statistically significant results are in bold

	Mean value	Standard deviation	T value, T=	Degrees of freedom	Two tailed significance (significant p < .05)	One tailed significance p =	Mann Whitney U U =	Two tailed significance p =	One tailed significance p =
Governments Heritage yes (HY)	**4.25**	**0.724**	-0.779	142	0.437	0.219	1445	0.476	0.239
Heritage no (HN)	**4.56**	**0.698**							
Building professionals (HY)	**3.76**	**0.753**	-0.174	142	0.862	0.431	1615	0.969	0.489
(HN)	**3.79**	**0.686**							
Local authorities (HY)	**2.96**	**0.804**	-0.260	142	0.795	0.398	1411.5	0.349	0.175
(HN)	**3.74**	**0.888**							
Homeowners (HY)	**2.87**	**0.676**	0.850	143	0.397	0.199	1490.5	0.410	0.200
(HN)	**3.33**	**0.701**							
English Heritage (HY)	**2.74**	**0.898**	-0.486	140	0.628	0.314	1512	0.818	0.410
(HN)	**4.37**	**0.681**							
Energy companies (HY)	**2.40**	**0.805**	-1.124	143	0.263	0.132	1414.5	0.220	0.111
(HN)	**2.79**	**0.772**							

It can be seen that none of the results in table 6 are statistically significant, despite the large difference in mean values for English Heritage.

Table 5: Independent T-Test and Mann-Whitney U test results for barriers to reducing carbon emissions. Comparing respondents who perceive heritage value in their buildings with those who do not. Statistically significant results are in bold

	Mean value	Standard deviation	T value, T=	Degrees of freedom	Two tailed significance (significant p < .05)	One tailed significance p =	Mann Whitney U U =	Two tailed significance p =	One tailed significance p =
Cost Heritage yes (HY)	**2.04**	**1.185**	0.031	140	0.975	0.488	1499	0.598	0.301
Heritage no (HN)	**2.04**	**1.503**							
Knowledge (HY)	**2.40**	**1.290**	-1.352	141	0.178	0.089	1415	0.309	0.155
(HN)	**2.79**	**1.595**							
Heritage sensitive options (HY)	**2.74**	**1.396**	-5.566	141	**p < .001**	**p < .001**	631	**p < .001**	**p < .001**
(HN)	**4.37**	**1.245**							
Availability of tradespeople (HY)	**2.87**	**1.342**	-1.649	141	0.101	0.0505	1261.5	0.108	0.054
(HN)	**3.33**	**1.177**							
Planning (HY)	**2.96**	**1.466**	-2.479	139	**0.014**	**0.007**	1100.5	**0.018**	**0.009**
(HN)	**3.74**	**1.534**							
Disruption (HY)	**3.34**	**1.271**	-0.6	142	0.55	0.275	1513.5	0.569	0.285
(HN)	**3.5**	**1.401**							
Feel we've done everything possible (HY)	**3.74**	**1.499**	-0.803	138	0.424	0.212	1379	0.434	0.217
(HN)	**4.00**	**1.468**							
Time (HY)	**3.48**	**1.240**	-0.461	142	0.646	0.323	1519	0.590	0.295
(HN)	**3.61**	**1.449**							

References

[1] Joost De Winter and Dimitra Dodou, 'Five-Point Likert Items: T Test versus Mann-Whitney-Wilcoxon (Addendum Added October 2012)', *Practical Assessment, Research and Evaluation* 15, no. 11 (2010): 18.

Appendix M) Retrofit modelling operational results for each case

Operational energy and carbon results from retrofits for each case study.

CS1 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS1 Baseline			**37,746**		**4,133**		**42,390**		**10,419**		
Loft insulation											
Natural	Main roof	180	35,637	5.6%	4,131	0.05%	2,111	5%	523	5.1%	103
Standard	Main roof	180	35,667	5.5%	4,131	0.05%	2,081	5%	516	5%	103
Technical	Main roof	180	35,558	5.8%	4,131	0.05%	2,190	5.2%	543	5.3%	103
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	All ext walls	50	27,129	28.1%	4,125	0.2%	10,625	25.1%	2,633	25.3%	136
Standard	All ext walls	50	26,718	29.2%	4,124	0.2%	11,037	26%	2,735	26%	136
Technical	All ext walls	20	26,961	28.6%	4,124	0.2%	10,794	25.5%	2,675	25.7%	136
Heritage	All ext walls	50	27,668	26.7%	4,125	0.2%	10,086	23.8%	2,499	24%	136
External Wall insulation											
Natural	All ext walls	100	24,755	34.4%	4,123	0.2%	13,001	30.7%	3,222	30.9%	136
Standard	All ext walls	100	24,453	35.2%	4,123	0.2%	13,303	31.4%	3,297	31.2%	136
Technical	All ext walls	120	25,976	31.2%	4,124	0.2%	11,779	27.8%	2,919	28%	136
Solid floor insulation											
Natural	Hall, pantry, shower floors	300	26,681	29.3%	4,119	0.3%	11,079	26.1%	2,745	26.3%	40
Standard	Hall, pantry, shower floors	60	26,953	28.6%	4,119	0.3%	10,807	25.5%	2,678	25.7%	40
Technical	Hall, pantry, shower floors	10	27,993	25.8%	4,120	0.3%	9,766	23%	2,420	23.2%	40
Suspended floor insulation											
Natural	Kitchen & E reception room	140	39,039	-3.4%	4,133	0%	-1,293	-3.1%	-320	-3.1%	37
Standard	Kitchen & E reception room	140	39,045	-3.4%	4,133	0%	-1,299	-3.1%	-322	-3.1%	37
Technical	Kitchen & E reception room	20	38,700	-2.5%	4,133	0%	-854	-2%	-236	-2.3%	37
Window Replacement											
Double wood	All windows	6, 13, 6	37,156	1.6%	4,151	-0.4%	572	1.3%	142	1.4%	51
Double UPVC	All windows	6, 13, 6	37,189	1.5%	4,151	-0.4%	539	1.3%	134	1.3%	51
Triple wood	All windows	3, 13, 2, 13, 3	36,756	2.6%	4,182	-1.2%	941	2.2%	234	2.2%	51
Triple UPVC	All windows	3, 13, 2, 13, 3	36,788	2.5%	4,182	-1.2%	909	2.1%	226	2.2%	51
Window additions											
Curtains	All windows	Curtains	37,484	0.7%	4,133	0%	262	0.6%	65	0.6%	43
Shutters	All windows	Shutters	37,407	0.9%	4,132	0.02%	340	0.8%	84	0.8%	47
Secondary glazing	All single glazed	Secondary	37,388	0.9%	4,131	0.05%	360	0.8%	89	0.9%	13
Heating systems and renewable technologies											
EE boiler	92% efficient	Oil boiler	20,027	46.9%	4,133	0%	17,719	41.8%	4,391	42.1%	N/A
Biomass boiler	87.3% efficient	Pellet boiler	21,178	43.9%	4,133	0%	16,568	39.1%	9,035	86.7%	N/A
Solar PV	S roof 30°	21.2% efficient	38,098	-0.9%	4,133	0%	-352	-0.8%	-87	-0.8%	Electricity generation 10,554kWh
Solar PV	Covering 25% of on site electricity demand	1,033kWh used on site	38,098	-0.9%	3,100	25%	681	1.6%	152	1.5%	N/A
Solar thermal	S roof 30°	DHW only	31,498	16.6%	4,879	-18%	5,502	13%	1,376	13.2%	DWH shift from main boiler to Solar T and immersion heater
Ground source heat pump	Underfloor and radiators, separate DHW	15kW peak heat	511	98.6%	10,442	-152.6%	31,437	74.2%	7,896	75.8%	N/A
Air source heat pump	Radiators at 55°C, and DHW	12.6kW peak heat	0	100%	11,788	-185.2%	30,091	71%	7,585	72.8%	Back up oil boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	4 CFL, 2 tungsten	37,814	-0.2%	4,057	1.8%	8	0.02%	1	0.01%	N/A
Thick wall hangings	E&W reception		37,338	1.1%	4,133	0%	408	1%	101	1%	Covers two wall in each reception room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	36,408	3.5%	4,132	0.02%	1,339	3.2%	332	3.2%	N/A
Draught proofing	Current 11 (m3/h/m2 @ 50 Pa)	20% = 8.8	36,956	2.1%	4,132	0.02%	791	1.9%	196	1.9%	N/A
Heating setting adjustments											
No bedroom heating	Master bedroom to unheated		35,151	6.9%	4,132	0.02%	2,596	6.1%	643	6.2%	N/A
No holiday heating	Heating off during holidays	5w 5d	37,619	0.3%	4,133	0%	127	0.3%	31	0.3%	N/A
Reduce heating set point 0.5°C	All set points reduced	0.5°C	34,105	9.6%	4,129	0.1%	3,645	8.6%	903	8.7%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	30,724	18.6%	4,125	0.2%	7,030	16.6%	1,742	16.7%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	27,560	27%	4,122	0.3%	10,197	24%	2,527	24.2%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	24,601	34.8%	4,118	0.4%	13,160	31%	3,261	31.3%	N/A

CS2 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS2 Baseline			13,889		1,007		14,896		3,443		
Loft insulation											
Natural	Main roof	50	13,880	0.1%	1,007	0%	9	0.1%	2.1	0.1%	14.3
Standard	Main roof	50	13,880	0.1%	1,007	0%	9	0.1%	2.1	0.1%	14.3
Technical	Main roof	50	13,879	0.1%	1,007	0%	10	0.1%	2.3	0.1%	14.3
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	Ext wall	50	8,127	73%	1,007	0%	5,762	64.8%	1,332	64.8%	87
Standard	Ext wall	50	7,911	75.8%	1,007	0%	5,978	67.2%	1,392	67.2%	87
Technical	Ext wall	20	8,025	74.3%	1,007	0%	5,864	65.9%	1,355	65.9%	87
Heritage	Ext wall	50	8,371	69.9%	1,007	0%	5,518	62%	1,275	62%	87
External Wall insulation											
Natural	Ext wall	100	7,420	82%	1,007	0%	6,469	72.7%	1,495	72.7%	87
Standard	Ext wall	100	7,320	83.4%	1,007	0%	6,579	74%	1,521	74%	87
Technical	Ext wall	120	8,228	71.8%	1,007	0%	5,661	63.6%	1,308	63.6%	87
Solid floor insulation											
Natural	All ground floors	300	13,662	2.9%	1,007	0%	227	2.6%	52	2.6%	35
Standard	All ground floors	60	13,636	3.2%	1,007	0%	253	2.8%	58	2.8%	35
Technical	All ground floors	10	13,673	2.7%	1,007	0%	216	2.4%	50	2.4%	35
Suspended floor insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Window Replacement											
Double wood	All windows	6, 13, 6	13,639	3.2%	1,016	-0.9%	241	2.7%	56	2.7%	9
Double UPVC	All windows	6, 13, 6	13,653	3%	1,016	-0.9%	227	2.6%	52	2.6%	9
Triple wood	All windows	3, 13, 2, 13, 3	13,678	2.7%	1,021	-1.4%	197	2.2%	46	2.2%	9
Triple UPVC	All windows	3, 13, 2, 13, 3	13,690	2.5%	1,021	-1.4%	185	2.1%	43	2.1%	9
Window additions											
Curtains	All windows	Curtains	13,806	1.1%	1,008	-0.1%	82	0.9%	19	0.9%	4
Shutters	All windows	Shutters	13,458	5.5%	1,009	-0.2%	429	4.8%	99	4.8%	9
Secondary glazing	All single glazed	Secondary	13,203	8.7%	1,012	-0.5%	681	7.7%	157	7.7%	9
Heating systems and renewable technologies											
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	15,091	-8.6%	1,053	-4.6%	-1,248	-8.4%	1,585	86.7%	N/A
Solar PV	S roof 30°	21.2% efficient	13,906	-0.2%	1,007	0%	-17	-0.2%	-3.9	-0.2%	Electricity generation 3,880kWh
Solar PV	Covering 25% of on site electricity demand	970kWh used on site	12,936	6.9%	1,007	0%	953	6.4%	220	6.4%	N/A
Solar thermal	S roof 30°	DHW only	12,814	7.7%	1,007	0	1,071	7.2%	3,195	7.2%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	4,488	67.7%	1,159	-15.1%	9,249	62.1%	2,138	62.1%	N/A
Air source heat pump	Radiators at 55°C, and DHW	6.8kW peak heat	8,174	41.1%	1,713	-70.1%	5,009	33.6%	1,158	33.6%	Back up electric boiler to meet peak load
Other retrofit measures											
LED bulbs	N/A										
Thick wall hangings	Living room		13,740	1.1%	1,007	0%	149	1%	34	1%	Covers one wall
Smart heating controls	N/A										
Draught proofing	Current 14 (m3/ h/m2 @ 50 Pa)	20% = 11.2	13,525	2.6%	1,007	0%	364	2.4%	84	2.4%	N/A
Heating setting adjustments											
No bedroom heating	Heating in both beds turned off		8,915	35.8%	1,007	0%	4,974	33.4%	1,150	33.4%	N/A
No holiday heating	Heating off during holidays	5w 5d	13,427	3.3%	1,007	0%	462	3.1%	107	3.1%	N/A
Reduce heating set point 0.5°C	All set points reduced	0.5°C	12,977	6.6%	1,007	0%	912	6.1%	211	6.1%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	12,118	12.8%	1,007	0%	1,771	11.9%	409	11.9%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	11,312	18.6%	1,007	0%	2,577	17.3%	596	17.3%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	10,550	24%	1,007	0%	3,339	22.4%	772	22.4%	N/A

