BUILDINGS & CITIES

SPECIAL COLLECTION: RETROFITTING AT SCALE: ACCELERATING CAPABILITIES FOR DOMESTIC BUILDING STOCKS

RESEARCH

Rethinking retrofit of residential heritage buildings

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ABSTRACT

What are the opportunities and challenges for upscaling the energy retrofit of heritage buildings? Heritage buildings comprise approximately 20% of the UK building stock and are challenging to retrofit sensitively because of their heritage values and traditional construction. These buildings may therefore be unconducive to standard retrofitting approaches. Twelve case studies in the UK are examined. Three key findings are presented together with their implications for upscaling retrofit. First, heritage residents are found to engage in positive energy behaviours, which differ from standard assumptions and have a significant impact on energy demand. Second, standard energy models are shown to considerably overestimate the energy use within heritage buildings, failing to accurately portray both traditional construction and residents' behaviours. Third, residents consider many common retrofits, such as replacement windows and wall insulation, to be unacceptable to their heritage values. A number of more acceptable and less invasive 'soft retrofits' were modelled and shown to have significant potential for reducing energy and carbon. Therefore, a more holistic approach to heritage building retrofitting needs to be taken, treating the complex interrelationship of buildings and their users as a system, and expanding notions of retrofitting to include soft retrofits and user behaviour.

POLICY RELEVANCE

This research identified the importance of appropriately retrofitting heritage buildings, which include around 20% of the UK building stock. Standard solutions such as wall insulation and window replacement are unlikely to be enacted by most heritage residents because they are not acceptable to their heritage values, suggesting the need to prioritise other measures. Standard energy models such as Reduced data Standard Assessment Procedure (RdSAP) were found to be inaccurate for heritage buildings, overestimating energy use by both buildings and occupants, and should not be used to inform retrofit decisions for these buildings. Notions of retrofit should be expanded beyond fabric

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KEYWORDS:
carbon; energy; heritage buildings; residential; retrofit; traditional buildings; user behaviour

TO CITE THIS ARTICLE:
Wise, F., Moncaster, A., & Jones, D. (2021). Rethinking retrofit of residential heritage buildings. *Buildings and Cities*, 2(1), pp. 495–517. DOI: *https://doi.org/10.5334/bc.94*

alterations to include behavioural changes and non-technical measures, including thermal curtains or shutters, which are more acceptable to residents and therefore more likely to be actioned. The potential exists to upscale retrofitting in heritage buildings, but approaches must consider specific user behaviour and view buildings and their occupants as interconnected systems.

1. INTRODUCTION

The built environment is a major source of energy use and resultant carbon emissions. It has long been accepted that these emissions must be urgently reduced to achieve carbon-reduction goals and help mitigate climate change (GABC *et al.* 2019). In Europe, the rate of building stock replacement is around 1% per year (Almeida *et al.* 2018); retrofitting existing buildings must therefore be a key strategy in achieving these aims, and is becoming an area of increasing policy focus (Economidou *et al.* 2020; Piddington *et al.* 2020).

This paper considers the specific case of heritage buildings, focusing on the UK but with applicability across Europe. Mazzarella (2015) defines heritage buildings as being based on building age, designation in planning regulations or specific features. The UK has some of the oldest building stock in Europe, with 5.9 million buildings (20.6%) built before 1919 and a further 4.3 million before 1944 (Piddington *et al.* 2020). National designations identify 1–2% of buildings via the individual 'listed building' system, while many areas and groups of buildings are designated as conservation areas, World Heritage Sites or National Parks (Cadw 2018; Historic England 2019; Historic Environment Scotland 2019). In addition, many undesignated older buildings are acknowledged to have important historic, aesthetic and communal values, which help to shape the character of urban and rural areas (Cadw 2011; Herrera-Avellanosa *et al.* 2019). In all, around 20–30% of UK domestic buildings are likely to have some form of heritage value (Pickles & McCaig 2017).

Heritage buildings are of particular concern for retrofit programmes. For designated heritage buildings, the types of retrofit that are allowed are usually limited by planning policy. For undesignated older buildings, residents' own perceptions of heritage value are often neglected by policy interpretations (Fouseki & Cassar 2014; Mısırlısoy & Günçe 2016), yet if residents feel that a retrofit measure will reduce the heritage values they invest in their building, they are unlikely to enact it (Haines & Mitchell 2014; Mallaband *et al.* 2013; Nicol *et al.* 2015; Sunikka-Blank & Galvin 2016) This paper therefore uses residents' own definition to determine heritage value as this is found to be a key determinant for retrofit acceptability in owner-occupied homes (Wise *et al.* 2021).

There are also a number of technical challenges for retrofitting these buildings. First, their traditional, often regionally specific and generally moisture-permeable construction affects the types of retrofits that may be suitable (Herrera-Avellanosa *et al.* 2019; May & Rye 2012). Second, and as with all buildings, the carbon-reduction potential of retrofits is contingent upon current energy use and therefore on occupant energy behaviours (Ben & Steemers 2014). Research in different countries has shown that the energy behaviours of heritage building residents may differ to that of residents in newer buildings and therefore to that assumed in models (Henry 2007; Li *et al.* 2012; Pili 2017), although this area is still poorly understood (Fouseki & Cassar 2014).

Finally, standard building energy models used to inform retrofit (BRE & DECC 2014) poorly represent the construction of many heritage buildings, leading to maladaptation risks (Ingram & Jenkins 2013; Pickles & Cattini 2015), and also ignore specific user behaviour (Kane *et al.* 2015; Majcen *et al.* 2013). These models therefore commonly give overestimations of current energy use in heritage buildings, which could lead to recommendations of retrofit measures which are potentially damaging to heritage with little or no actual carbon benefits (Pracchi 2014).

These challenges are likely to result in standard retrofit approaches being recommended that may not be suitable or acceptable for implementation in heritage buildings and therefore fail to achieve carbon-reduction goals. Retrofitting programmes must therefore start considering alternative approaches to retrofitting this significant proportion of the building stock, starting with a better understanding of these complex and interlinked issues.

This paper adds to this understanding. It uses twelve heritage building case studies to examine the energy behaviours of residents, compare actual energy use with results for standard modelling, and explore the potential of a wider range of 'soft' retrofits and behavioural measures which are identified as acceptable by residents.

2. BACKGROUND

'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 theoretically provides a broad scope; however, in reality retrofitting discourses often focus on changes to the building fabric or technologies (Gram-Hanssen *et al.* 2018; Mazzarella 2015), such as additional insulation or new building heating systems (Fisk *et al.* 2020). Decisions are generally informed by building energy simulation models (Kane *et al.* 2015). Across Europe these models are used to produce Energy Performance Certificates (EPCs) (European Union 2018). EPCs are designed to encourage energy-efficiency improvements to the building stock, and to identify potential savings from particular retrofit measures (BEIS 2020a); however, their effectiveness in developing practices of retrofitting has been questioned in many countries (Bartiaux *et al.* 2014).

The UK modelling tool for producing EPCs for existing buildings is the Reduced data Standard Assessment Procedure (RdSAP) (DCLG 2017). EPCs derived from RdSAP often inform government funded retrofit programmes, such as the Green Deal, the Energy Company Obligation and the 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, as shown in large studies of the German and Dutch building stocks (Galvin 2010; Majcen *et al.* 2013). For heritage buildings these models often fail to accurately portray either residents' energy behaviours (Berg *et al.* 2017) or the performance of traditional materials and construction (Galvin & Sunikka-Blank 2016; Ingram & Jenkins 2013; Pickles & Cattini 2015). A study of the German building stock found that lower rated (mainly older) buildings consumed up to 40% less energy than modelled, while higher rated buildings used more (Sunikka-Blank & Galvin 2012), and this has been echoed in studies of other countries (Gram-Hanssen *et al.* 2018; Majcen *et al.* 2013).

For effective energy and carbon reduction from retrofitting, clearly the pre-retrofit energy use must be understood (Kohler & Hassler 2012). As eloquently stated by Gram-Hanssen (2014: 396):

> Homes do not consume energy; people in homes with different types of practices and different technologies consume energy.

Energy behaviours in heritage buildings have been shown to differ in some contexts to those in modern buildings (Li *et al.* 2012; Pili 2017) and often 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 (Curtis 2010; Henry 2007; Pender & Lemieux 2020). Non-permanent fittings can improve occupant comfort and reduce heat loss, thereby reducing energy and carbon (Curtis 2010; Humphreys *et al.* 2011; Khan 2018). Traditional window additions, such as shutters, thermal curtains and secondary glazing, can reduce heat loss by a comparable amount to replacing single-glazing with modern double-glazing (Wood *et al.* 2009), while spot heating can reduce the need to heat the whole building (Aste *et al.* 2016; Pan *et al.* 2018), emphasising the need to keep people, rather than buildings, warm (Humphreys *et al.* 2011). Personal insulation has been found to be one of the most effective ways to improve thermal comfort (Shove 2018), and tentative findings suggest higher winter clothing levels may be linked to the age of buildings, as well as more likely in households with higher education levels (Hansen *et al.* 2018).

Various studies have shown that, not just in heritage buildings but more broadly, residents often negotiate creative and informal comfort practices specific to their own circumstances and contexts, although these frequently pass under the radar of policymakers (Hampton 2017; Hansen *et al.*

2018). This is particularly found in buildings considered to be less energy efficient, and while this may sometimes be as a result of fuel poverty, it is acknowledged that these practices are in many cases conscious choice, related to a sense of sufficiency and frugality (Galvin & Sunikka-Blank 2016; Royston 2014), especially in older buildings (Hansen *et al.* 2018; Madsen 2018).

Overall, these behaviour variations and soft retrofits can have a greater impact on energy reduction than physical retrofits (Ben & Steemers 2014; Berg & Fuglseth 2018; Harrestrup & Svendsen 2015). They are also less likely to negatively affect heritage values compared with more significant fabric alterations, in some cases even creating heritage enhancement (Pender & Lemieux 2020), and are likely to have much lower financial costs (Fouseki & Cassar 2014). The need to support such positive user interactions with their buildings and systems has been highlighted (Gram-Hanssen 2014; Gram-Hanssen *et al.* 2018). However such aspects are rarely considered by models, or as being within the remit of retrofit measures, for either heritage or non-heritage buildings (Berg *et al.* 2017; Gram-Hanssen *et al.* 2018; Kohler & Hassler 2012), and are therefore a significant contributor to the performance gap between actual and modelled savings from retrofit interventions (Galvin & Sunikka-Blank 2016; Jain *et al.* 2020).