CS3 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving (kgCO_2e)	Total carbon saving (%)	Area (m2) or note
CS3 Baseline			**17,718**		**3,975**		**21,693**		**4,164**		
	Loft insulation										
Natural	Bay window	150	17,671	0.3%	3,974	0.03%	48	0.2%	8.8	0.2%	1.5
Standard	Bay window	150	17,671	0.3%	3,974	0.03%	48	0.2%	8.8	0.2%	1.5
Technical	Bay window	150	17,670	0.3%	3,974	0.03%	49	0.2%	9	0.2%	1.5
	Ceiling insulation										
Natural	N/A										
Standard	N/A										
Technical	N/A										
	Internal Wall Insulation										
Natural	Ext wall	50	14,830	16.3%	3,940	0.9%	2,923	13.5%	537	12.9%	119
Standard	Ext wall	50	14,694	17.1%	3,939	0.9%	3,060	14.1%	562	13.5%	119
Technical	Ext wall	20	14,771	16.6%	3,940	0.9%	2,982	13.7%	548	13.2%	119
	External Wall insulation										
Natural	Ext wall	100	14,016	20.9%	3,933	1.1%	3,744	17.3%	688	16.5%	119
Standard	Ext wall	100	13,936	21.3%	3,932	1.1%	3,825	17.6%	703	16.9%	119
Technical	Ext wall	120	14,393	18.8%	3,938	0.9%	3,362	15.5%	618	14.8%	119
	Solid floor insulation										
Natural	All ground floors	300	17,595	0.7%	3,979	-0.1%	119	0.5%	22	0.5%	89
Standard	All ground floors	60	17,718	0%	3978	-0.1%	-3	-0.01%	-1	-0.02%	89
Technical	All ground floors	10	17,725	-0.04%	3,977	-0.1%	-9	-0.04%	-2	-0.04%	89
	Suspended floor insulation										
Natural	N/A										
Standard	N/A										
Technical	N/A										
	Window Replacement										
Double wood	All windows	6, 13, 6	16,521	6.8%	3,986	-0.3%	1,186	5.5%	217	5.2%	33
Double UPVC	All windows	6, 13, 6	16,544	6.6%	3,986	-0.3%	1,163	5.4%	212	5.1%	33
Triple wood	All windows	3, 13, 2, 13, 3	16,350	7.7%	3,999	-0.6%	1,344	6.2%	245	5.9%	33
Triple UPVC	All windows	3, 13, 2, 13, 3	16,371	7.6%	3,999	-0.6%	1,323	6.1%	241	5.8%	33
	Window additions										
Curtains	All windows	Curtains	17,492	1.3%	3,972	0%	226	1%	41	1%	17
Shutters	All windows	Shutters	16,914	4.5%	3,968	0.2%	811	3.7%	149	3.6%	33
Secondary glazing	All single glazed	Secondary	16,262	8.2%	3,969	0.2%	1,462	6.7%	268	6.4%	32
	Heating systems and renewable technologies										
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	17,632	0.5%	3,975	0%	-397	-1.8%	2,890	69.4%	Still 483kWh of gas use for cooking which is included in total savings.
Solar PV	W roof	21.2% efficiency	17,730	-0.1%	3,975	0%	-12	-0.1%	-2.2	-0.05%	Electricity generation 2,096kWh
Solar PV	Covering 25% of on site electricity demand	528kWh used on site	17,730	-0.1%	3,447	13.3%	516	2.4%	120	2.9%	N/A
Solar thermal	W roof 42°	DWH only	13,407	24.3%	5,961	-50%	2,325	10.7%	331	7.9%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	15kW peak heat	483	97.3%	12,074	-203.7%	9,136	42.1%	1,285	30.9%	N/A
Air source heat pump	Radiators at 55°C, and DHW	12.7kW peak heat	664	96.3%	13,549	-240.9%	7,480	34.5%	1,643	39.5%	Back up gas boiler to meet peak load
	Other retrofit measures										
LED bulbs	All non LED lights replaced	9 CFL and linear off control	17,889	-1%	3,434	13.6%	370	1.7%	94	2.3%	
Thick wall hangings	Dining room and office		17,636	0.5%	3,949	0.7%	108	0.5%	21	0.5%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	14,539	17.9%	4,089	-2.9%	3,065	14.1%	556	13.4%	N/A
Draught proofing	Current 15 (m3/h/m2 @ 50 Pa)	20% = 12	17,186	3%	3,953	0.6%	554	2.6%	103	2.5%	N/A
	Heating setting adjustments										
No bedroom heating	Heating in all beds turned off		15,190	14.3%	4,134	-4%	2,369	10.9%	426	10.2%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	16,814	5.1%	3,935	1%	944	4.4%	175	4.2%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	15,948	10%	3,897	2%	1,848	8.5%	342	8.2%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	15,124	14.6%	3,859	2.9%	2,710	12.5%	502	12.1%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	14,338	19.1%	3,822	3.8%	3,533	16.3%	654	15.7%	N/A

CS5 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS5 Baseline			**19,893**		**2,296**		**22,189**		**4,174**		
Loft insulation											
Natural	Main roof	150	19,621	1.4%	2,296	0%	272	1.2%	50	1.2%	61
Standard	Main roof	150	19,627	1.3%	2,296	0%	266	1.2%	49	1.2%	61
Technical	Main roof	150	19,608	1.4%	2,296	0%	285	1.3%	52	1.3%	61
Ceiling insulation											
Natural	Kitchen	150	19,681	1.1%	2,296	0%	212	1%	39	0.9%	4.52 (sloped) 9.4 (flat)
Standard	Kitchen	150	19,669	1.1%	2,296	0%	224	1%	41	1%	4.52 (sloped) 9.4 (flat)
Technical	Kitchen	20	19,719	0.9%	2,296	0%	174	0.8%	32	0.8%	4.52 (sloped) 9.4 (flat)
Internal Wall Insulation											
Natural	All ext	50	12,394	37.7%	2,288	0.3%	7,507	33.8%	1,375	32.9%	194
Standard	All ext	50	11,997	39.7%	2,288	0.3%	7,904	35.6%	1,448	34.7%	194
Technical	All ext	20	12,179	38.8%	2,288	0.3%	7,722	34.8%	1,415	33.9%	194
Heritage	All ext	50	12,774	35.8%	2,289	0.3%	7,126	32.1%	1,306	31.3%	194
External Wall insulation											
Natural	All ext	100	11,486	42.3%	2,291	0.2%	8,412	37.9%	1,541	36.9%	194
Standard	All ext	100	11,276	43.3%	2,291	0.2%	8,622	38.9%	1,579	37.8%	194
Technical	All ext	120	12,415	37.6%	2,292	0.2%	7,482	33.7%	1,371	32.8%	194
Solid floor insulation											
Natural	Kitchen and hall floor	300	20,145	-1.3%	2,296	0%	-252	-1.1%	-46	-1.1%	20
Standard	Kitchen and hall floor	60	20,053	-0.8%	2,296	0%	-160	-0.7%	-29	-0.7%	20
Technical	Kitchen and hall floor	10	20,043	-0.8%	2,296	0%	-150	-0.7%	-27	-0.7%	20
Suspended floor insulation											
Natural	Dining room	140	20,078	-0.9%	2,296	0%	-185	-0.8%	-34	-0.8%	25
Standard	Dining room	140	20,081	-0.9%	2,296	0%	-188	-0.8%	-34	-0.8%	25
Technical	Dining room	20	20,016	-0.6%	2,296	0%	-123	-0.6%	-23	-0.5%	25
Window Replacement											
Double wood	All windows	6, 13, 6	19,426	2.3%	2,307	-0.5%	456	2.1%	83	2%	22
Double UPVC	All windows	6, 13, 6	19,435	2.3%	2,308	-0.5%	446	2%	81	1.9%	22
Triple wood	All windows	3, 13, 2, 13, 3	19,251	3.2%	2,323	-1.2%	615	2.8%	111	2.7%	22
Triple UPVC	All windows	3, 13, 2, 13, 3	19,264	3.2%	2,323	-1.2%	602	2.7%	109	2.6%	22
Window additions											
Curtains	All windows	Curtains	19,783	0.6%	2,295	0.04%	111	0.5%	20	0.5%	6
Shutters	All windows	Shutters	19,417	2.4%	2,298	-0.09%	474	2.1%	87	2.1%	22
Secondary glazing	All single glazed	Secondary	19,315	2.9%	2,298	-0.09%	576	2.6%	105	2.5%	13
Heating systems and renewable technologies											
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	19,814	0.4%	2,296	0%	-445	-2%	3,247	77.8%	Still 524kWh of gas use for cooking which is included in total savings.
Solar PV	S roof 30°	21.2% efficiency	19,976	-0.4%	2,296	0%	-83	-0.4%	-15	-0.4%	Electricity generation 5,502kWh
Solar PV	Covering 25% of on site electricity demand	574kWh used on site	19,976	-0.4%	1,722	25%	491	2.2%	117	2.8%	N/A
Solar thermal	S roof 30°	DWH only	19,040	4.3%	2,902	-26.4%	247	1.1%	16.2	0.4%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	15kW peak heat	524	97.4%	8,993	-292%	12,672	57.1%	2,000	47.9%	N/A
Air source heat pump	Radiators at 55°C, and DHW	14.5kW peak heat	601	97%	13,606	-492.6%	7,982	36%	920	22%	Back up gas boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	5 CFL	20,078	-0.9%	2,034	11.4%	77	0.3%	61	0.6%	N/A
Thick wall hangings	Dining room and living room		19,737	0.8%	2,296	0%	156	0.7%	29	0.7%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	17,194	13.6%	2,292	0.2%	2,703	12.2%	495	11.9%	N/A
Draught proofing	Current 14 (m3/ h/m2 @ 50 Pa)	20% = 11.2	19,377	2.6%	2,296	0%	516	2.3%	95	2.3%	N/A
Heating setting adjustments											
No bedroom heating	Heating in all beds turned off		17,632	11.4%	2,294	0.1%	2,263	10.2%	415	9.9%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	18,636	6.3%	2,294	0.1%	1,259	5.7%	231	5.5%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	17,417	12.4%	2,292	0.2%	2,480	11.2%	454	10.9%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	16,242	18.4%	2,290	0.3%	3,657	16.5%	670	16.1%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	15,114	24%	2,288	0.3%	4,787	21.6%	877	21%	N/A

CS6 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS6 Baseline			33,661		4,397		38,058		7,182		
Loft insulation											
Natural	Main roof	150	32,720	2.8%	4,397	0%	941	2.5%	172	2.4%	94
Standard	Main roof	150	32,731	2.8%	4,397	0%	930	2.4%	170	2.4%	94
Technical	Main roof	150	32,686	2.9%	4,397	0%	975	2.6%	179	2.5%	94
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	Main, victorian & modern	50	25,370	24.6%	4,390	0.2%	8,298	21.8%	1,520	21.2%	168
Standard	Main, victorian & modern	50	25,023	25.7%	4,389	0.2%	8,646	22.7%	1,584	22.1%	168
Technical	Main, victorian & modern	20	25,226	25.1%	4,390	0.2%	8,442	22.2%	1,547	21.5%	168
External Wall insulation											
Natural	Main, victorian & modern	100	24,024	28.6%	4,389	0.2%	9,645	25.3%	1,767	24.6%	168
Standard	Main, victorian & modern	100	23,755	29.4%	4,389	0.2%	9,914	26%	1,816	25.3%	168
Technical	Main, victorian & modern	120	24,950	25.9%	4,390	0.2%	8,718	22.9%	1,597	22.2%	168
Solid floor insulation											
Natural	Living, sitting, kitchen utility	300	32,026	4.9%	4,395	0.05%	1,637	4.3%	300	4.2%	113
Standard	Living, sitting, kitchen utility	60	32,144	4.5%	4,395	0.05%	1,519	4%	278	3.9%	113
Technical	Living, sitting, kitchen utility	10	32,803	2.5%	4,396	0.02%	859	2.3%	157	2.2%	113
Suspended floor insulation											
Natural	Over cellar	140	33,527	0.4%	4,397	0%	134	0.4%	25	0.3%	12
Standard	Over cellar	140	33,523	0.4%	4,397	0%	138	0.4%	25	0.4%	12
Technical	Over cellar	20	33,565	0.3%	4,397	0%	96	0.3%	18	0.2%	12
Window Replacement											
Double wood	All windows	6, 13, 6	32,831	2.5%	4,406	-0.2%	821	2.2%	150	2.1%	44
Double UPVC	N/A										
Triple wood	All windows	3, 13, 2, 13, 3	32,440	3.6%	4,435	-0.9%	1,183	3.1%	215	3%	44
Triple UPVC	All windows	3, 13, 2, 13, 3	32,474	3.5%	4,435	-0.9%	1,149	3%	209	2.9%	44
Window additions											
Curtains	All windows	Curtains	33,430	0.7%	4,397	0%	231	0.6%	42	0.6%	33
Shutters	All windows	Shutters	33,260	1.2%	4,397	0%	401	1.1%	73	1%	33
Secondary glazing	N/A										
Heating systems and renewable technologies											
EE boiler	90.1% efficient	Gas boiler	33,297	1.1%	4,397	0%	364	1%	67	0.9%	
Biomass boiler	87.3% efficient	Pellet boiler	33,494	0.5%	4,397	0%	-753	-2%	5,490	76.4%	Still 920kWh of gas use for cooking which is included in total savings.
Solar PV	S roof 33°	21.2% efficiency	33,771	-0.3%	4,398	-0.02%	-111	-0.3%	-20	-0.3%	Electricity generation 7,631kWh
Solar PV	Covering 25% of on site electricity demand	1,100kWh used on site	33,771	-0.3%	3,298	25%	989	2.6%	234	3.3%	N/A
Solar thermal	S roof 33°	DHW only	28,077	16.6%	6,817	-55%	3,164	8.3%	463	6.5%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	15kW peak heat	920	97.3%	17,294	-293.3%	19,844	52.1%	3,016	42%	N/A
Air source heat pump	Radiators at 55°C, and DHW	14.6kW peak heat	936	97.2%	24,905	-466.4%	12,217	32.1%	1,254	17.5%	Back up gas boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	1 CFL	33,734	-0.2%	4,304	2.1%	20	0.05%	8.1	0.1%	N/A
Thick wall hangings	Living room and sitting room		32,942	2.1%	4,397	0%	719	1.9%	132	1.8%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	27,908	17.1%	4,390	0.2%	5,760	15.1%	1,055	16.7%	N/A
Draught proofing	Current 14 (m3/h/m2 @ 50 Pa)	20% = 11.2	32,614	3.1%	4,397	0%	1,047	2.8%	192	2.7%	N/A
Heating setting adjustments											
No bedroom heating	Heating in all beds turned off		29,729	11.7%	4,395	0.05%	3,934	10.3%	721	10%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	31,733	5.7%	4,395	0.05%	1,930	5.1%	534	4.9%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	29,906	11.2%	4,393	0.1%	3,759	9.9%	689	9.6%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	28,136	16.4%	4,390	0.2%	5,532	14.5%	1,014	14.1%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	26,442	21.4%	4,388	0.2%	7,228	19%	1,324	18.4%	N/A

CS7 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS7 Baseline			**21,230**		**6,497**		**27,727**		**6,763**		
Loft insulation											
Natural	Extension	100	21,173	0.3%	6,497	0%	57	0.2%	14	0.2%	54
Standard	Extension	100	21,187	0.2%	6,497	0%	43	0.2%	11	0.2%	54
Technical	Extension	100	21,216	0.1%	6,497	0%	14	0.1%	3.5	0.1%	54
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	Main & extension	50	17,463	17.7%	6,258	3.7%	4,006	14.4%	989	14.6%	191
Standard	Main & extension	50	17,484	17.6%	6,244	3.9%	3,999	14.4%	987	14.6%	191
Technical	Main & extension	20	17,472	17.7%	6,251	3.8%	4,004	14.4%	988	14.6%	191
Heritage	Main & extension	50	17,783	16.2%	6,272	3.5%	3,672	13.2%	906	13.4%	191
External Wall insulation											
Natural	Main & extension	100	15,926	25%	6,242	3.9%	5,559	20%	1,373	20.3%	191
Standard	Main & extension	100	15,795	25.6%	6,236	4%	5,696	20.5%	1,407	20.8%	191
Technical	Main & extension	120	16,598	21.8%	6,274	3.4%	4,855	17.5%	1,199	17.7%	191
Solid floor insulation											
Natural	All except garden room	300	20,826	1.9%	6,504	-0.1%	397	1.4%	99	1.5%	154
Standard	All except garden room	60	20,619	2.9%	6,506	-0.1%	602	2.2%	149	2.2%	154
Technical	All except garden room	10	20,911	1.5%	6,502	-0.1%	314	1.1%	78	1.2%	154
Suspended floor insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Window Replacement											
Double wood	N/A										
Double UPVC	N/A										
Triple wood	All windows	3, 13, 2, 13, 3	21,296	-0.3%	6,514	-0.3%	-83	-0.3%	-20	-0.3%	35
Triple UPVC	All windows	3, 13, 2, 13, 3	21,320	-0.4%	6,514	-0.3%	-107	-0.4%	-26	-0.4%	35
Window additions											
Curtains	All windows	Curtains	21,138	0.4%	6,496	0.02%	93	0.3%	23	0.3%	18
Shutters	All windows	Shutters	21,051	0.8%	6,495	0.03%	181	0.7%	45	0.7%	35
Secondary glazing	Dairy window	Secondary glazing	21,146	0.4%	6,497	0%	84	0.3%	21	0.3%	2
Heating systems and renewable technologies											
EE boiler	92% efficient	Oil boiler	14,947	29.6%	6,497	0%	6,283	22.7%	1,557	23%	N/A
Biomass boiler	87.3% efficient	Pellet boiler	19,521	8%	6,497	0%	1,709	6.2%	4,966	73.4%	N/A
Solar PV	S roof 32°	21.2% efficiency	21,287	-0.3%	6,498	-0.02%	-60	-0.2%	-15	-0.2%	Electricity generation 12,491kWh
Solar PV	Covering 25% of on site electricity demand	1,625kWh used on site	21,287	-0.3%	4,873	25%	1,567	5.7%	361	5.3%	N/A
Solar thermal	S roof 32°	DHW only	17,057	19.7%	7,764	-19.5%	2,906	10.5%	741	11%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	24kW peak heat	0	100%	14,489	-123%	13,238	47.7%	3,414	50.5%	N/A
Air source heat pump	Radiators at 55°C, and DHW	25.3kW peak heat	0	100%	15,622	-140.4%	12,105	43.7%	3,152	46.6%	Back up oil boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	Linear off	21,272	-0.2%	6,353	2.2%	102	0.4%	23	0.4%	All bulbs were already LEDs but control improved
Thick wall hangings	Lounge		20,926	1.4%	6,497	0%	304	1.1%	75	1.1%	Covers one wall in room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	16,198	23.7%	6,508	-0.2%	5,021	18.1%	1,244	18.4%	N/A
Draught proofing	Current 13 (m3/ h/m2 @ 50 Pa)	20% = 10.4	20,884	1.6%	6,451	0.7%	392	1.4%	96	1.4%	N/A
Heating setting adjustments											
No bedroom heating	Heating in guest beds turned off	only heated part of year	20,270	4.5%	6,498	-0.02%	959	3.5%	238	3.5%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	19,644	7.5%	6,288	3.2%	1,795	6.5%	441	6.5%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	17,947	15.5%	6,005	7.6%	3,775	13.6%	927	13.7%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	16,232	23.5%	5,810	10.6%	5,685	20.5%	1,397	20.7%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	14,823	30.2%	5,700	12.3%	7,204	26%	1,772	26.2%	N/A

CS8 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS8 Baseline			**24,134**		**4,379**		**28,513**		**5,432**		
Loft insulation											
Natural	Main roof	100	24,098	0.1%	4,378	0.02%	37	0.1%	6.8	0.1%	46
Standard	Main roof	100	24,099	0.1%	4,378	0.02%	36	0.1%	6.6	0.1%	46
Technical	Main roof	100	24,095	0.2%	4,378	0.02%	40	0.1%	7.4	0.1%	46
Ceiling insulation											
Natural	Kitchen	150	23,010	4.7%	4,377	0.05%	1,126	3.9%	206	3.8%	6.2 (sloped) 10.3 (flat)
Standard	Kitchen	150	23,010	4.7%	4,377	0.05%	1,126	3.9%	206	3.8%	6.2 (sloped) 10.3 (flat)
Technical	Kitchen	20	23,200	3.9%	4,377	0.05%	936	3.3%	172	3.2%	6.2 (sloped) 10.3 (flat)
Internal Wall Insulation											
Natural	Front & rear & kitchen	50	20,498	15.1%	4,374	0.1%	3,641	12.8%	667	12.3%	94
Standard	Front & rear & kitchen	50	20,304	15.9%	4,374	0.1%	3,835	13.5%	703	12.9%	94
Technical	Front & rear & kitchen	20	20,411	15.4%	4,374	0.1%	3,728	13.1%	683	12.6%	94
Heritage	Front & rear & kitchen	50	20,716	14.2%	4,374	0.1%	3,423	12%	627	11.5%	94
External Wall insulation											
Natural	Front & rear & kitchen	100	19,804	17.9%	4,374	0.1%	4,335	15.2%	794	14.6%	94
Standard	Front & rear & kitchen	100	19,623	18.7%	4,373	0.1%	4,517	15.8%	828	15.2%	94
Technical	Front & rear & kitchen	120	20,314	15.8%	4,374	0.1%	3,825	13.4%	701	12.9%	94
Solid floor insulation											
Natural	Dining & kitchen	300	23,689	1.8%	4,377	0.05%	447	1.6%	82	1.5%	30
Standard	Dining & kitchen	60	23,691	1.8%	4,377	0.05%	445	1.6%	82	1.5%	30
Technical	Dining & kitchen	10	23,934	0.8%	4,378	0.02%	201	0.7%	37	0.7%	30
Suspended floor insulation											
Natural	Over cellar (sitting, hall, office)	140	23,894	1%	4,378	0.02%	241	0.8%	44	0.8%	39
Standard	Over cellar (sitting, hall, office)	140	23,889	1%	4,378	0.02%	246	0.9%	45	0.8%	39
Technical	Over cellar (sitting, hall, office)	20	24,015	0.5%	4,378	0.02%	120	0.4%	22	0.4%	39
Window Replacement											
Double wood	N/A	6, 13, 6	22,554	6.5%	4,400	-0.5%	1,559	5.5%	285	5.2%	34
Double UPVC	N/A	6, 13, 6	22,580	6.4%	4,400	-0.5%	1,533	5.4%	279	5.2%	34
Triple wood	All windows	3, 13, 2, 13, 3	22,109	8.4%	4,422	-1%	1,982	7%	361	6.6%	34
Triple UPVC	All windows	3, 13, 2, 13, 3	22,144	8.2%	4,422	-1%	1,947	6.8%	355	6.5%	34
Window additions											
Curtains	All windows	Curtains	24,021	0.5%	4,379	0%	113	0.4%	21	0.4%	25
Shutters	All windows	Shutters	23,633	2.1%	4,379	0%	501	1.8%	92	1.7%	34
Secondary glazing	All single glazed	Secondary glazing	23,463	2.8%	4,387	-0.2%	663	2.3%	121	2.3%	17
Heating systems and renewable technologies											
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	19,521	8%	6,497	0%	1,709	6.2%	4,966	73.4%	N/A
Solar PV	E roof, 21°	21.2% efficiency	24,140	-0.02%	4,379	0%	-6	-0.02%	-1.1	-0.02%	Electricity generation 3,518kWh
Solar PV	Covering 25% of on site electricity demand	880kWh used on site	24,140	-0.02%	3,499	20.1%	874	3.1%	202	3.7%	N/A
Solar thermal	E roof, 21°	DHW only	21,000	13%	5,723	-30.7%	1,790	6.3%	263	4.8%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	394	98.4%	13,306	-203.9%	14,813	52%	2,285	42.1%	N/A
Air source heat pump	Radiators at 55°C, and DHW	9.9kW peak heat	556	97.7%	18,230	-316.3%	9,727	34.1%	1,117	20.6%	Back up oil boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	Linear off	24,500	-1.5%	3,825	12.7%	188	0.7%	61	1.1%	N/A
Thick wall hangings	Sitting room and study		24,031	0.4%	4,378	0.02%	104	0.4%	19	0.4%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	22,015	8.8%	4,376	0.1%	2,112	7.4%	389	7.2%	N/A
Draught proofing	Current 14 (m3/ h/m2 @ 50 Pa)	20% = 11.2	23,382	3.1%	4,378	0.02%	753	2.6%	138	2.5%	N/A
Heating setting adjustments											
No bedroom heating	Heating in all beds turned off		22,167	8.2%	4,378	0.02%	1,968	6.9%	361	6.9%	N/A
No holiday heating	N/A	7w 1d	23,999	0.6%	4,378	0%	136	0.5%	25	0.5%	
Reduce heating set point 0.5°C	All set points reduced	0.5°C	22,743	5.8%	4,377	0.05%	1,393	4.9%	255	4.7%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	21,408	11.3%	4,374	0.1%	2,731	9.6%	500	9.2%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	20,129	16.6%	4,373	0.1%	4,011	14.1%	735	13.5%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	18,898	21.7%	4,371	0.2%	5,244	18.4%	961	17.7%	N/A