A further contributor to this performance gap is known as the 'rebound effect' in which better energy efficiency post-retrofit leads to heating the building to a higher temperature (Galvin 2015). Studies of direct rebound effects for home retrofitting in the UK have found rebounds between 0% and 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, often related to fuel poverty (Sorrell *et al.* 2009). Where residents are satisfied with comfort levels there is still considered to be a potential rebound effect of around 20% (Aydin *et al.* 2017; Giraudet *et al.* 2021).

The inaccurate modelling of energy use also has implications for the reduction of life-cycle carbon (Pracchi 2014). For a retrofit project this includes the 'embodied carbon' costs of manufacturing, transporting, installing, maintaining and finally disposing of any measures, as well as the 'operational carbon' savings from any resultant reduction in energy used in the building. Embodied carbon is currently excluded from standard models, and rarely considered in retrofit projects (Wise *et al.* 2019). If operational energy use is lower than that modelled to start with, retrofit measures will fail to produce the predicted savings; furthermore, if these savings are less than the embodied carbon costs, the life-cycle carbon will actually be increased (Asdrubali *et al.* 2019; Iyer-Raniga & Wong 2012). The non-permanent and behavioural changes described above also often have much lower embodied carbon costs (Iyer-Raniga & Wong 2012), making it much more likely that the whole-life impacts will be reduced. Understanding current energy behaviours in heritage buildings, and their potentially significant impact on energy use, is therefore critical (Morgan 2019).

It is also important to understand what measures are likely to be acceptable to heritage building owners and residents, as these are those most likely to be implemented (Wise *et al.* 2021). Heritage value is usually seen as that defined by planning designations (Harrestrup & Svendsen 2015; Zagorskas *et al.* 2014), which tend to have been decided in a top-down manner (Eriksson 2018; Tweed & Sutherland 2007). Residents' heritage values meanwhile are often specific to their own individual buildings (Herrera-Avellanosa *et al.* 2019), and rarely receive detailed consideration in either the literature (Lidelöw *et al.* 2019) or planning decisions. However, even in undesignated older buildings, residents' retrofit decisions are strongly influenced by their specific heritage values (Sunikka-Blank & Galvin 2016). Therefore, recommended standard retrofit solutions are unlikely to be acceptable to some residents of such buildings.

3. METHODS

Twelve case studies of residential heritage buildings in Cumbria (north-west England) were developed (***Table 1***). Each case included site visits, interviews, energy modelling and energy diaries (***Figure 1***). Cumbria is a predominantly rural and mountainous upland area, including the Lake District National Park, recently inscribed as a cultural landscape World Heritage Site (LDNPA 2020).

CASE STUDY	LOCATION	BUILDING AGE AND DESIGNATION	DESCRIPTION	HEATING SYSTEM	HOUSEHOLD
CS1	Hamlet, Eden	1820s with earlier elements Grade II Listed. Semi-detached	Georgian squire's house	Oil central heating	Two adults, retired
CS2	Rural, Lake District	1740s. Grade II* Listed curtilage. Detached	Miller's cottage	Storage heaters with hydropower	Two adults, working
CS3	Town, Eden	1928. Conservation area. Semi-detached	Stately home in miniature	Gas central heating	Two adults, working. Three at university
CS5	Village, South Lakeland	1897 with earlier elements. Undesignated. Detached	Late Victorian house, former chapel	Gas central heating	Two adults retired
CS6	Village, Carlisle	Early 1700s with a Victorian extension. Conservation area. Detached	Large, detached former farmhouse	Gas central heating	Two adults, semi-retired
CS7	Hamlet, South Lakeland	1789. Undesignated. Detached	Large Georgian farmhouse	Oil central heating	Two adults, semi-retired
CS8	Town, South Lakeland	1871. Conservation area. Mid-terrace	Four-storey Victorian townhouse	Gas central heating	Two adults, retired
CS9	Large village, Lake District	1896. Conservation area. Mid-terrace	Small late Victorian house	Gas central heating	Two adults, working
CS11	Hamlet, Lake District	1760s. Undesignated. Mid-terrace	Small cottage	Wood stove in living room	One adult, working
CS13	Coastal town, Allerdale	1834. Grade II listed. Semi-detached	Georgian, former courthouse	Gas central heating	Two adults, working
CS14	Rural Allerdale	1770s. Undesignated. Semi-detached	Georgian farmhouse	Gas central heating	Two adults, working. Two children under 10 years of age
CS15	Small town, South Lakeland	1850s, Conservation area. Semi-detached	Victorian town house	Gas central heating	One adult, retired

Table 1 Case study details.

Note: Case study numbers are not sequential because CS4, CS10 and CS12 were postponed due to the Covid-19 pandemic.

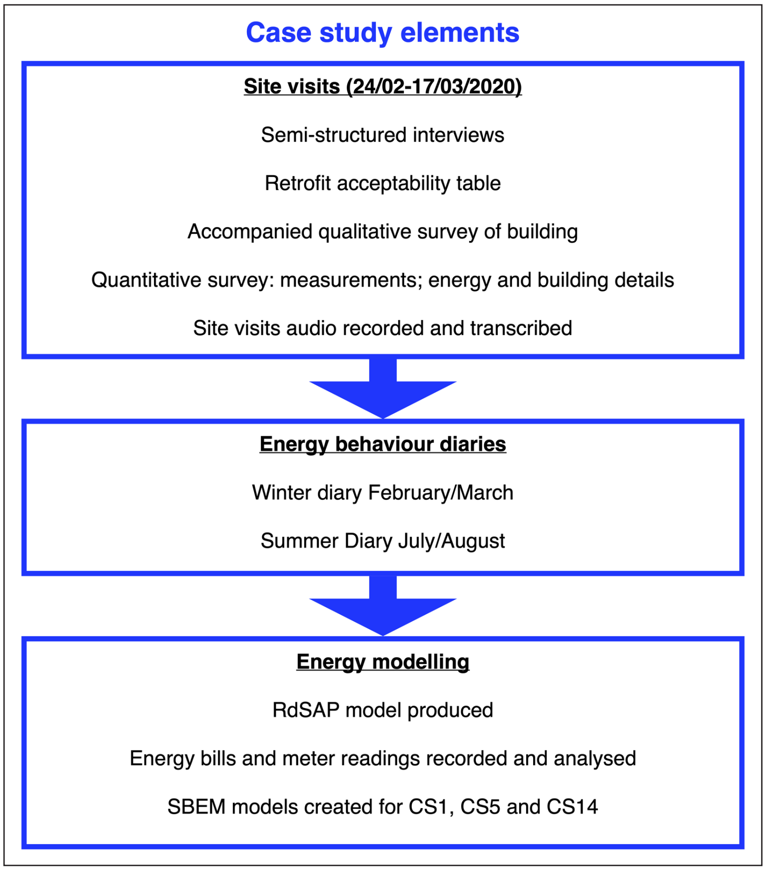


Figure 1: Details of the case study elements.

Case study participants were recruited from participants to a previous survey of pre-1940 Cumbrian buildings (Wise *et al.* 2021). A sufficient number of participants was selected to ensure that a diverse range of building types, ages, locations, household compositions and energy usage were included, and therefore follows principles of maximum variation selection (Flyvbjerg 2006). Findings from the cases did not contradict findings from the previous wider survey, suggesting that they are reasonably representative of wider Cumbrian heritage buildings. These cases are not, however, representative of the wider UK heritage building stock since most of the case study residents are relatively affluent, there is a lack of households with young children, and a lack of urban and brick buildings. However, it is considered that the rich data can still provide lessons applicable to a wide range of heritage buildings in both UK and international contexts.

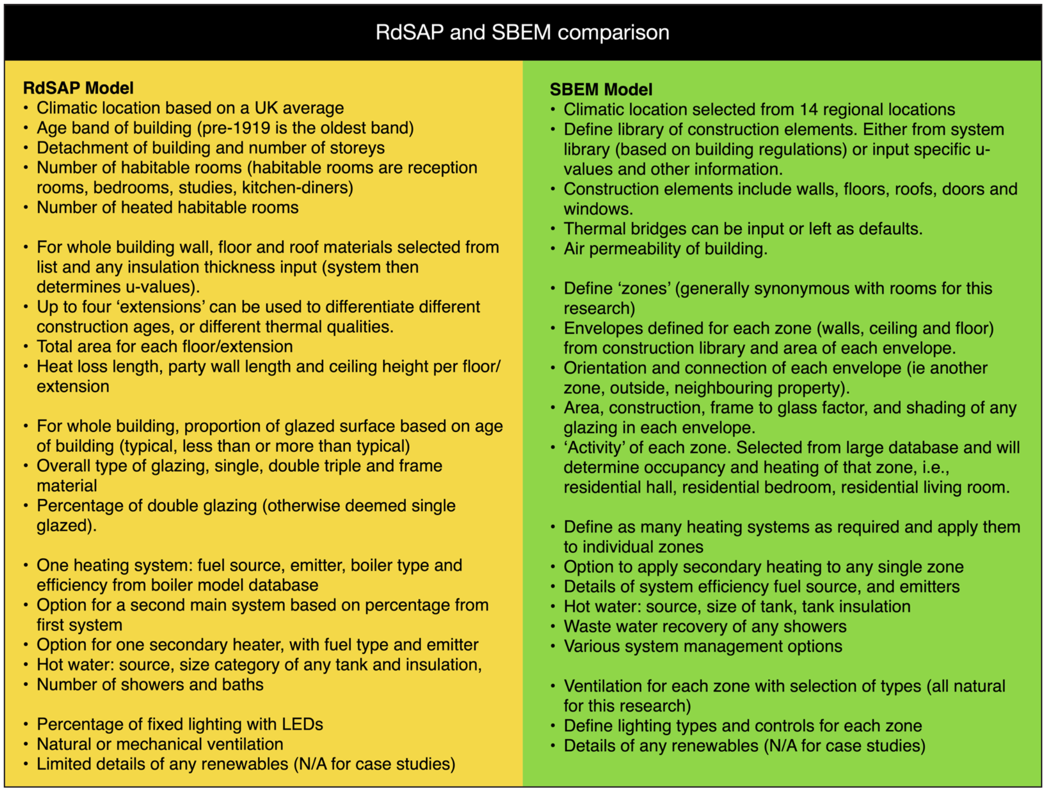
A site visit was made to each building. This included a semi-structured interview covering: the building's history; residents' attitudes to heritage retention and carbon reduction; energy behaviours; and carbon-reduction barriers. Interviews were generally with one household member, although other residents added occasional comments; interviews with CS1, CS2 and CS7 involved both household members for the full interview. Participants also completed tables on the acceptability of various retrofit measures, identifying key barriers, and provided the researcher with energy bills and/or meter readings. Participants then led the researcher on a 'walk though' of their building, identifying both energy systems and heritage features that they valued.