CS9 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS9 Baseline			**14,114**		**5,187**		**19,301**		**3,784**		
	Loft insulation										
Natural	Main roof	50	14,038	0.5%	5,187	0%	76	0.4%	14	0.4%	50
Standard	Main roof	50	14,038	0.5%	5,187	0%	76	0.4%	14	0.4%	50
Technical	Main roof	50	14,029	0.6%	5,187	0%	85	0.4%	15.6	0.4%	50
	Ceiling insulation										
Natural	Bay window	150	14,111	0.02%	5,187	0%	3	0.02%	0.5	0%	3.4
Standard	Bay window	150	14,113	0.01%	5,187	0%	1	0.01%	0.2	0%	3.4
Technical	Bay window	150	14,112	0.01%	5,187	0%	2	0.01%	0.4	0%	3.4
	Internal Wall Insulation										
Natural	Main wall only	50	11,975	15.2%	5,170	0.3%	2,156	11.2%	396	10.4%	40
Standard	Main wall only	50	11,896	15.7%	5,169	0.3%	2,236	11.6%	410	10.8%	40
Technical	Main wall only	20	11,907	15.6%	5,165	0.4%	2,229	11.5%	409	10.8%	40
Heritage	Main wall only	50	12,068	14.5%	5,171	0.3%	2,062	10.7%	378	10%	40
	External Wall insulation										
Natural	Main wall only	100	11,726	16.9%	5,152	0.7%	2,423	12.6%	445	11.7%	40
Standard	Main wall only	100	11,658	17.4%	5,148	0.8%	2,495	12.9%	459	12.1%	40
Technical	Main wall only	120	11,924	15.5%	5,154	0.6%	2,223	11.5%	409	10.8%	40
	Solid floor insulation										
Natural	Cellar & extension	300	13,842	1.9%	5,186	0.02%	273	1.4%	50	1.3%	43
Standard	Cellar & extension	60	13,856	1.8%	5,185	0.04%	260	1.3%	48	1.3%	43
Technical	Cellar & extension	10	14,026	0.6%	5,187	0%	88	0.5%	16	0.4%	43
	Suspended floor insulation										
Natural	Over cellar (kitchen, hall, extnsn)	140	13,951	1.2%	5,188	-0.02%	162	0.8%	30	0.8%	34
Standard	Over cellar (kitchen, hall, extnsn)	140	13,947	1.2%	5,188	-0.02%	166	0.9%	30	0.8%	34
Technical	Over cellar (kitchen, hall, extnsn)	20	14,074	0.3%	5,187	0%	40	0.2%	7.3	0.2%	34
	Window Replacement										
Double wood	All but extension	6,13, 6	13,098	7.2%	5,192	-0.1%	1,011	5.2%	185	4.9%	21
Double UPVC	All but extension	6,13, 7	13,104	7.2%	5,193	-0.1%	1,004	5.2%	184	4.9%	21
Triple wood	All windows	3, 13, 2, 13, 3	12,768	9.5%	5,207	-0.4%	1,326	6.9%	242	6.4%	27
Triple UPVC	All windows	3, 13, 2, 13, 3	12,789	9.4%	5,207	-0.4%	1,304	6.8%	238	6.3%	27
	Window additions										
Curtains	All windows	Curtains	13,747	2.6%	5,186	0.02%	368	1.9%	67	1.8%	17
Shutters	All windows	Shutters	13,437	4.8%	5,182	0.1%	682	3.5%	125	3.3%	21
Secondary glazing	All single glazed	Secondary glazing	13,037	7.6%	5,184	0.1%	1,080	5.6%	198	5.2%	12
	Heating systems and renewable technologies										
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	13,028	7.7%	5,187	0%	-292	-1.5%	2,136	56.4%	1,378 gas demand for cooking is also included in the totals
Solar PV	S roof 25°	21.2% efficiency	14,129	-0.1%	5,188	-0.02%	-16	-0.08%	-3	-0.08%	Electricity generation 1,119kWh
Solar PV	Covering 25% of on site electricity demand	280kWh used on site	14,129	-0.1%	4,908	5.4%	264	1.4%	62	1.6%	N/A
Solar thermal	S roof 25°	DHW only	12,288	12.9%	6,345	-22.3%	668	3.5%	67	1.8%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	1,378	90.2%	9,813	-89.2%	8,110	42%	1,264	33.4%	N/A
Air source heat pump	Radiators at 55°C, and DHW	8.7kW peak heat	1,378	90.2%	12,260	-136.4%	13,638	29.3%	698	18.4%	Back up oil boiler to meet peak load
	Other retrofit measures										
LED bulbs	All non LED lights replaced	5 CFL 1 spotlight	15,063	-6.7%	3,559	31.4%	679	3.5%	202	5.4%	N/A
Thick wall hangings	Living room		14,201	-0.6%	5,188	-0.02%	-88	-0.5%	-16	-0.4%	Covers one wall in room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	9,117	35.4%	5,165	0.4%	5,019	26%	920	24.3%	N/A
Draught proofing	Current 13 (m3/h/m2 @ 50 Pa)	20% = 10.4	13,798	2.2%	5,186	0.02%	317	1.6%	58	1.5%	N/A
	Heating setting adjustments										
No bedroom heating	N/A										
No holiday heating	Heating off during holidays	2w 6d	13,699	2.9%	5,178	0.2%	424	2.2%	78	2.1%	2w 6d
Reduce heating set point 0.5°C	All set points reduced	0.5°C	13,078	7.3%	5,168	0.4%	1,055	5.5%	194	5.1%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	12,193	13.6%	5,146	0.8%	1,962	10.2%	361	9.5%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	11,461	18.8%	5,127	1.2%	2,713	14.1%	500	13.2%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	10,771	23.7%	5,106	1.6%	3,424	17.7%	631	16.7%	N/A

CS11 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS11 Baseline			5,126		779		5,905		258		
Loft insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Ceiling insulation											
Natural	Main roof	150	5,028	1.9%	779	0%	98	1.7%	1.5	0.6%	36
Standard	Main roof	150	5,024	2%	779	0%	102	1.7%	1.5	0.6%	36
Technical	Main roof	20	5,057	1.3%	779	0%	69	1.2%	1	0.4%	36
Heritage	Main roof	50	5,056	1.4%	779	0%	70	1.2%	1.1	0.4%	36
Internal Wall Insulation											
Natural	Main wall	50	4,492	12.4%	779	0%	634	10.7%	10	3.7%	31
Standard	Main wall	50	4,470	12.8%	779	0%	656	11.1%	10	3.9%	31
Technical	Main wall	20	4,482	12.6%	779	0%	644	10.9%	10	3.8%	31
Heritage	Main wall	50	4,517	11.9%	779	0%	609	10.3%	9	3.6%	31
External Wall insulation											
Natural	Main & extension	100	4,644	9.4%	779	0%	482	8.2%	7.3	2.8%	31
Standard	Main & extension	100	4,634	9.6%	779	0%	492	8.3%	7.4	2.9%	31
Technical	Main & extension	120	4,690	8.5%	779	0%	436	7.4%	6.6	2.6%	31
Solid floor insulation											
Natural	All ground floors	300	5,248	-2.4%	779	0%	-122	-2.1%	-1.8	-0.7%	35
Standard	All ground floors	60	5,250	-2.4%	779	0%	-124	-2.1%	-1.9	-0.7%	35
Technical	All ground floors	10	5,201	-1.5%	779	0%	-75	-1.3%	-1.1	-0.4%	35
Suspended floor insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Window Replacement											
Double wood	All windows	6, 13, 6	5,033	1.8%	787	-1%	85	1.4%	-0.4	-0.2%	10
Double UPVC	All windows	6, 13, 7	5,036	1.8%	787	-1%	82	1.4%	-0.5	-0.2%	10
Triple wood	All windows	3, 13, 2, 13, 3	5,022	2%	792	-1.7%	91	1.5%	-1.4	-0.6%	10
Triple UPVC	All windows	3, 13, 2, 13, 3	5,026	2%	792	-1.7%	87	1.5%	-1.5	-0.6%	10
Window additions											
Curtains	All windows	Curtains	5,121	0.1%	779	0%	5	0.08%	0.08	0.03%	3
Shutters	All windows	Shutters	5,051	1.5%	780	-0.1%	74	1.3%	0.9	0.4%	10
Secondary glazing	All single glazed	Secondary glazing	4,989	2.7%	783	-0.5%	133	2.3%	1.1	0.4%	10
Heating systems and renewable technologies											
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	2,153	58%	658	15.5%	3,094	52.4%	73	28.5%	N/A
Solar PV	S roof 32°	21.2% efficiency	21,287	-0.3%	6,498	-0.02%	-60	-0.2%	-15	-0.2%	Electricity generation 2,267kWh
Solar PV	Covering 25% of on site electricity demand	195kWh used on site	5,242	-2.3%	584	25%	79	1.3%	43	16.8%	N/A
Solar thermal	W Roof 29°	DHW only	5,151	-0.5%	660	15.3%	94	1.6%	27	10.5%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	0	100	1,646	-111.3%	4,259	72.1%	-122	-47.7%	N/A
Air source heat pump	Radiators at 55°C, and DHW	6.6kW peak heat	0	100%	2,392	-207.1%	3,513	59.5%	-295	-114.6%	Back up electric boiler to meet peak load
Other retrofit measures											
LED bulbs	All non LED lights replaced	1 CFL	5,129	-0.1%	764	1.9%	12	0.2%	3.4	1.3%	N/A
Thick wall hangings	Living room		4,996	2.5%	779	0%	130	2.2%	2	0.8%	Covers one wall in room
Smart heating controls	N/A										
Draught proofing	Current 15 (m3/ h/m2 @ 50 Pa)	20% = 12	5,066	1.2%	779	0%	60	1%	0.9	0.4%	N/A
Heating setting adjustments											
No bedroom heating	N/A										
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	4,763	7.1%	779	0%	363	6.1%	5.5	2.1%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	4,415	13.9%	779	0%	711	12%	11	4.2%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	4,069	20.6%	779	0%	1,057	17.9%	16	6.2%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	3,787	26.1%	779	0%	1,339	22.7%	20	7.9%	N/A

CS12 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS12 Baseline			**10,062**		**2,703**		**12,765**		**2,468**		
Loft insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	Main wall only	50	9,187	8.7%	2,702	0.04%	876	6.9%	164	6.5%	20
Standard	Main wall only	50	9,169	8.9%	2,702	0.04%	894	7%	164	6.6%	20
Technical	Main wall only	20	9,180	8.8%	2,702	0.04%	883	6.9%	162	6.6%	20
Heritage	Main wall only	50	9,227	8.2%	2,702	0.04%	836	6.5%	153	6.2%	20
External Wall insulation											
Natural	Main wall only	100	8,865	11.9%	2,702	0.04%	1,198	9.4%	219	8.9%	20
Standard	Main wall only	100	8,831	12.2%	2,702	0.04%	1,232	9.7%	226	9.1%	20
Technical	Main wall only	120	8,992	10.6%	2,703	0%	1,070	8.4%	196	7.9%	20
Solid floor insulation											
Natural	All ground floors	300	8,605	14.5%	2,698	0.2%	1,462	11.5%	268	10.9%	35
Standard	All ground floors	60	8,183	18.7%	2,697	0.2%	1,885	14.8%	346	14%	35
Technical	All ground floors	10	8,643	14.1%	2,698	0.2%	1,424	11.2%	261	10.6%	35
Suspended floor insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Window Replacement											
Double wood	All windows	6, 13, 6	9,908	1.5%	2,704	-0.04%	153	1.2%	28	1.1%	9
Double UPVC	All windows	6, 13, 7	9,912	1.5%	2,704	-0.04%	149	1.2%	27	1.1%	9
Triple wood	All windows	3, 13, 2, 13, 3	9,797	2.6%	2,706	-0.1%	262	2.1%	48	1.9%	9
Triple UPVC	All windows	3, 13, 2, 13, 3	9,806	2.5%	2,706	-0.1%	253	1%	46	1.9%	9
Window additions											
Curtains	All windows	Curtains	10,001	0.6%	2,703	0%	61	0.5%	11	0.5%	5
Shutters	All windows	Shutters	9,965	1%	2,703	0%	97	0.7%	18	0.7%	7
Secondary glazing	All single glazed	Secondary glazing	10,029	0.3%	2,703	0%	33	0.3%	6	0.2%	2
Heating systems and renewable technologies											
EE boiler	90.1% efficient	Gas boiler	9,955	1.1%	2,703	0%	107	0.8%	20	0.8%	N/A
Biomass boiler	87.3% efficient	Pellet boiler	9,831	2.3%	2,703	0%	-221	-1.7%	1,611	65.3%	452kWh of gas remains for cooking. Included in totals
Solar PV	W Roof 31°	21.2% efficiency	10,073	-0.1%	2,703	0%	-11	-0.1%	-2	-0.8%	Electricity generation 1,201kWh
Solar PV	Covering 25% of on site electricity demand	300kWh used on site	10,073	-0.1%	2,403	11.1%	289	2.3%	67	2.7%	N/A
Solar thermal	W roof 31°	DHW only	8,609	14.4%	3,403	-25.9%	753	5.9%	104	4.2%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	452	95.5%	6,071	-124.6%	6,242	48.9%	982	39.8%	N/A
Air source heat pump	Radiators at 55°C, and DHW	5.1kW peak heat	452	95.5%	7,818	-189.2%	4,495	35.2%	578	23.4%	Back up gas boiler to meet peak load
Other retrofit measures											
LED bulbs	N/A										
Thick wall hangings	Dining room		10,037	0.2%	2,703	0%	25	0.2%	4.6	0.2%	Covers one wall in room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	9,490	5.7%	2,702	0.03%	573	4.5%	105	4.3%	N/A
Draught proofing	Current 14 (m3/h/m2 @ 50 Pa)	20% = 11.2	9,674	3.9%	2,702	0.04%	389	3%	71	2.9%	N/A
Heating setting adjustments											
No bedroom heating	Heating turned of in main bed		9,367	6.9%	2,700	0.1%	698	5.5%	128	5.2%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	9,424	6.3%	2,701	0.1%	640	5%	117	4.8%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	8,805	12.5%	2,700	0.1%	1,260	9.9%	231	9.4%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	8,228	18.2%	2,698	0.2%	1,839	14.4%	337	13.7%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	7,680	23.7%	2,697	0.2%	2,388	18.7%	438	17.7%	N/A

CS13 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving (kgCO₂e)	Total carbon saving (%)	Area (m2) or note
CS13 Baseline			19,749		2,842		22,591		4,274		
	Loft insulation										
Natural	Both extensions	100	19,527	1.1%	2,842	0%	222	1%	41	1%	36
Standard	Both extensions	100	19,530	1.1%	2,842	0%	219	1%	40	0.9%	36
Technical	Both extensions	100	19,508	1.2%	2,842	0%	241	1.1%	44	1%	36
	Ceiling insulation										
Natural	N/A										
Standard	N/A										
Technical	N/A										
	Internal Wall Insulation										
Natural	Main & dining	50	14,534	26.4%	2,836	0.2%	5,221	23.1%	957	22.4%	131
Standard	Main & dining	50	14,326	27.5%	2,835	0.2%	5,430	24%	995	23.3%	131
Technical	Main & dining	20	14,438	26.9%	2,836	0.2%	5,317	23.5%	974	22.8%	131
Heritage	Main & dining	50	14,801	25.1%	2,836	0.2%	4,954	21.9%	908	21.2%	131
	External Wall insulation										
Natural	Main & dining	100	13,434	32%	2,835	0.2%	6,322	28%	1,158	27.1%	131
Standard	Main & dining	100	13,315	32.6%	2,834	0.3%	6,442	28.5%	1,180	27.6%	131
Technical	Main & dining	120	14,030	29%	2,835	0.2%	5,726	25.3%	1,049	24.5%	131
	Solid floor insulation										
Natural	All ground floors	300	19,598	0.8%	2,842	0%	151	0.7%	28	0.6%	85
Standard	All ground floors	60	19,651	0.5%	2,842	0%	98	0.4%	18	0.4%	85
Technical	All ground floors	10	19,659	0.5%	2,842	0%	90	0.4%	16	0.4%	85
	Suspended floor insulation										
Natural	N/A										
Standard	N/A										
Technical	N/A										
	Window Replacement										
Double wood	N/A	6, 13, 6	18,655	5.5%	2,869	-1%	1,067	4.7%	194	4.5%	24
Double UPVC	N/A	6, 13, 7	18,672	5.4%	2,869	-1%	1,050	4.6%	191	4.5%	24
Triple wood	All windows	3, 13, 2, 13, 3	18,492	6.4%	2,898	-2%	1,201	5.3%	217	5.1%	24
Triple UPVC	All windows	3, 13, 2, 13, 3	18,509	6.3%	2,898	-2%	1,184	5.2%	214	5%	24
	Window additions										
Curtains	All windows	Curtains	19,451	1.5%	2,843	-0.04%	297	1.3%	54	1.3%	13
Shutters	All windows	Shutters	19,113	3.2%	2,849	-0.2%	629	2.8%	115	2.7%	24
Secondary glazing	All single glazed	Secondary glazing	18,799	4.8%	2,855	-0.5%	937	4.1%	171	4%	9
	Heating systems and renewable technologies										
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	19,884	-0.7%	2,842	0%	-447	-2%	3,259	76.3%	312kWh of gas remain for cooking and are incl. in totals
Solar PV	S roofs	21.2% efficiency	19,791	-0.2%	2,842	0%	-42	-0.2%	-7.7	-0.2%	Electricity generation 3,357kWh
Solar PV	Covering 25% of on site electricity demand	711kWh used on site	19,791	-0.2%	2,131	25%	669	3%	157	3.7%	N/A
Solar thermal	S roofs	DHW only	17,558	11.1%	3,615	-27.2%	1,418	6.3%	223	5.2%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	312	98.4%	14,396	-406.5%	7,883	34.9%	890	20.8%	N/A
Air source heat pump	Radiators at 55°C, and DHW	10.2kW peak heat	312	98.4%	14,420	-407.4%	7,859	34.8%	884	20.7%	Back up gas boiler to meet peak load
	Other retrofit measures										
LED bulbs	All non LED lights replaced	2 CFL	19,930	-0.9%	2,594	8.7%	67	0.3%	24	0.6%	N/A
Thick wall hangings	Living and Dining room		19,438	1.6%	2,844	-0.1%	309	1.4%	57	1.3%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	14,631	25.9%	2,836	0.2%	5,124	22.7%	3,335	22%	N/A
Draught proofing	Current 10 (m3/h/m2 @ 50 Pa)	20% = 8	19,313	2.2%	2,842	0%	436	1.9%	80	1.9%	N/A
	Heating setting adjustments										
No bedroom heating	Heating in main bed turned off		17,597	10.9%	2,839	0.1%	2,155	9.5%	395	9.2%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	18,383	6.9%	2,840	0.1%	1,368	6.1%	251	5.9%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	17,100	13.4%	2,838	0.1%	2,653	11.7%	486	11.4%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	15,721	20.4%	2,836	0.2%	4,034	17.9%	739	17.3%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	14,415	27%	2,834	0.3%	5,342	23.6%	979	22.9%	N/A

CS14 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS14 Baseline			14,051		5,923		19,974		3,943		
	Loft insulation										
Natural	Main roof	150	13,860	1.4%	5,918	0.1%	196	1%	36	0.9%	57
Standard	Main roof	150	13,870	1.3%	5,917	0.1%	187	0.9%	34	0.9%	57
Technical	Main roof	150	13,855	1.4%	5,919	0.01%	200	1%	37	0.9%	57
	Ceiling insulation										
Natural	Kitchen and slope	150	12,761	9.2%	5,927	-0.07%	1,286	6.4%	235	6%	25
Standard	Kitchen and slope	150	12,747	9.3%	5,927	-0.07%	1,300	6.5%	238	6%	25
Technical	Kitchen and slope	20	13,119	6.6%	5,924	-0.02%	931	4.7%	170	4.3%	25
Heritage	Kitchen and slope	50	13,087	6.9%	5,921	0.03%	966	4.8%	177	4.5%	25
	Internal Wall Insulation										
Natural	Main & kitchen (not cellar)	50	10,861	22.7%	5,913	0.2%	3,200	16%	587	14.9%	86
Standard	Main & kitchen (not cellar)	50	10,739	23.6%	5,908	0.3%	3,327	16.7%	610	15.5%	86
Technical	Main & kitchen (not cellar)	20	10,814	23%	5,909	0.2%	3,251	16.3%	596	15.1%	86
Heritage	Main & kitchen (not cellar)	50	11,016	21.6%	5,911	0.2%	3,047	15.3%	559	14.2%	86
	External Wall insulation										
Natural	Main & kitchen (not cellar)	100	10,225	27%	5,915	0.1%	3,804	19%	697	17.7%	86
Standard	Main & kitchen (not cellar)	100	10,191	27.5%	5,914	0.2%	3,869	19.4%	709	18%	86
Technical	Main & kitchen (not cellar)	120	10,581	24.7%	5,912	0.2%	3,481	17.4%	638	16.2%	86
	Solid floor insulation										
Natural	Living, kitchen & utility	300	14,035	0.1%	5,922	0.02%	17	0.09%	3.2	0.08%	45
Standard	Living, kitchen & utility	60	14,079	-0.2%	5,920	0.05%	-25	-0.1%	-4.4	-0.1%	45
Technical	Living, kitchen & utility	10	14,102	-0.4%	5,920	0.05%	-48	-0.2%	-8.6	-0.2%	45
	Suspended floor insulation										
Natural	Dining & hall	140	13,937	0.8%	5,914	0.2%	123	0.6%	23	0.6%	38
Standard	Dining & hall	140	13,933	0.8%	5,917	0.1%	124	0.6%	23	0.6%	38
Technical	Dining & hall	20	13,972	0.6%	5,920	0.05%	82	0.4%	15	0.4%	38
	Window Replacement										
Double wood	All windows	6,13, 6	13,810	1.7%	5,928	-0.1%	233	1.2%	42	1.1%	14
Double UPVC	All windows	6,13, 6	13,818	1.7%	5,931	-0.1%	225	1.1%	41	1%	14
Triple wood	All windows	3, 13, 2, 13, 3	13,591	3.3%	5,936	-0.2%	447	2.2%	81	2.1%	14
Triple UPVC	All windows	3, 13, 2, 13, 3	13,600	3.2%	5,937	-0.2%	437	2.2%	79	2%	14
	Window additions										
Curtains	All windows	Curtains	14,012	0.3%	5,917	0.1%	45	0.2%	8.5	0.2%	10
Shutters	All windows	Shutters	13,849	1.4%	5,922	0.02%	203	1%	37	0.9%	14
Secondary glazing	All single glazed	Secondary glazing	13,564	3.5%	5,926	-0.1%	384	2.4%	89	2.2%	14
	Heating systems and renewable technologies										
EE boiler	90% efficient	Gas Combi	13,898	1.1%	5,923	0%	153	0.8%	28	0.7%	N/A
Biomass boiler	87.3% efficient	Pellet boiler	14,061	-0.1%	5,923	0%	-315	-1.6%	2,305	58.5%	Totals include 305kWh of cooking gas
Solar PV	E roof 25º	21.2% efficiency	14,054	-0.02%	5,932	-0.2%	-12	-0.1%	-2.6	-0.1%	Electricity generation 2,880kWh
Solar PV	Covering 25% of on site electricity demand	720kWh used on site	14,054	-0.02%	5,212	12%	708	3.5%	164	4.2%	N/A
Solar thermal	E roof 25º	DHW only	11,322	19.4%	7,152	-20.7%	1,500	7.5%	216	5.5%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	305	97.8%	11,462	-93.5%	8,207	41.1%	1,238	31.4%	N/A
Air source heat pump	Radiators at 55ºC, and DHW	11.3kW peak heat	305	97.8%	13,646	-130.4%	6,023	30.2%	733	18.6%	Back up gas boiler to meet peak load
	Other retrofit measures										
LED bulbs	N/A										
Thick wall hangings	Living & dining room		13,883	1.2%	5,921	0.03%	170	0.9%	31	0.8%	Covers one wall in each room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	12,320	12.3%	5,909	0.2%	1,745	8.7%	320	8.1%	N/A
Draught proofing	Current 17 (m3/ h/m2 @ 50 Pa)	20% = 13.6	13,681	2.6%	5,916	0.1%	377	1.9%	69	1.8%	N/A
	Heating setting adjustments										
No bedroom heating	Heating in two beds turned off		12,660	9.9%	5,918	0.1%	1,396	7%	256	6.5%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5ºC	All set points reduced	0.5ºC	13,350	5%	5,920	0.1%	704	3.5%	129	3.3%	N/A
Reduce heating set point 1ºC	All set points reduced	1ºC	12,655	9.9%	5,921	0.03%	1,398	7%	256	6.5%	N/A
Reduce heating set point 1.5ºC	All set points reduced	1.5ºC	11,978	14.8%	5,915	0.1%	2,081	10.4%	382	9.7%	N/A
Reduce heating set point 2ºC	All set points reduced	2ºC	11,310	19.5%	5,916	0.1%	2,748	13.8%	504	11.8%	N/A