A survey of the building was also completed during the site visit, including building measurements and construction and energy details in order to create energy models for each building using RdSAP, the approved UK EPC tool for existing domestic buildings (DCLG 2017).

In order to undertake RdSAP models, certification as a domestic energy assessor was completed to develop methodological competence, and the certified method was followed to create models comparable with those commonly used (DCLG 2017; Quidos 2020). Eight of the cases regularly use secondary heating such as wood or multifuel stoves. Of these, four (CS1, CS7, CS11 and CS13) knew how much fuel they used; this amount was converted into kilowatt-hour equivalents and included in actual energy totals (see Appendix C in the supplemental data online). For consistency no secondary heating was modelled in RdSAP for the four cases who did not know how much secondary fuel they used, meaning that the secondary heating for CS2, CS5, CS9 and CS14 is not included in either actual or modelled energy totals.

Two energy-behaviour diaries were also completed by each household, one in February–March and the second in July–August, to give typical behaviour in both winter and summer. Each diary was completed over five days, covering a weekend and three weekdays, and involved listing thrice daily: activities; location in the building; clothing levels; and any heating, lighting or ventilation used. Delays resulting from the Covid-19 pandemic means that research is still ongoing and CS3, CS13 and CS15 have yet to return their energy diaries.

For three of the buildings (CS1, CS5 and CS14) more detailed models using the Simplified Building Energy Model (SBEM) were created (BRE 2020). SBEM is intended to produce EPCs for non-domestic buildings but is significantly more detailed than RdSAP (***Figure 2***). These SBEM models were used to assess energy and carbon savings for several retrofit options, detailed in ***Table 2***. Time constraints only allowed detailed modelling for a subset of the cases. CS1, CS5 and CS14 were chosen as they represent a good range of the different buildings and household characteristics covered by the broader case study sample, including different building types, sizes, heating systems, heritage designations, household sizes and heating behaviours (***Table 1***). In line with the wider literature, a rebound effect of 20% was applied to the packages of potential savings identified in SBEM modelling.



RdSAP and SBEM comparison

RdSAP Model	SBEM Model
• Climatic location based on a UK average • Age band of building (pre-1919 is the oldest band) • Detachment of building and number of storeys • Number of habitable rooms (habitable rooms are reception rooms, bedrooms, studies, kitchen-diners) • Number of heated habitable rooms	• Climatic location selected from 14 regional locations • Define library of construction elements. Either from system library (based on building regulations) or input specific u-values and other information. • Construction elements include walls, floors, roofs, doors and windows. • Thermal bridges can be input or left as defaults. • Air permeability of building.
• For whole building wall, floor and roof materials selected from list and any insulation thickness input (system then determines u-values). • Up to four 'extensions' can be used to differentiate different construction ages, or different thermal qualities. • Total area for each floor/extension • Heat loss length, party wall length and ceiling height per floor/ extension	• Define 'zones' (generally synonymous with rooms for this research) • Envelopes defined for each zone (walls, ceiling and floor) from construction library and area of each envelope. • Orientation and connection of each envelope (ie another zone, outside, neighbouring property). • Area, construction, frame to glass factor, and shading of any glazing in each envelope. • 'Activity' of each zone. Selected from large database and will determine occupancy and heating of that zone, i.e., residential hall, residential bedroom, residential living room.
• For whole building, proportion of glazed surface based on age of building (typical, less than or more than typical) • Overall type of glazing, single, double triple and frame material • Percentage of double glazing (otherwise deemed single glazed).	
• One heating system: fuel source, emitter, boiler type and efficiency from boiler model database • Option for a second main system based on percentage from first system • Option for one secondary heater, with fuel type and emitter • Hot water: source, size category of any tank and insulation, • Number of showers and baths	• Define as many heating systems as required and apply them to individual zones • Option to apply secondary heating to any single zone • Details of system efficiency fuel source, and emitters • Hot water: source, size of tank, tank insulation • Waste water recovery of any showers • Various system management options
• Percentage of fixed lighting with LEDs • Natural or mechanical ventilation • Limited details of any renewables (N/A for case studies)	• Ventilation for each zone with selection of types (all natural for this research) • Define lighting types and controls for each zone • Details of any renewables (N/A for case studies)

Figure 2: Comparison of Reduced data Standard Assessment Procedure (RdSAP) with Simplified Building Energy Model (SBEM).

DESCRIPTION OF MEASURE	VARIATIONS
Baseline	See Appendix A for baseline models and Appendix B for retrofit assumptions in the supplemental data online
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 10 mm aerogel blanket	
Double-glazing for all windows to current building regulations	
Replace the old boiler with an efficient modern one	Modelled for CS1, who only have an old, inefficient boiler. CS5 and CS14 already have efficient modern boilers
Additional loft insulation	CS1 currently have 100 mm and CS5 and CS14 150 mm; these were increased to 250 mm in all cases
Combination of measures: interior shutters to all windows; floor insulation; wall hangings; door retrofitted; additional loft insulation; and air infiltration improvement	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

Table 2 Details of retrofits modelled in the Simplified Building Energy Model (SBEM).

4. RESULTS

4.1 ENERGY BEHAVIOURS OF HERITAGE BUILDING RESIDENTS

The majority of participants reported engaging in a range of positive energy behaviours and making energy-efficient choices around lighting and appliances (***Figure 3***).

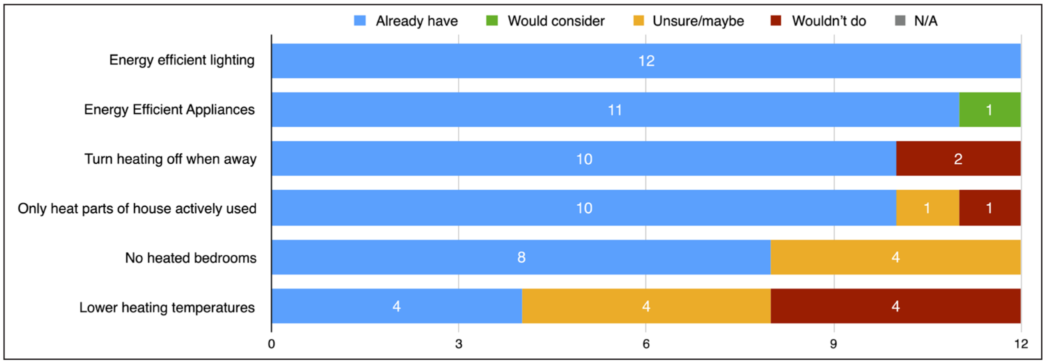


Figure 3: Energy behaviours from the retrofit matrix.

A third of participants felt they heated their building to below-average temperatures, and several identified that although they were comfortable with household temperatures, others might find conditions cool. This is strongly indicative of adaptive comfort strategies (Carlucci *et al.* 2018; Nicol & Humphreys 1973).

> CS1: We use very little central heating really do we?
>
> No, I think that people who like to live at 25°C wouldn't like it here but [...]!
>
> CS5: Our visitors complain but we find it fine.
>
> CS6: Normally the heating would not be on at this time. It's when we realised that the decorators are starting to wear overcoats! That it might be a bit cold for them!

It was also noticeable, however, that two-thirds of participants would rather not reduce their heating temperatures because they found conditions comfortable. One participant (CS9) felt they might be willing to reduce temperatures if the evidence for carbon savings supported it.

Two-thirds of participants generally do not heat their bedrooms, stating that they like a cool room to sleep in or enjoy having the windows open for fresh air. Instead of room heating, several use limited spot heating to keep warm:

> CS11: A piece of shocking decadence, I have an electric blanket. [...] I warm my bed up with that! It's highly efficient 50 Watts, something like that? It's tiny, and that's when it's on [...] in a cold bedroom, yes, it's good.
>
> 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.

The use of spot heating is a strong theme, with most participants regularly using alternative heating to their main systems, for better control or only to heat spaces they are occupying. These systems are generally either used by those who work from home or in the evenings to heat living spaces.

> CS7: I've got an electric heater in my study so if I'm in the house on my own the central heating goes off during the day.
>
> CS9: B just usually heats his office during the day.
>
> CS14: We would usually be in the living room, that usually means that either the fire is on or a blanket is on, sometimes both for the snuggle, we like a blanket.

Some participants highlighted that items such as wood-burning stoves had a psychological impact in addition to providing thermal comfort.

> CS5: Because the radiator was sized, deliberately undersized cos, you know, we knew we had the stove, so why duplicate? And maybe that was a mistake because you have to light the stove to be adequately warm in winter, but we like to have it because it's a nice focal point.

> CS11: But its [the stove] got a lot more character than. [...] I haven't got a television and there's nothing on television I want to look at really.

The use of these types of spot heating and not heating all rooms in the house can have energy-reduction benefits. Turning the heating off when away was practiced by most participants (***Figure 3***), although three used 'away settings' for insurance purposes and to keep their cats warm. The two (CS1 and CS2) who kept their heating on cited the amount of time it took to warm up on their return as a barrier.

> CS1: The house becomes really cold and it [...].
> It takes days.
> Yes, or even weeks, to get back up to temperature and dry again.

Completed winter energy diaries showed that participants had varied winter heating regimes and occupancy schedules (***Table 3***). However, most participants spent significant time at home, being either retired or working at least partially from home. This reflects pre-pandemic homeworking and is representative for Cumbria, which has a high percentage of homeworking and retiree households (CLEP 2019).

CASE STUDY	DAILY HEATING SETTINGS	OCCUPATION
CS1	18°C in hall continuous	Mostly in, retired
CS2	11 h at 21°C downstairs and 18°C upstairs	Mostly in, both WFH
CS5	Twice daily 19°C	Mostly in, retired
CS6	Twice daily 18°C	Often out, semi-retired
CS7	11 h at 21°C, 13 h at 10°C	Mostly in, retired and WFH
CS8	Overnight 17°C, daytime 18°C, evening 19.5°C	Mostly in, retired
CS9	Various, higher morning and evening	One WFH, one out for work
CS11	Wood stove 5–6 h every evening.	Mix of WFH and external work
CS14	40 min in morning, 2.5 h in evening at 19°C	Mix of WFH and external work

Table 3 Winter heating regimes and occupancy.

Note: WFH = work from home.

Only three participants (CS1, CS14 and CS9) used central heating in summer, although other participants occasionally used stoves or room heaters. CS1 and CS14 have challenges with moisture in their buildings: CS1 has no damp proof course and is situated on a site suffering from hydrostatic head causing rising damp. CS14 has a stream running through their cellar and previously had challenges with a leaking chimney; this has now been fixed but the building is still drying out. CS14's damp challenges are exacerbated as their building has been previously rendered with non-breathable cement, an example of maladaptation to traditional construction. CS9 have their sitting room in a semi-basement, and report legacy damp issues from when the basement was previously derelict, in addition to a high water table. CS1 prevents damp with continuous low-level heating, whilst CS14 and CS9 manage moisture with ventilation and short twice-daily heating periods.