CS15 All measures

	Note	Thickness (mm)	Gas/Oil/wood/ heating demand (kWh)	Saving (%)	Electricity demand (kWh)	Saving (%)	Total energy saving (kWh)	Total energy saving (%)	Total carbon saving ($kgCO_2e$)	Total carbon saving (%)	Area (m2) or note
CS15 Baseline			12,638		3,107		15,745		3,033		
Loft insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Ceiling insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Internal Wall Insulation											
Natural	Main walls	50	8,486	32.9%	3,102	0.2%	4,157	26.4%	762	25.1%	105
Standard	Main walls	50	8,313	34.2%	3,101	0.2%	4,331	27.5%	794	26.2%	105
Technical	Main walls	20	8,404	33.5%	3,102	0.2%	4,239	26.9%	777	25.6%	105
External Wall insulation											
Natural	Main walls	100	7,768	38.5%	3,101	0.2%	4,876	31%	893	29.5%	105
Standard	Main walls	100	7,669	39.3%	3,101	0.2%	4,975	31.6%	912	30.1%	105
Technical	Main walls	120	8,201	35.1%	3,102	0.2%	4,442	28.2%	814	26.8%	105
Solid floor insulation											
Natural	N/A										
Standard	N/A										
Technical	N/A										
Suspended floor insulation											
Natural	Over cellar (all ground floor)	140	12,348	2.3%	3,107	0%	290	1.8%	53	1.8%	55
Standard	Over cellar (all ground floor)	140	12,341	2.4%	3,107	0%	297	1.9%	54	1.8%	55
Technical	Over cellar (all ground floor)	20	12,532	0.8%	3,107	0%	106	0.7%	19	0.6%	55
Window Replacement											
Double wood	All windows	6, 13, 6	12,328	2.5%	3,124	-0.5%	293	1.9%	53	1.7%	19
Double UPVC	All windows	6, 13, 6	12,341	2.4%	3,124	-0.5%	280	1.8%	50	1.7%	19
Triple wood	All windows	3, 13, 2, 13, 3	12,294	2.7%	3,145	-1.2%	306	1.9%	54	1.8%	19
Triple UPVC	All windows	3, 13, 2, 13, 3	12,297	2.7%	3,145	-1.2%	303	1.9%	54	1.8%	19
Window additions											
Curtains	All windows	Curtains	12,533	0.8%	3,108	-0.03%	104	0.7%	19	0.6%	16
Shutters	All windows	Shutters	12,426	1.7%	3,110	-0.1%	209	1.3%	38	1.3%	18
Secondary glazing	All single glazed	Secondary glazing	12,220	3.3%	3,115	-0.3%	410	2.6%	75	2.5%	19
Heating systems and renewable technologies											
EE boiler	N/A										
Biomass boiler	87.3% efficient	Pellet boiler	12,686	-0.4%	3,107	0%	-285	-1.8%	2,080	68.6%	237kWh of gas remains for cooking, included in totals
Solar PV	S roof 32°	21.2% efficiency	12,662	-0.2%	3,107	0%	-24	-0.2%	-4.4	-0.1%	Electricity generation 3,525kWh
Solar PV	Covering 25% of on site electricity demand	777kWh used on site	12,662	-0.2%	2,330	25%	753	4.8%	175	5.8%	N/A
Solar thermal	S roof 32°	DHW only	10,000	20.9%	4,168	-34.1%	1,577	10%	238	7.8%	N/A
Ground source heat pump	Underfloor and radiators, separate DHW	12.6kW peak heat	237	98.1%	9,536	-206.9%	5,972	37.9%	785	25.9%	N/A
Air source heat pump	Radiators at 55°C, and DHW	7.3kW peak heat	237	98.1%	10,725	-245.2%	4,783	30.4%	511	16.8%	Back up gas boiler to meet peak load
Other retrofit measures											
LED bulbs	13 CFL (all rooms)		12,947	-2.4%	2,453	21%	345	2.2%	95	3.1%	
Thick wall hangings	Living room		12,419	1.7%	3,107	0%	219	1.4%	40	1.3%	Covers one wall in room
Smart heating controls	Temperature set points adjusted	Based on TRV setting	10,658	15.7%	3,105	0.1%	1,982	12.6%	363	12%	
Draught proofing	Current 14 (m3/ h/m2 @ 50 Pa)	20% = 11.2	12,276	2.9%	3,107	0%	362	2.3%	66	2.2%	N/A
Heating setting adjustments											
No bedroom heating	Heating in all beds turned off		11,141	11.8%	3,106	0.03%	1,498	9.5%	274	9%	N/A
No holiday heating	N/A										
Reduce heating set point 0.5°C	All set points reduced	0.5°C	11,844	6.3%	3,106	0.03%	795	5%	146	4.8%	N/A
Reduce heating set point 1°C	All set points reduced	1°C	11,096	12.2%	3,105	0.1%	1,544	9.8%	283	9.3%	N/A
Reduce heating set point 1.5°C	All set points reduced	1.5°C	10,379	17.9%	3,104	0.1%	2,263	14.4%	415	13.7%	N/A
Reduce heating set point 2°C	All set points reduced	2°C	9,710	23.2%	3,103	0.2%	2,933	18.6%	537	17.7%	N/A

Appendix N) Retrofit Packages more details

Tables showing the measures included in each retrofit package for individual cases can be seen below. The deep colours show where multiple options within a category were possible, and the X shows which were chosen. For example, Package 1 (Policy) did not specify the type of insulation, so all types are coloured, but the standard insulation has been chosen (shown with an X).

Package 1: Policy

Retrofit measures	PP1 CS1	PP1 CS2	PP1 CS3	PP1 CS5	PP1 CS6	PP1 CS7	PP1 CS8	PP1 CS9	PP1 CS11	PP1 CS12	PP1 CS13	PP1 CS14	PP1 CS15
Loft insulation natural: Cosywool													
Loft ins standard: Supersoft	x												
Loft ins technical: Ultrawool													
Ceiling insulation natural: Gutex thermoflex													
Ceiling ins standard: Knauf rocksilk				x		x	x		x			x	
Ceiling ins technical: Aerogel													
Ceiling ins heritage: Diathonite													
IWI natural: Gutex thermoroom													
IWI standard: Knauf omnifit	x	x	x		x		x				x		x
IWI technical: Aerogel													
IWI heritage: Diathonite													
EWI natural: Gutex multitherm													
EWI standard: Knauf rocksilk				x		x			x			x	
EWI technical: Isohemp blocks													
Solid floor insulation natural: Geocell foamglass													
Solid Floor ins standard: Kingspan Kooltherm		x							x		x		
Solid Floor ins technical: aerogel bonded chipboard													
Suspended floor insulation natural: Thermofloc													
Suspended floor ins standard: Knauf omnifit	x												
Suspended floor ins technical: Aerogel bonded to chipboard													
Window replacement: Low E double glazed, hardwood frames, Munster Joinery													
Window R: Low E double glazed, UPVC frames Munster Joinery							x		x				
Window R:: Low E triple glazed, hardwood frames Munster Joinery													
Window R: Low E triple glazed, UPVC frames Munster Joinery													
Window additions: Curtains													
Window A: Interior shutters													
Window A: Secondary glazing													
EE lighting: LED bulbs	x												
Thick wall hangings													
EE bioler	x					x							
Biomass pellet boiler													
Solar PV: Maxeon 3 black							x						
Solar thermal: evacuated tubes									x				
GSHP: flat or borehole collector with underfloor heating													
ASHP: high temperature with radiators													
Smart heating controls: wifi controlled room thermostat													
Draught proofing							x		x				
Rd temperatures													
Bedroom heating													
Holiday heating													

Package 2: Operational

Retrofit measures	PO2 CS1	PO2 CS2	PO2 CS3	PO2 CS5	PO2 CS6	PO2 CS7	PO2 CS8	PO2 CS9	PO2 CS11	PO2 CS12	PO2 CS13	PO2 CS14	PO2 CS15
Loft insulation natural: Cosywool						x							
Loft ins standard: Supersoft													
Loft ins technical: Ultrawool	x	x	x	x	x		x	x			x	x	
Ceiling insulation natural: Gutex thermoflex							x	x	x				
Ceiling ins standard: Knauf rocksilk				x								x	
Ceiling ins technical: Aerogel													
Ceiling ins heritage: Diathonite													
IWI natural: Gutex thermoroom													
IWI standard: Knauf omnifit									x				
IWI technical: Aerogel													
IWI heritage: Diathonite													
EWI natural: Gutex multitherm													
EWI standard: Knauf rocksilk	x	x	x	x	x	x	x	x		x	x	x	x
EWI technical: Isohemp blocks													
Solid floor insulation natural: Geocell foamglass			x		x		x	x			x	x	
Solid Floor ins standard: Kingspan Kooltherm	x	x				x				x			
Solid Floor ins technical: aerogel bonded chipboard													
Suspended floor insulation natural: Thermofloc								x				x	
Suspended floor ins standard: Knauf omnifit					x		x						x
Suspended floor ins technical: Aerogel bonded to chipboard													
Window replacement: Low E double glazed, hardwood frames, Munster Joinery													
Window R: Low E double glazed, UPVC frames Munster Joinery													
Window R:: Low E triple glazed, hardwood frames Munster Joinery	x			x	x		x	x		x	x		
Window R: Low E triple glazed, UPVC frames Munster Joinery													
Window additions: Curtains													
Window A: Interior shutters						x							
Window A: Secondary glazing		x	x						x			x	x
EE lighting: LED bulbs	x		x	x	x	x	x	x	x		x		x
Thick wall hangings	x	x	x	x	x	x	x		x	x	x	x	x
EE bioler													
Biomass pellet boiler	x	x	x	x	x	x	x	x	x	x	x	x	x
Solar PV: Maxeon 3 black	x	x	x	x	x	x	x	x	x	x	x	x	x
Solar thermal: evacuated tubes													
GSHP: flat or borehole collector with underfloor heating													
ASHP: high temperature with radiators													
Smart heating controls: wifi controlled room thermostat	x		x	x	x	x	x	x		x	x	x	x
Draught proofing	x	x	x	x	x	x	x	x	x	x	x	x	x
Rd temperatures	x	x	x	x	x	x	x	x	x	x	x	x	x
Bedroom heating	x	x	x	x	x		x			x	x	x	x
Holiday heating	x	x					x	x					

Package 3: Lifecycle

Retrofit measures	PL3 CS1	PL3 CS2	PL3 CS3	PL3 CS5	PL3 CS6	PL3 CS7	PL3 CS8	PL3 CS9	PL3 CS11	PL3 CS12	PL3 CS13	PL3 CS14	PL3 CS15
Loft insulation natural: Cosywool				x		x	x					x	
Loft ins standard: Supersoft													
Loft ins technical: Ultrawool	x		x		x			x			x		
Ceiling insulation natural: Gutex thermoflex							x					x	
Ceiling ins standard: Knauf rocksilk				x									
Ceiling ins technical: Aerogel													
Ceiling ins heritage: Diathonite													
IWI natural: Gutex thermoroom													
IWI standard: Knauf omnifit													
IWI technical: Aerogel									x				
IWI heritage: Diathonite													
EWI natural: Gutex multitherm		x	x			x					x	x	x
EWI standard: Knauf rocksilk	x			x	x		x	x		x			
EWI technical: Isohemp blocks													
Solid floor insulation natural: Geocell foamglass	x												
Solid Floor ins standard: Kingspan Kooltherm					x	x	x	x		x	x		
Solid Floor ins technical: aerogel bonded chipboard													
Suspended floor insulation natural: Thermofloc					x							x	x
Suspended floor ins standard: Knauf omnifit							x	x					
Suspended floor ins technical: Aerogel bonded to chipboard													
Window replacement: Low E double glazed, hardwood frames, Munster Joinery													
Window R: Low E double glazed, UPVC frames Munster Joinery													
Window R:: Low E triple glazed, hardwood frames Munster Joinery	x				x		x	x		x	x		
Window R: Low E triple glazed, UPVC frames Munster Joinery													
Window additions: Curtains													
Window A: Interior shutters		x		x		x							
Window A: Secondary glazing			x									x	x
EE lighting: LED bulbs						x							
Thick wall hangings	x	x	x	x	x	x	x				x	x	x
EE bioler													
Biomass pellet boiler	x	x	x	x	x	x	x	x		x	x	x	x
Solar PV: Maxeon 3 black	x	x		x					x				
Solar thermal: evacuated tubes			x		x	x	x	x		x	x	x	x
GSHP: flat or borehole collector with underfloor heating													
ASHP: high temperature with radiators													
Smart heating controls: wifi controlled room thermostat	x		x	x	x	x	x	x		x	x	x	x
Draught proofing	x	x	x	x	x	x	x	x		x	x	x	x
Rd temperatures	x	x	x	x	x	x	x	x	x	x	x	x	x
Bedroom heating	x	x	x	x	x	x	x	x		x	x	x	x
Holiday heating	x	x					x	x					

Package 4: Acceptable

Retrofit measures	PA4 CS1	PA4 CS2	PA4 CS3	PA4 CS5	PA4 CS6	PA4 CS7	PA4 CS8	PA4 CS9	PA4 CS11	PA4 CS12	PA4 CS13	PA4 CS14	PA4 CS15
Loft insulation natural: Cosywool				x		x	x					x	
Loft ins standard: Supersoft													
Loft ins technical: Ultrawool	x		x		x			x			x		
Ceiling insulation natural: Gutex thermoflex				x			x					x	
Ceiling ins standard: Knauf rocksilk													
Ceiling ins technical: Aerogel													
Ceiling ins heritage: Diathonite													
IWI natural: Gutex thermoroom													
IWI standard: Knauf omnifit					x								
IWI technical: Aerogel													
IWI heritage: Diathonite													
EWI natural: Gutex multitherm													
EWI standard: Knauf rocksilk													
EWI technical: Isohemp blocks													
Solid floor insulation natural: Geocell foamglass													
Solid Floor ins standard: Kingspan Kooltherm		x	x							x	x		
Solid Floor ins technical: aerogel bonded chipboard													
Suspended floor insulation natural: Thermofloc							x	x				x	
Suspended floor ins standard: Knauf omnifit													
Suspended floor ins technical: Aerogel bonded to chipboard													
Window replacement: Low E double glazed, hardwood frames, Munster Joinery													
Window R: Low E double glazed, UPVC frames Munster Joinery													
Window R:: Low E triple glazed, hardwood frames Munster Joinery													
Window R: Low E triple glazed, UPVC frames Munster Joinery													
Window additions: Curtains			x		x	x							x
Window A: Interior shutters	x			x							x		
Window A: Secondary glazing		x					x	x	x	x			x
EE lighting: LED bulbs													
Thick wall hangings				x							x	x	
EE bioler	x					x							
Biomass pellet boiler													
Solar PV: Maxeon 3 black		x	x	x									
Solar thermal: evacuated tubes												x	
GSHP: flat or borehole collector with underfloor heating		x											
ASHP: high temperature with radiators													
Smart heating controls: wifi controlled room thermostat	x			x				x				x	x
Draught proofing	x	x	x	x		x	x	x	x		x	x	
Rd temperatures	x							x					
Bedroom heating													
Holiday heating													

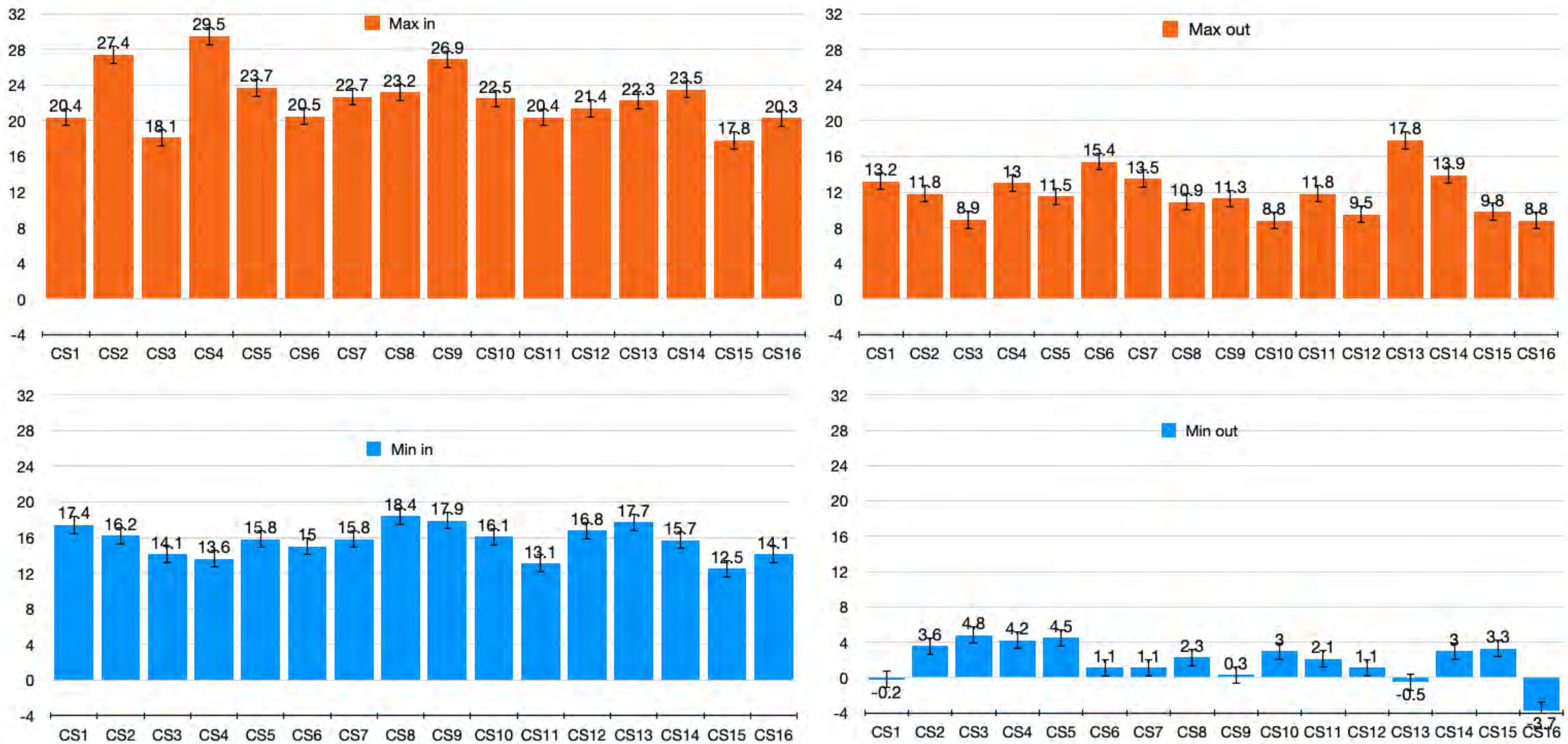
Package 5: Balanced

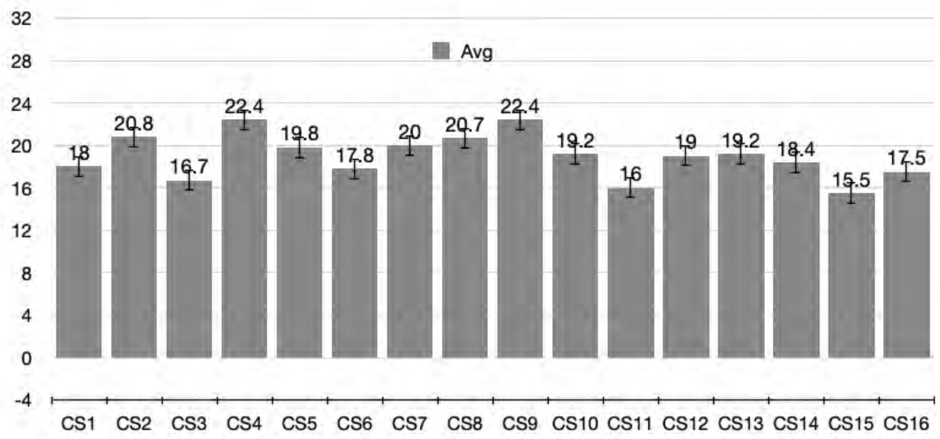
Retrofit measures	PC5 CS1	PC5 CS2	PC5 CS3	PC5 CS5	PC5 CS6	PC5 CS7	PC5 CS8	PC5 CS9	PC5 CS11	PC5 CS12	PC5 CS13	PC5 CS14	PC5 CS15
Loft insulation natural: Cosywool				X		X						X	
Loft ins standard: Supersoft													
Loft ins technical: Ultrawool	X		X		X			X			X		
Ceiling insulation natural: Gutex thermoflex				X			X					X	
Ceiling ins standard: Knauf rocksilk													
Ceiling ins technical: Aerogel													
Ceiling ins heritage: Diathonite													
IWI natural: Gutex thermoroom	X		X		X		X				X		X
IWI standard: Knauf omnifit													
IWI technical: Aerogel		X		X				X					
IWI heritage: Diathonite													
EWI natural: Gutex multitherm						X						X	
EWI standard: Knauf rocksilk													
EWI technical: Isohemp blocks													
Solid floor insulation natural: Geocell foamglass	X												
Solid Floor ins standard: Kingspan Kooltherm		X	X		X	X	X	X		X	X		
Solid Floor ins technical: aerogel bonded chipboard													
Suspended floor insulation natural: Thermofloc					X		X	X				X	X
Suspended floor ins standard: Knauf omnifit													
Suspended floor ins technical: Aerogel bonded to chipboard													
Window replacement: Low E double glazed, hardwood frames, Munster Joinery													
Window R: Low E double glazed, UPVC frames Munster Joinery													
Window R:: Low E triple glazed, hardwood frames Munster Joinery					X								
Window R: Low E triple glazed, UPVC frames Munster Joinery													
Window additions: Curtains						X	X	X					X
Window A: Interior shutters	X	X		X						X	X	X	
Window A: Secondary glazing			X				X	X					X
EE lighting: LED bulbs													
Thick wall hangings	X	X	X	X	X	X	X				X	X	X
EE bioler													
Biomass pellet boiler				X	X	X						X	
Solar PV: Maxeon 3 black				X					X				
Solar thermal: evacuated tubes	X		X		X	X				X	X	X	
GSHP: flat or borehole collector with underfloor heating		X	X							X			
ASHP: high temperature with radiators	X						X	X			X		X
Smart heating controls: wifi controlled room thermostat	X		X	X		X	X	X			X	X	X
Draught proofing	X	X	X	X	X	X	X	X		X	X	X	X
Rd temperatures	X	X	X	X	X	X	X	X	X	X	X	X	X
Bedroom heating	X	X	X	X	X		X			X	X	X	X
Holiday heating	X	X					X	X					

Appendix O) Summarised thermometer recordings for each diary period for each case study

The average maximum and minimum recorded values for inside and outside thermometers for each diary period for each case are shown. The average value takes the mean of the all the maximum and minimum recordings over each five-day period (average of 20 readings). Readings have error bars of +/-1°C as this was the accuracy level of the thermometers.