During the summer diary most participants were spending more time at home than normal as a result of the pandemic, but even so many felt this had not had much effect on energy use.

The energy diaries also requested participants' clothing levels three times a day. ***Figure 4*** shows that participants generally wear slippers and jumpers in their houses; there is seasonal variation in some, but not all, households.

Energy diary data are also supported by participant comments and researcher observation during site visits.

> 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.

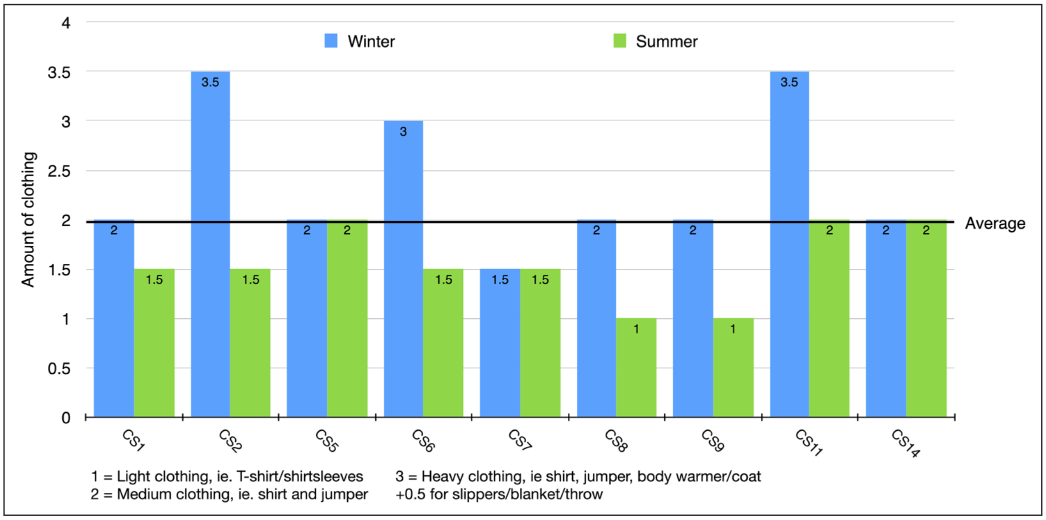


Figure 4: Level of clothing.

> CS14: 'I will wear a jumper with a cardigan over the top. [...] The heating goes off when the kids go to bed, that's our timer [...] we'll put another jumper on and maybe light the stove'.

Nearly all participants expressed satisfaction with comfort in their buildings during the site visits, supporting previous survey findings about comfort satisfaction in Cumbrian heritage buildings (Wise *et al.* 2021). Only CS2 (who have recently moved) were dissatisfied, finding their storage heaters ineffective for maintaining comfortable conditions. Although several participants desired their buildings to use less energy or have fewer draughts, they did not find them uncomfortable to inhabit or want them to be generally warmer. Some participants also linked their comfort to the building's heritage nature, suggesting they were more willing to overlook potential comfort challenges because of the building's character.

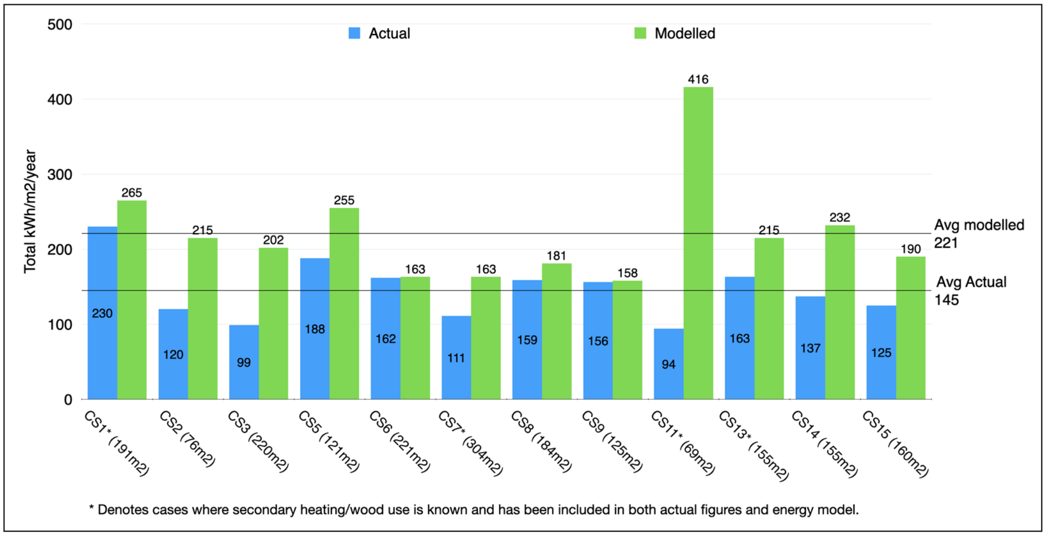
> CS11: You can get a bit of warmth from the character in a way.
>
> CS14: [Y]ou get used to it, [managing moisture] and it's part of the character of the house in the end, but to anyone who lives in a modern house and doesn't like this kind of thing, would think you were insane.

Participant behaviours in the heritage building case studies have therefore been identified as often only heating occupied spaces, and using personal and spot heating and personal insulation, with a general satisfaction with the resultant comfort levels.

4.2 MODELS VERSUS REALITY

RdSAP results were compared with actual energy data (***Figure 5***). The model consistently overestimated energy use in the case study buildings, compared with actual energy use derived from energy bills and meter readings.

The only two case studies where this is less evident are CS6 and CS9. As identified above, CS9 heats their house all year round. Additionally, both CS6 and CS9 have large modern extensions and research has shown that energy use is often underestimated in modern construction (Majcen *et al.* 2013; Sunikka-Blank & Galvin 2012), potentially contributing in these two houses to a modelled value closer to reality. In contrast, CS11 is a committed environmentalist who only uses minimal energy to heat a single room with a wood-burning stove in the evening, so it is unsurprising that the model is particularly inaccurate for this household. CS11's direct electric water heating, and it being the only case without loft insulation, may contribute to the particularly high modelled energy use. Meanwhile, CS3, which also has a very low actual energy use which the model significantly overestimates, has only intermittent occupation due to travel for work and education.



* Denotes cases where secondary heating/wood use is known and has been included in both actual figures and energy model.

Figure 5: Actual versus modelled energy use based on floor area.

Figure 6 shows the average actual consumption of the eight cases using gas central heating (the most common UK fuel type) compared with the average UK gas range of 84–179 kWh/m^2/year based on typical consumption figures (Ofgem 2020) and average domestic floor area (Piddington *et al.* 2020), and with an average UK heating value of 133 kWh/m^2/year (ODYSSEE-MURE 2018). The modelled gas use for all cases is higher than the UK average, which would support the theory that heritage buildings are modelled as being energy inefficient. However, the actual data show that all the cases are within the Ofgem range and that over half (five) have a lower demand than the ODYSSEE average.

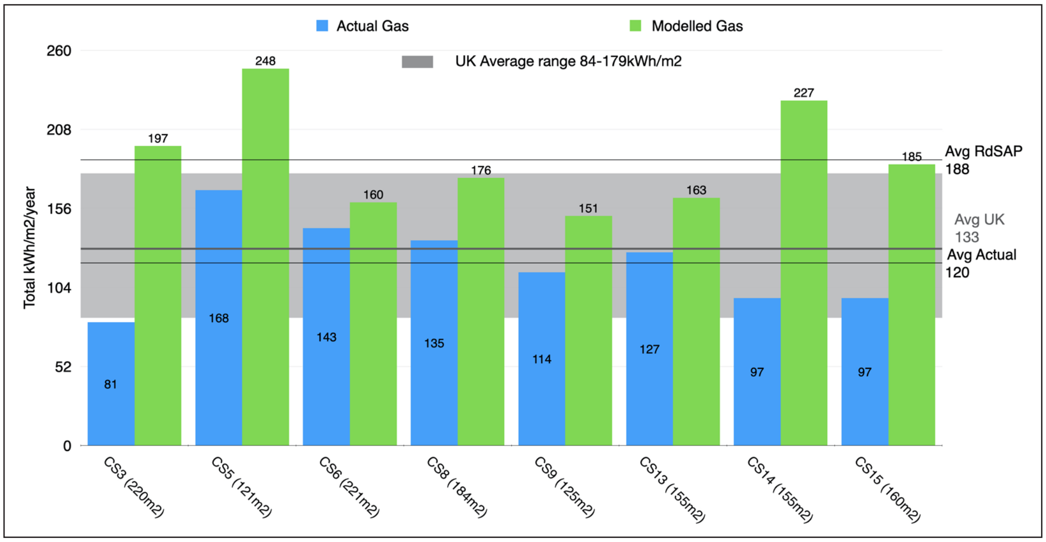


Figure 6: Actual versus modelled gas use and comparison with average UK data, based on floor area.

The average overestimate of the model is 66% (or 41% if CS11 is excluded as an outlier) (***Figure 7***). However, it should be noted that plug loads, which make up 14% of average UK household energy use (Palmer & Cooper 2014), are not modelled in RdSAP. The real overestimate is therefore even higher than indicated.

The discrepancy between actual and modelled carbon emissions (***Figure 8***) is exacerbated for some of the buildings in which electric heating is used, because the model's current conversion factors for grid electricity do not reflect the decarbonisation that has taken place in recent years. The latest government conversion factor for grid electricity is: 0.27511 kgCO$_2$/kWh (BEIS 2019), compared with 0.5190 kgCO$_2$/kWh used in RdSAP (BRE & DECC 2014). This discrepancy is an issue for all RdSAP assessments, not only heritage buildings. While most heating is not electric for these buildings, CS2 relies on electric heating, and so this explains the particularly significant discrepancy between actual and modelled carbon emissions for this case.

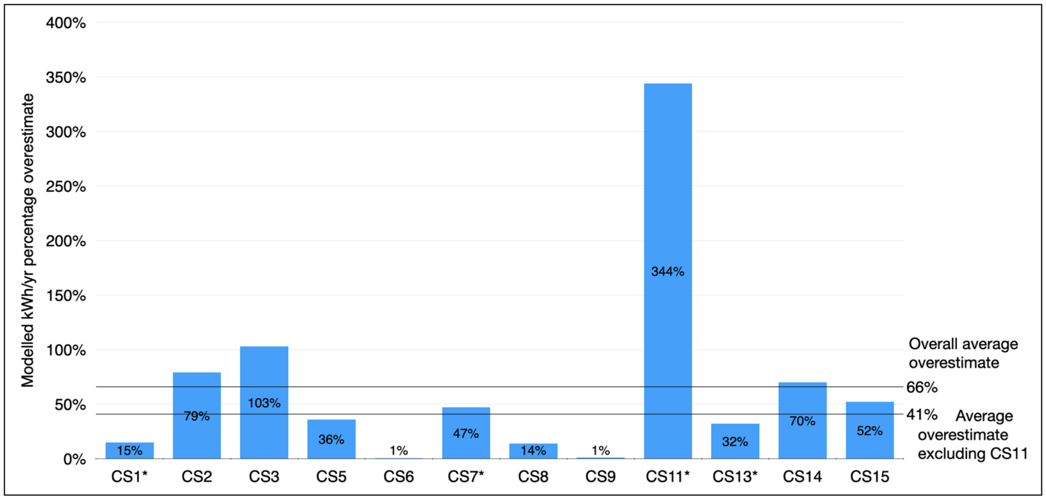
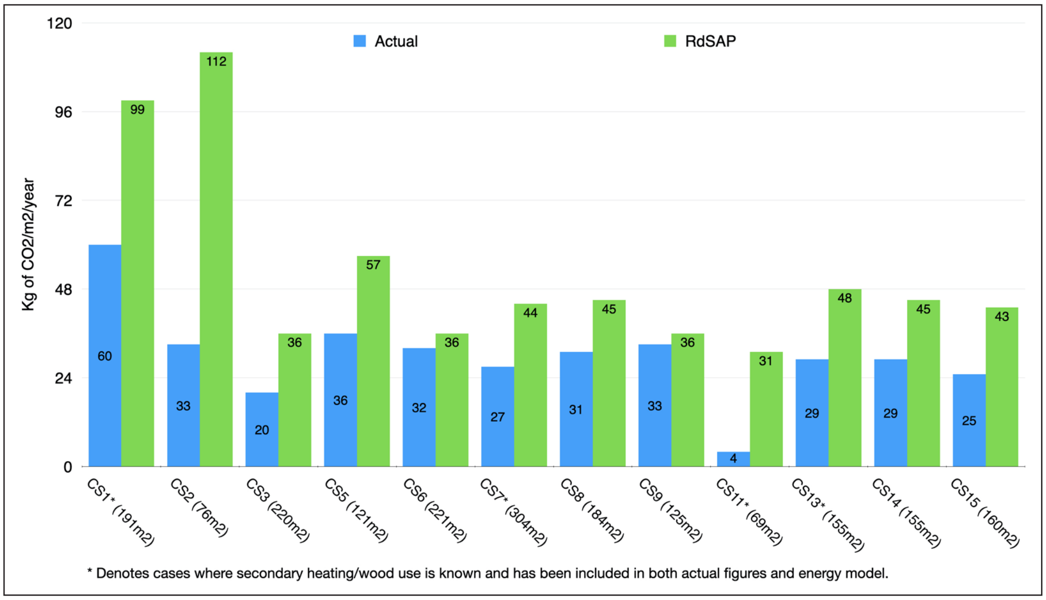


Figure 7: Percentage overestimate between modelled and actual energy use.



* Denotes cases where secondary heating/wood use is known and has been included in both actual figures and energy model.

Figure 8: Actual versus modelled carbon emissions based on floor area.

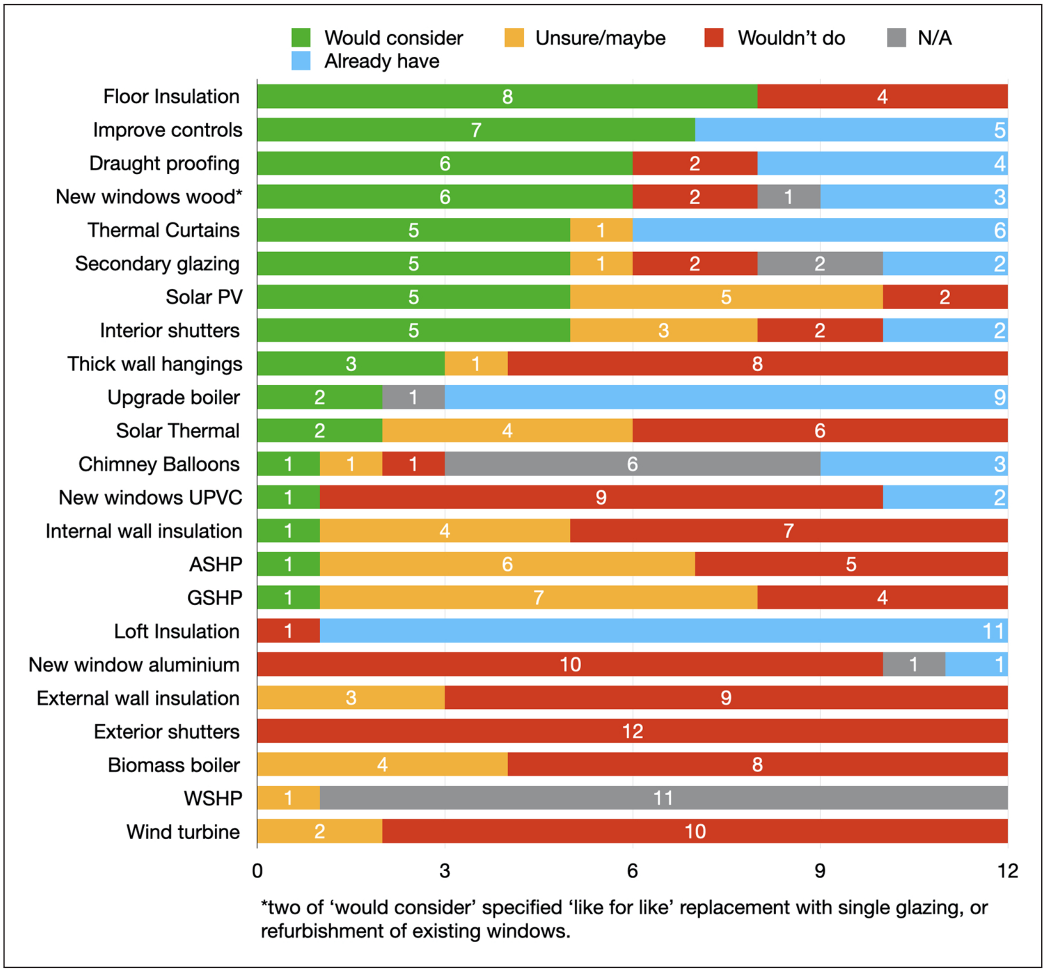
CS1 and CS7 have oil-fuelled central heating; CS2 is entirely electric; and CS11 only uses a wood-burning stove. Year 2019 National grid factors (BEIS 2019) have been used for the actual CO_2 calculations. However, in reality two-thirds of CS2's electricity comes from their micro-hydro plant, while six other cases have green electricity tariffs and CS9 also has a green gas tariff. Therefore, over half the participants are also contributing to national decarbonisation.

4.3 RETROFITTING POTENTIALS

A key challenge for retrofitting heritage buildings is that many measures may unacceptably affect heritage values and therefore not be enacted by residents. The interviews found that many common retrofits would not be implemented by most residents and that solutions with a lower visual impact were generally preferred (***Figure 9***).

Window alterations were a significant discussion point in most interviews, with participants displaying clear preferences:

> CS5: We try to maintain it [the character of the area] by not putting in horrible plastic windows or whatever it might be.
>
> CS14: I love those windows and I think they are absolutely gorgeous, and I get terribly twitchy when I think of someone ripping them out […].



*two of 'would consider' specified 'like for like' replacement with single glazing, or refurbishment of existing windows.

Figure 9: Acceptability of different retrofit measures to case study participants.

However, window additions such as thermal curtains, interior shutters or window refurbishment were more acceptable (***Figure 8***), and several participants highlighted the benefits of these types of additions.

> CS1: We've got functioning shutters in two of the downstairs windows which is great, so we don't have secondary glazing in those, they're very good.

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

Wall insulation, especially externally, was another measure generally unacceptable to residents.

> CS1: External walls, no! No, we wouldn't want to do that, it would destroy the house.

> CS9: We couldn't do it to this, it would look hideous.

> CS11: They've drylined it, this wonderful old stonework and they've drylined it. I'd rather be cold than that!

The only three participants who thought it might be acceptable had rendered facades.

A number of the measures identified by participants as more acceptable were modelled in SBEM for three of the case studies (as described in ***Figure 2***) in order to calculate their potential savings (***Figure 10***). For calculation details, see Appendix B in the supplemental data online.

The first four options looked at the impact of different window measures, compared with replacement double-glazing to current building standards (option 5) (HM Government 2018). These measures had little effect for CS1, which already has a combination of shutters, secondary glazing and wooden double-glazing. For CS5 and CS14 interior shutters (option 2) or secondary glazing and curtains (option 4) could reduce energy by a similar amount to double-glazing