O.1) Winter readings




Avg
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24
20
16
12
8
4
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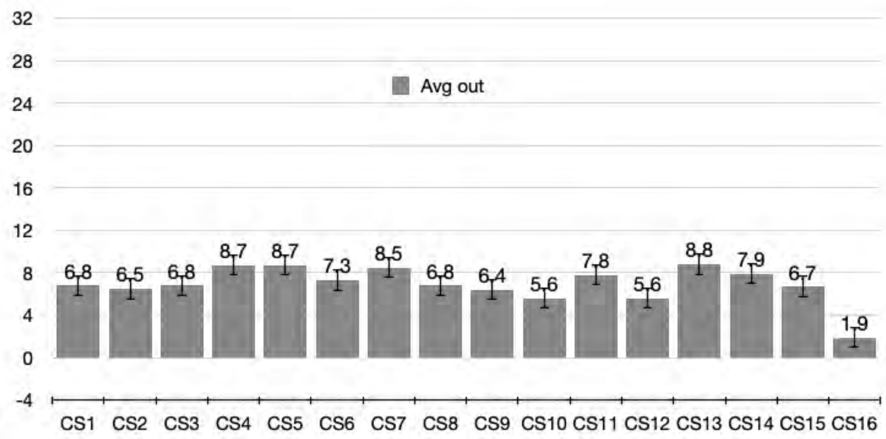
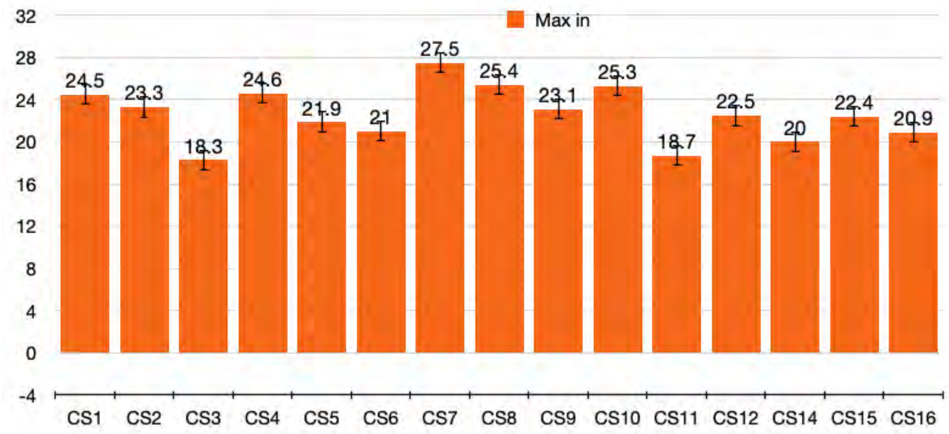
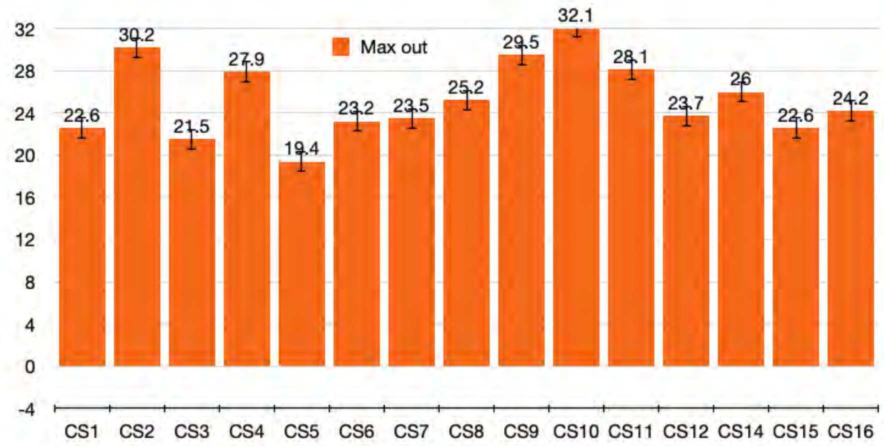
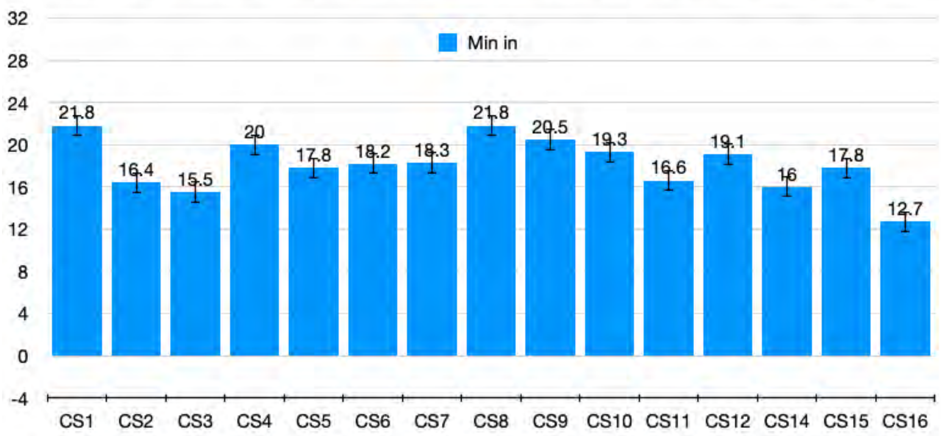
-4
18
20.8
16.7
22.4
19.8
17.8
20
20.7
22.4
19.2
16
19
19.2
18.4
15.5
17.5
CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8 CS9 CS10 CS11 CS12 CS13 CS14 CS15 CS16

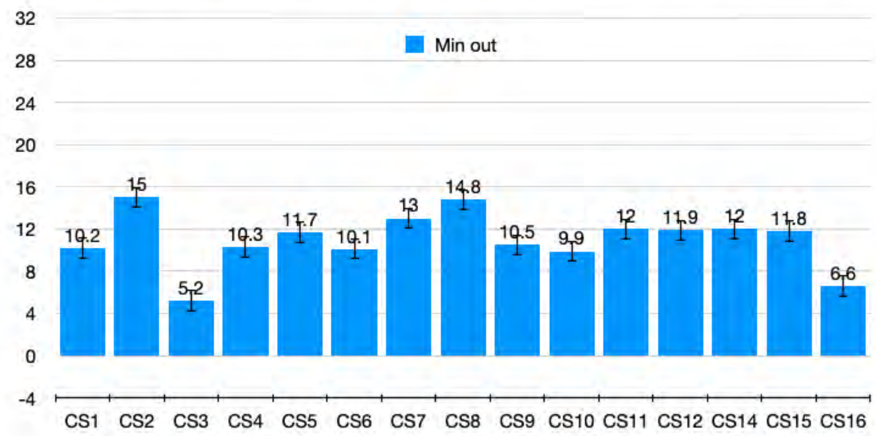

Avg out
32
28
24
20
16
12
8
4
0
-4
6.8
6.5
6.8
8.7
8.7
7.3
8.5
6.8
6.4
5.6
7.8
5.6
8.8
7.9
6.7
1.9
CS1 CS2 CS3 CS4 CS5 CS6 CS7 CS8 CS9 CS10 CS11 CS12 CS13 CS14 CS15 CS16

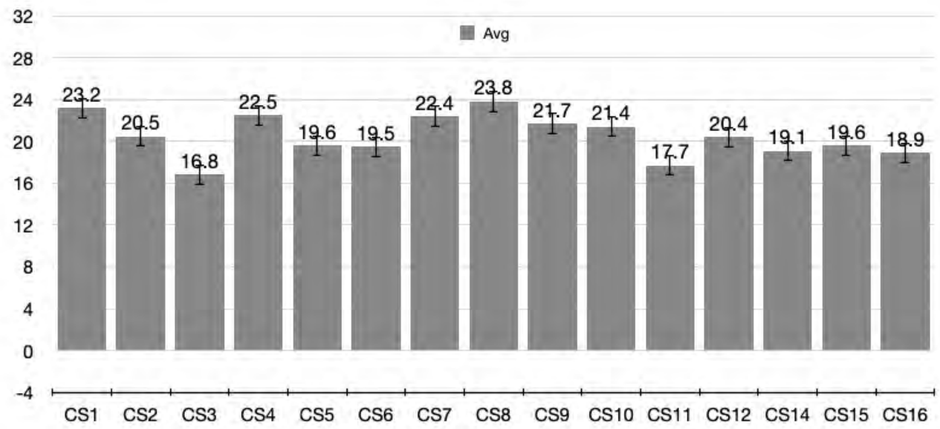
O.2) Summer readings










Avg
32
28
24
20
16
12
8
4
0
-4
23.2
20.5
16.8
22.5
19.6
19.5
22.4
23.8
21.7
21.4
17.7
20.4
19.1
19.6
18.9
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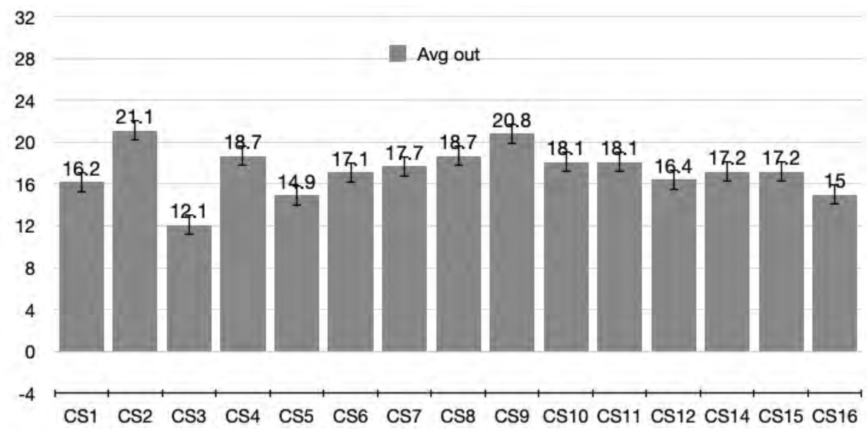
CS12
CS14
CS15
CS16


Avg out
32
28
24
20
16
12
8
4
0
-4
16.2
21.1
12.1
18.7
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17.1
17.7
18.7
20.8
18.1
18.1
16.4
17.2
17.2
15
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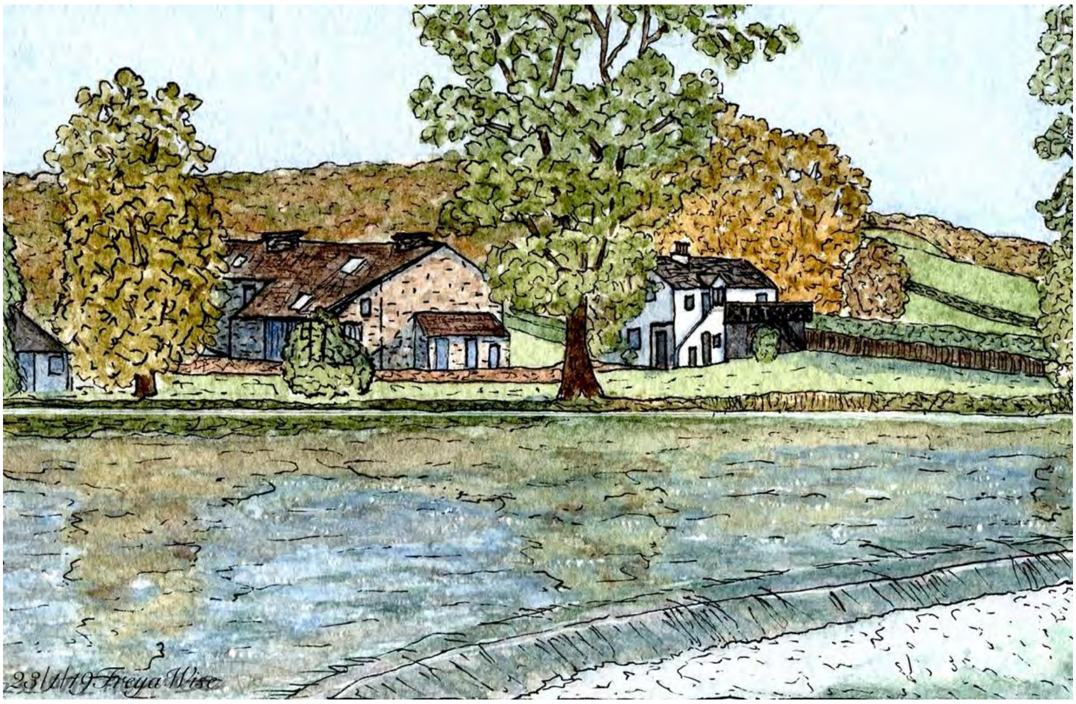
CS12
CS14
CS15
CS16



The End