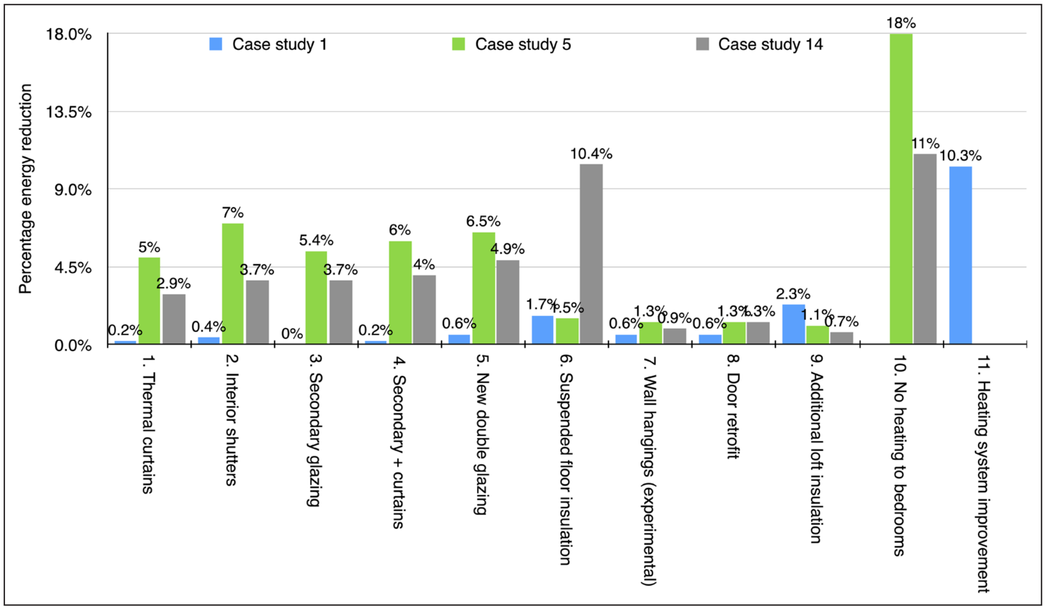
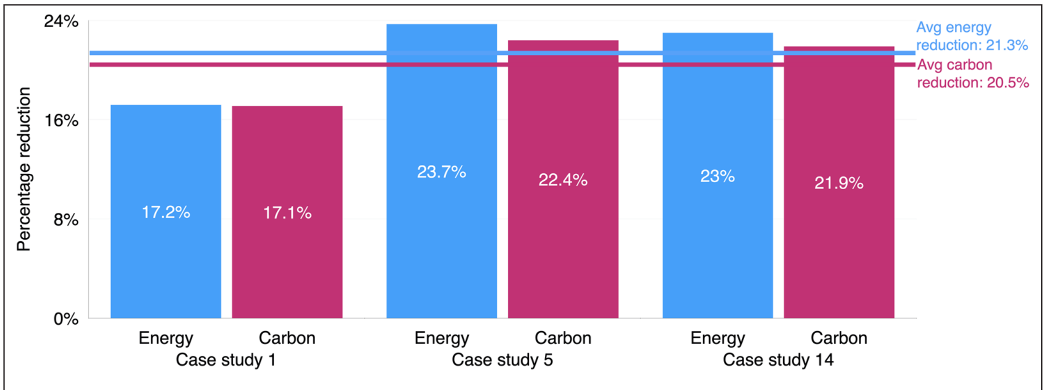


Figure 10: Percentage reduction in the energy use of different retrofit options.

(option 5). Option 6 considered the impact of floor insulation. All three cases had a mix of solid and suspended floors, but CS14 has a large, damp cellar, perhaps explaining the significant impact. Wall hangings (option 7) and retrofitting doors (option 8) had a small impact for all three cases. Loft insulation was already present (CS1 = 100 mm, CS5 and CS14 = 150 mm), but was increased to 250 mm by option 9; the biggest impact, not surprisingly, was for CS1. However, it is noticeable that the largest reduction results from a behavioural change, removing heating from bedrooms for CS5 and CS14 (option 10), something that residents viewed positively, rather than physical alterations. In option 11, CS1's 65% efficient, 40-year-old oil boiler was replaced with a modern, 83.1% efficient oil boiler (CS5 and CS14 already had modern gas boilers with > 90% efficiency).

A package of these changes was then modelled for each case, including the following options: interior shutters, suspended floor insulation, wall hangings, door retrofit and additional loft insulation for all three cases, plus no heating for bedrooms for CS5 and CS14, and a heating system improvement for CS1. The impact of these packages is shown in ***Figure 11***. For this package a rebound effect of 20% was applied in line with general estimates for home energy retrofitting in the UK (Sorrell *et al.* 2009).



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%.

Figure 11: Percentage energy and carbon reduction of retrofit packages per year.

This suggests that significant energy and carbon reductions could be made using measures that are acceptable to heritage residents. If these types of measures could be scaled up to even half of UK domestic heritage buildings, even taking into account a 20% rebound effect, they could make estimated savings of 5.3 $MtCO_2$/year, around 8.1% of total residential emissions (see Appendix D in the supplemental data online).

There are also other, more informal measures that may be harder to quantify but which can still have a valuable impact on thermal comfort and carbon reduction. Some steps taken by participants illustrate this point. CS1, for example, manage their conservatory for solar gain and use traditional blinds to manage the heat in summer.

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

CS13 have created a draught excluder that moves with their original front door to keep the prevailing wind from their living room. CS2, meanwhile, have an undersized wood stove, used daily to supplement their storage heaters. Rather than buying a larger stove at considerable financial and environmental cost, they are now using fans to disperse the heat.

> CS2: They operate off the heat, they've been brilliant, we've noticed a massive improvement.

These types of measures are unlikely to be considered in standard retrofit projects, but they clearly have effects deemed valuable by their users.

5. DISCUSSION

It is clear that the case study participants already engage in many positive energy behaviours, such as personal insulation (clothing and blankets), using individual and spot heating, and partial rather than full house heating. These behaviours have benefits in terms of avoided energy and carbon but may also be positive for residents' sense of comfort, with participants identifying, for example, the visual appeal of a wood stove or the affective qualities of blankets and throws. These behaviours resonate with theories of adaptive thermal comfort and suggestions that increased control and thermal variation can lead to increased comfort satisfaction (Altomonte *et al.* 2020; Hampton 2017; Humphreys *et al.* 2011). This finding may also highlight the need to interrogate current meanings of thermal comfort and to consider the metrics used to measure it (Altomonte *et al.* 2020; Pender & Lemieux 2020). The results show that understanding residents' behavioural interactions with their buildings is vital to determining current energy use and identifying appropriate retrofit measures.

This research has shown that RdSAP significantly overestimated energy and carbon in the case study heritage buildings, supporting other similar findings across Europe (Gram-Hanssen *et al.* 2018; Majcen *et al.* 2013; Pickles & Cattini 2015; Sunikka-Blank & Galvin 2012). Two important factors are likely to be poor representation of the performance of traditional construction and poor portrayal of energy behaviours.

The research reported in this paper shows clearly that the behaviours of these case study participants are very different to the standard heating regimes assumed in RdSAP. Other research has found that heating and comfort behaviours in heritage buildings may differ from those in more modern buildings (Henry 2007; Li *et al.* 2012; Pili 2017). This is an area that would benefit from further research to determine whether there is a link between heritage perceptions and specific behaviours, especially in a UK context. Although the phenomena of lower heating demand in older houses is well known, this is often attributed to fuel poverty (Majcen *et al.* 2013; Sunikka-Blank & Galvin 2012). This study suggests, however, that, at least for these particular cases, residents have made positive choices to reduce heating demand through the use of diverse and creative comfort practices, also highlighting that thermal satisfaction is subjective and specific (Galvin & Sunikka-Blank 2016; Hansen *et al.* 2018).

As a compliance tool the standard behavioural assumptions in RdSAP enable comparison between buildings (Jain *et al.* 2020). However, these tools are also designed to encourage energy and carbon reduction, providing retrofit recommendations and informing decisions for government funded retrofit programmes (BEIS 2020b). For this purpose, it is critical that they provide a reasonably accurate picture of actual energy use and that retrofit recommendations are tailored to the actual building and its residents' behaviours and values (Gram-Hanssen 2014).

The current overestimations create a highly inaccurate picture of heritage building energy performance, and strongly suggest that RdSAP is unfit for purpose for heritage buildings.

Furthermore, the heritage values that residents invest in their buildings determine the acceptability of retrofit measures and may preclude interventions commonly promoted for existing older buildings such as wall insulation and window replacement (Bristol City Council 2015; Glew *et al*. 2017). This study examined the energy-saving potential of several less-invasive measures, which are more acceptable to heritage residents, and demonstrated that they can significantly reduce operational energy and carbon. They are also likely to have lower embodied carbon (Curtis 2010). Additional 'soft retrofits' that residents had already undertaken, such as stove fans and draught excluders, also appear to have significant potential for comfort improvement (Morgan 2019). 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, something considered important to support heritage value retention (McCaig *et al*. 2018). They are likely to be less susceptible to maladaptation than more sweeping physical changes such as wall insulation, which has been found to often suffer from unintended consequences, particularly with regards moisture management in traditional buildings (Glew *et al*. 2017; May & Rye 2012).

A further important point highlighted by this study is the need to understand the current pre-retrofit condition of the building, something outside the scope of standard models (Alembic Research *et al*. 2019). For example, removing previous negative additions to buildings, such as CS14's cement render, and replacing with appropriate systems that work with rather than against breathing buildings' ways of managing moisture could be one of the most important changes to improve health and comfort within buildings and to get them to suitable positions for further retrofit (Pender & Lemieux 2020). This is something commonly identified as critical in whole house retrofit approaches, but is often overlooked in funding programmes which focus on specific retrofits and targets (Alembic Research *et al*. 2019).

These findings point towards the need for an approach that treats the building and its inhabitants as an interconnected system, considering specific circumstances and behaviours to identify the most effective retrofit measures. If instead retrofit decisions and policy instruments continue to be based on assumptions from tools such as RdSAP, the result is likely to be significant overestimations of energy and carbon savings, placing both environmental and financial targets in jeopardy and contributing to the performance gap. The potential resultant loss of heritage value will be without either environmental or financial gain.

6. CONCLUSIONS

The research has revealed a diverse range of positive energy behaviours in which heritage residents already engage, suggesting that an understanding of these behaviours should inform retrofit decisions. However, these behaviours are not included in common tools such as the Reduced data Standard Assessment Procedure (RdSAP). RdSAP overestimated energy use for the case study buildings by an average of 66%, suggesting that such tools are not appropriate for modelling the energy and carbon of heritage buildings. Their use is likely to lead to retrofit measures that in reality never achieve the expected savings. Not only is this unhelpful for individual buildings, but also it contributes to poor portrayal of both resident behaviour and traditional construction.

Heritage residents are unlikely to enact measures that are unacceptable to their heritage values, including many thermal envelope improvements. Meanwhile energy system changes such as efficient lighting had already been undertaken in most cases. This suggests that opportunities to upscale these measures for carbon reduction in heritage buildings may be limited. Residents' behaviours, values and building contexts were also shown to have important implications for the most appropriate retrofit options. Measures including behaviour change and/or non-fabric additions are often considered outside the scope of retrofit projects, but these measures were shown to have significant energy and carbon-reduction potential. They were also more acceptable to many more residents, increasing the likelihood of them being enacted at scale across the significant number of UK heritage buildings.

Therefore, more holistic views of retrofit are advocated that open a dialogue with residents and help develop retrofits and actions that take notice of their comfort perceptions, heritage values and the traditional nature of the construction. Better models are needed to inform this debate. There should also be efforts to get buildings working well and in good repair, and financial support and an individual building approach is likely to be needed for this.

Energy Performance Certificates (EPCs) are increasing being used as policy instruments aiming to improve the actual performance of buildings (Alembic Research *et al.* 2019), such as the current requirement for minimum ratings for rented buildings (BEIS 2020a), and recommendations that this be improved and extended to all buildings within the next decade (CCC 2020). If EPCs are going to be used in this way they need to be fit for purpose, and to provide an accurate picture of current energy use, as well as relevant and detailed recommendations for building improvements (Alembic Research *et al.* 2019). For the heritage buildings explored in this research, it is clear that EPCs based on RdSAP do not achieve these requirements, poorly reflecting both their traditional construction and their occupants' behaviours.

In order to successfully upscale the retrofit of the significant proportion of UK heritage buildings, the following recommendations are made.

First, the accuracy of tools such as RdSAP for heritage buildings must be significantly improved in order for it to be fit to inform retrofit decisions. This could be achieved by using EPCs in combination with metrics reflecting actual measured energy use (Fawcett & Topouzi 2020), adding options for behavioural tailoring and assessing the physical condition of the building (Alembic Research *et al.* 2019), and reviewing average performance values for traditional construction (Li *et al.* 2015).

Second, it is clear that one-size-fits-all solutions for heritage retrofit are unlikely to achieve climate goals, because standard retrofit options such as solid-wall insulation and window replacement are unlikely to be implemented by residents where they are unacceptable to their heritage values. The types of measures commonly included in retrofit projects should be expanded to include 'soft' non-fabric alterations, which are more acceptable to residents and more likely to be enacted at scale in heritage buildings. Indeed, they may be one of the only ways for owner-occupied heritage buildings where residents' values have been shown to strongly influence their retrofit choices. These types of approaches should engage with the current condition of the building and use any positive low-energy design features such as reinstating traditional shutters, and taking opportunities to correct previous building alterations that may have created moisture challenges. This provides opportunities to help ensure that buildings are functioning as intended in heritage-sensitive ways. It is likely that funding provision for retrofit may need to be more flexible to allow support for a wider range of solutions which, while on an individual level may be small, in combination have significant potential for carbon reduction and comfort improvements.

The third and related recommendation is that a greater understanding of, and engagement with, the potential for behavioural changes is needed, alongside a discussion of what standards of comfort are appropriate and desirable. User behaviour has long been a neglected area in building energy policies (Bordass 2020; Gram-Hanssen *et al.* 2018) yet has been shown to have significant potential to reduce carbon, often to a greater extent than physical alterations. However, this must be part of a tailored approach to energy and carbon reduction that seeks active engagement with users and their comfort practices, and support must be provided, especially for those homes that are forced into lower energy use by fuel poverty, not through active and positive choices.

Finally, this research has identified that there is a need for a more tailored and holistic approach that views heritage buildings and their residents as a complex and interrelated socio-technical system. This approach is needed to inform effective and heritage-appropriate retrofits which can make significant carbon reductions and therefore help mitigate climate change.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the input of the case study participants and they thank Quidos for providing access to its RdSAP modelling interface. None of the views expressed reflect those of Quidos.

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AUTHOR CONTRIBUTIONS

The first author was primarily responsible for data collection and analysis and the drafting of the paper. The second and third authors substantially contributed to the conception and design of the study and were responsible for critically revising the paper. All authors approved the final version of the paper to be published and agree to be accountable for all aspects of the work and to be named as authors.

COMPETING INTERESTS

The authors have no competing interests to declare.

ETHICAL APPROVAL

Ethical approval was provided by The Open University's Human Research Ethics Committee (ethics review number HREC/3452/Wise). Participants gave informed consent.

FUNDING

This research was funded by the Arts and Humanities Research Council (AHRC) (grant number AH/L503770/1).

SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: *https://doi.org/10.5334/bc.94.s1*

A supplementary file is provided, containing four appendixes:

- Appendix A: Assumptions for SBEM models
- Appendix B: SBEM retrofit modelling details
- Appendix C: RdSAP assumptions and actual energy and carbon by case study
- Appendix D: Calculation of carbon savings from package of retrofit measures

REFERENCES

Alembic Research, Energy Action Scotland, & **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* (p. 191). Scottish Government. *https://www.gov.scot/publications/review-domestic-non-domestic-energy-performance-certificates-scotland/pages/18/*

Almeida, M., Ferreira, M., & **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*, 8(8), 103. DOI: *https://doi.org/10.3390/buildings8080103*

Altomonte, S., Allen, J., Bluyssen, P. M., Brager, G., Heschong, L., Loder, A., Schiavon, S., Veitch, J. A., Wang, L., & **Wargocki, P.** (2020). Ten questions concerning well-being in the built environment. *Building and Environment*, 180, 106949. DOI: *https://doi.org/10.1016/j.buildenv.2020.106949*

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., & **Guattari, C.** (2019). Energy and environmental payback times for an NZEB retrofit. *Building and Environment*, 147, 461–472. DOI: *https://doi.org/10.1016/j.buildenv.2018.10.047*

ASHRAE. (2019). *ASHRAE terminology. ASHRAE searchable terminology tool*. American Association of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE). *https://www.ashrae.org/technical-resources/authoring-tools/terminology*

Aste, N., Torre, S. D., Adhikari, R. S., Buzzetti, M., Del Pero, C., Leonforte, F., & **Manfren, M.** (2016). Sustainable church heating: The Basilica di Collemaggio case-study. *Energy and Buildings*, 116, 218–231. DOI: *https://doi.org/10.1016/j.enbuild.2016.01.008*

Aydin, E., Kok, N., & **Brounen, D.** (2017). Energy efficiency and household behavior: The rebound effect in the residential sector. *RAND Journal of Economics*, 48(3), 749–782. DOI: *https://doi.org/10.1111/1756-2171.12190*

Bartiaux, F., Gram-Hanssen, K., Fonseca, P., Ozoliņa, L., & **Christensen, T. H.** (2014). A practice–theory approach to homeowners' energy retrofits in four European areas. *Building Research & Information*, 42(4), 525–538. DOI: *https://doi.org/10.1080/09613218.2014.900253*

BEIS. (2019, November 18). *Greenhouse gas reporting: Conversion factors 2019*. Department for Business, Energy and Industrial Strategy (BEIS). *https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019*

BEIS. (2020a, May 4). *Domestic private rented property: Minimum energy efficiency standard—Landlord guidance*. Department for Business, Energy and Industrial Strategy (BEIS). *https://www.gov.uk/guidance/domestic-private-rented-property-minimum-energy-efficiency-standard-landlord-guidance*

BEIS. (2020b, November 18). *Green Homes Grant: Make energy improvements to your home*. Department for Business, Energy and Industrial Strategy (BEIS). *https://www.gov.uk/guidance/apply-for-the-green-homes-grant-scheme*

Ben, H., & **Steemers, K.** (2014). Energy retrofit and occupant behaviour in protected housing: A case study of the Brunswick Centre in London. *Energy and Buildings*, 80, 120–130. DOI: *https://doi.org/10.1016/j.enbuild.2014.05.019*

Berg, F., Flyen, A.-C., Godbolt, Å. L., & **Broström, T.** (2017). User-driven energy efficiency in historic buildings: A review. *Journal of Cultural Heritage*, 28, 188–195. DOI: *https://doi.org/10.1016/j.culher.2017.05.009*

Berg, F., & **Fuglseth, M.** (2018). Life cycle assessment and historic buildings: Energy-efficiency refurbishment versus new construction in Norway. *Journal of Architectural Conservation*, 24(2), 152–167. DOI: *https://doi.org/10.1080/13556207.2018.1493664*

Bordass, B. (2020). Metrics for energy performance in operation: The fallacy of single indicators. *Buildings and Cities*, 1(1), 260–276. DOI: *https://doi.org/10.5334/bc.35*

BRE. (2020). *iSBEM (5.6.b)* [Computer software]. Ministry for Housing, Communities and Local Government. *https://www.uk-ncm.org.uk/index.jsp*

BRE & Department for Energy and Climate Change (DECC). (2014). *The government's Standard Assessment Procedure for energy rating of dwellings: 2012 edition*. Building Research Establishment (BRE). *https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf*

Bristol City Council. (2015). *A Bristolian's guide to solid wall insulation: A guide to the responsible retrofit of traditional homes in Bristol* (pp. 1–90). Bristol City Council. *http://files.site-fusion.co.uk/webfusion58199/file/2015_bristolsolidwallinsulationguidance.pdf*

Cadw. (2011). *Criteria for assessing historic buildings for the purposes of grant assistance* (pp. 1–3). Welsh Government. *https://cadw.gov.wales/docs/cadw/publications/Criteria_assessing_grant_assistance_ENG.pdf*

Cadw. (2018). *Understanding listing in Wales* (Advice and Support, p. 32). Cadw. *https://cadw.gov.wales/advice-support/historic-assets/listed-buildings/understanding-listing#section-introduction*

Carlucci, S., Bai, L., de Dear, R., & **Yang, L.** (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, 137, 73–89. DOI: *https://doi.org/10.1016/j.buildenv.2018.03.053*

CCC. (2020). *The Sixth Carbon Budget: The UK's path to Net Zero* (p. 448). UK Committee on Climate Change (CCC). *https://www.theccc.org.uk/publication/sixth-carbon-budget/*

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., & **Jackson, T.** (2014). Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. *Ecological Economics*, 106, 12–32. DOI: *https://doi.org/10.1016/j.ecolecon.2014.07.003*

CLEP. (2019). *Cumbria's local industrial strategy* (p. 97). Cumbria Local Enterprise Partnership (CLEP). *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*, 16(3), 7–27. DOI: *https://doi.org/10.1080/13556207.2010.10785073*

DCLG. (2017). *A guide to energy performance: Certificates for the marketing, sale and let of dwellings: Improving the energy efficiency of our buildings*. Department for Communities and Local Government (DCLG). *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/671018/A_guide_to_energy_performance_certificates_for_the_marketing__sale_and_let_of_dwellings.pdf*

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & **Castellazzi, L.** (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings*, 225, 110322. DOI: *https://doi.org/10.1016/j.enbuild.2020.110322*

Eriksson, P. (2018). Character defining elements: Relations between heritage regulations, user perspectives and energy saving objectives. *Energy Efficiency in Historic Buildings 2018*, 549–556. *http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-379648*

European Union. (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*, L 156(75). *http://data.europa.eu/eli/dir/2018/844/oj*

Fawcett, T., & **Topouzi, M.** (2020). Residential retrofit in the climate emergency: The role of metrics. *Buildings and Cities*, 1(1), 475–490. DOI: *https://doi.org/10.5334/bc.37*

Fisk, W. J., Singer, B. C., & **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*, 180, 107067. DOI: *https://doi.org/10.1016/j.buildenv.2020.107067*

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2), 219–245. DOI: *https://doi.org/10.1177/1077800405284363*

Fouseki, K., & **Cassar, M.** (2014). Energy efficiency in heritage buildings—future challenges and research needs. *The Historic Environment: Policy & Practice*, 5(2), 95–100. DOI: *https://doi.org/10.1179/1756750514Z.00000000058*

GABC, IEA, & **UNEP.** (2019). *2019 Global Status Report for Buildings and Construction: Towards a zero-emission, efficient and resilient buildings and construction sector* (p. 41). Global Alliance for Buildings and Construction (GABC), International Energy Agency (IEA), & United Nations Environment Programme (UNEP). *https://www.unep.org/resources/publication/2019-global-status-report-buildings-and-construction-sector*

Galvin, R. (2010). Thermal upgrades of existing homes in Germany: The building code, subsidies, and economic efficiency. *Energy and Buildings*, 42(6), 834–844. DOI: *https://doi.org/10.1016/j.enbuild.2009.12.004*

Galvin, R. (2014). Estimating broad-brush rebound effects for household energy consumption in the EU 28 countries and Norway: Some policy implications of Odyssee data. *Energy Policy*, 73, 323–332. DOI: *https://doi.org/10.1016/j.enpol.2014.02.033*

Galvin, R. (2015). *The rebound effect in home heating: A guide for policymakers and practitioners*. Routledge. DOI: *https://doi.org/10.4324/9781315696942*

Galvin, R., & **Sunikka-Blank, M.** (2016). Quantification of (p)rebound effects in retrofit policies—Why does it matter? *Energy*, 95, 415–424. DOI: *https://doi.org/10.1016/j.energy.2015.12.034*

Giraudet, L.-G., Bourgeois, C., & **Quirion, P.** (2021). Policies for low-carbon and affordable home heating: A French outlook. *Energy Policy*, 151, 112140. DOI: *https://doi.org/10.1016/j.enpol.2021.112140*

Glew, D., Smith, M. B., Miles-Shenton, D., & **Gorse, C.** (2017). Assessing the quality of retrofits in solid wall dwellings. *International Journal of Building Pathology and Adaptation*, 35(5), 501–518. DOI: *https://doi.org/10.1108/IJBPA-05-2017-0022*

Gram-Hanssen, K. (2014). Retrofitting owner-occupied housing: Remember the people. *Building Research & Information*, 42(4), 393–397. DOI: *https://doi.org/10.1080/09613218.2014.911572*

Gram-Hanssen, K., Georg, S., Christiansen, E., & **Heiselberg, P.** (2018). What next for energy-related building regulations?: The occupancy phase. *Building Research & Information*, 46(7), 790–803. DOI: *https://doi.org/10.1080/09613218.2018.1426810*

Haines, V., & **Mitchell, V.** (2014). A persona-based approach to domestic energy retrofit. *Building Research & Information*, 42(4), 462–476. DOI: *https://doi.org/10.1080/09613218.2014.893161*

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*, 28, 1–10. DOI: *https://doi.org/10.1016/j.erss.2017.03.012*

Hansen, A. R., Gram-Hanssen, K., & **Knudsen, H. N.** (2018). How building design and technologies influence heat-related habits. *Building Research & Information*, 46(1), 83–98. DOI: *https://doi.org/10.1080/09613218.2017.1335477*

Harrestrup, M., & **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*, 85, 123–133. DOI: *https://doi.org/10.1016/j.buildenv.2014.12.005*

Henry, M. C. (2007). The heritage building envelope as a passive and active climate moderator: Opportunities and issues in reducing dependency on air-conditioning. In *Contribution to the experts' roundtable on sustainable climate management strategies,* April 2007, Tenerife, Spain. The Getty Conservation Institute. *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., & **Troi, A.** (2019). Deep renovation of historic buildings: The IEA-SHC Task 59 path towards the lowest possible energy demand and CO_2 emissions. *International Journal of Building Pathology and Adaptation*, 38(4), 539–553. DOI: *https://doi.org/10.1108/IJBPA-12-2018-0102*

Historic England. (2019). *Listed Buildings|Historic England*. Historic England. *https://historicengland.org.uk/listing/what-is-designation/listed-buildings/*

Historic Environment Scotland. (2019). *Scotland's listed buildings* (p. 13). Historic Environment Scotland. *https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=34c90cb9-5ff3-45c3-8bc3-a58400fcbc44*

HM Government. (2018). *Building Regulations: Conservation of fuel and power in existing dwellings*. HM Government. *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/697629/L1B_secure-1.pdf*

Humphreys, M., Nicol, F., & **Roaf, S.** (2011). *Keeping warm in a cooler house* (Technical Papers No. 14, p. 28). Historic Scotland. *https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f2f2ebfd-ff37-4417-be92-a59400bb2665*

Ingram, V., & **Jenkins, D.** (2013). *Evaluating energy modelling for traditionally constructed dwellings* (Technical Paper No. 18, p. 50). Historic Scotland. *https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=1d90d4c3-f8ca-4468-8049-a59400b32e50*

Iyer-Raniga, U., & **Wong, J. P. C.** (2012). Evaluation of whole life cycle assessment for heritage buildings in Australia. *Building and Environment*, 47, 138–149. DOI: *https://doi.org/10.1016/j.buildenv.2011.08.001*

Jain, N., Burman, E., Stamp, S., Mumovic, D., & **Davies, M.** (2020). Cross-sectoral assessment of the performance gap using calibrated building energy performance simulation. *Energy and Buildings*, 224, 110271. DOI: *https://doi.org/10.1016/j.enbuild.2020.110271*

Kane, T., Firth, S., & **Lomas, K.** (2015). How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. *Energy and Buildings*, 86, 817–832. DOI: *https://doi.org/10.1016/j.enbuild.2014.10.011*

Khan, S. (2018). Thermal comfort and joy. *The Society for the Protection of Ancient Buildings Magazine*, Winter 2018, 74–75. *https://www.rmears.co.uk/2019/01/15/sarah-khans-article-thermal-comfort-and-joy-is-published-in-spab-magazine-winter-edition/*

Kohler, N., & **Hassler, U.** (2012). Alternative scenarios for energy conservation in the building stock. *Building Research & Information*, 40(4), 401–416. DOI: *https://doi.org/10.1080/09613218.2012.675714*

LDNPA. (2020). *English Lake District World Heritage Site. Statement of outstanding universal value*. Lake District National Park Authority (LDNPA). *http://lakesworldheritage.co.uk/world-heritage/souv/*

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., & **Oreszczyn, T.** (2015). Solid-wall *U*-values: Heat flux measurements compared with standard assumptions. *Building Research & Information*, 43(2), 238–252. DOI: *https://doi.org/10.1080/09613218.2014.967977*

Li, Q., Sun, X., Chen, C., & **Yang, X.** (2012). Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study. *Energy and Buildings*, 49, 317–326. DOI: *https://doi.org/10.1016/j.enbuild.2012.02.023*

Lidelöw, S., Örn, T., Luciani, A., & **Rizzo, A.** (2019). Energy-efficiency measures for heritage buildings: A literature review. *Sustainable Cities and Society*, 45, 231–242. DOI: *https://doi.org/10.1016/j.scs.2018.09.029*

Madsen, L. V. (2018). Materialities shape practices and notions of comfort in everyday life. *Building Research & Information*, 46(1), 71–82. DOI: *https://doi.org/10.1080/09613218.2017.1326230*

Majcen, D., Itard, L. C. M., & **Visscher, H.** (2013). Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. *Energy Policy*, 54, 125–136. DOI: *https://doi.org/10.1016/j.enpol.2012.11.008*

Mallaband, B., Haines, V., & **Mitchell, V.** (2013). Barriers to domestic retrofit: Learning from past home improvement experiences. In W. Swan & P. Brown (Eds.), *Retrofitting the built environment* (pp. 184–199). Wiley. DOI: *https://doi.org/10.1002/9781118273463.ch14*

May, N., & **Rye, C.** (2012). *Responsible retrofit of traditional buildings: A report on existing research and guidance with recommendations* (p. 133). Sustainable Traditional Buildings Alliance. *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*, 95, 23–31. DOI: *https://doi.org/10.1016/j.enbuild.2014.10.073*

McCaig, I., Pickles, D., & **Pender, R.** (2018). *Energy efficiency in historic buildings: How to improve energy efficiency* (pp. 1–50). Historic England. *https://historicengland.org.uk/images-books/publications/eehb-how-to-improve-energy-efficiency/*

Mısırlısoy, D., & **Günçe, K.** (2016). Adaptive reuse strategies for heritage buildings: A holistic approach. *Sustainable Cities and Society*, 26, 91–98. DOI: *https://doi.org/10.1016/j.scs.2016.05.017*

Morgan, C. (2019). *Sustainable renovation: Improving homes for energy, health and environment* (2nd ed., Vol. 1). The Pebble Trust.

Nicol, J. F., & **Humphreys, M. A.** (1973). Thermal comfort as part of a self-regulating system. *Building Research and Practice*, 6, 191–197. DOI: *https://doi.org/10.1080/09613217308550237*

Nicol, S., Roys, M., Ormandy, D., & **Ezratty, V.** (2015). *The cost of poor housing in the European Union* (p. 76). Building Research Establishment (BRE). *https://www.bre.co.uk/filelibrary/Briefing%20papers/92993_BRE_Poor-Housing_in_-Europe.pdf*

ODYSSEE-MURE. (2018). *Households: Heating consumption per m² and per dwelling*. ODYSSEE-MURE. *https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/heating-consumption-per-m2.html*

Ofgem. (2020). *Decision for typical domestic consumption values 2020*. Office of Gas and Electricity Markets (Ofgem). *https://www.ofgem.gov.uk/publications-and-updates/decision-typical-domestic-consumption-values-2020*

Palmer, J., & **Cooper, I.** (2014). *United Kingdom housing energy fact file 2013* (Housing Energy Fact File, p. 172). Department for Energy and Climate Change (DECC). *https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013*

Pan, S., Li, Z., Loveday, D., & **Demian, P.** (2018). *'Intelligent furniture': The potential for heated armchairs to deliver thermal comfort with energy savings in the UK residential context*. Loughborough University. *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*

Pender, R., & **Lemieux, D. J.** (2020). The road not taken: Building physics, and returning to first principles in sustainable design. *Atmosphere*, 11(6), 620. DOI: *https://doi.org/10.3390/atmos11060620*

Pickles, D., & **Cattini, C.** (2015). *Energy efficiency and historic buildings: Energy Performance Certificate* (pp. 1–20). Historic England. *https://historicengland.org.uk/images-books/publications/eehb-energy-performance-certificates/*

Pickles, D., & **McCaig, I.** (2017). *Energy efficiency & historic buildings: Application of Part L of the Building Regulations to historic & traditionally constructed buildings* (pp. 1–44). Historic England. *https://historicengland.org.uk/images-books/publications/energy-efficiency-historic-buildings-ptl/heag014-energy-efficiency-partll/*

Piddington, J., Nicol, S., Garrett, H., & **Custard, M.** (2020). *The housing stock of the United Kingdom* (pp. 1–23). BRE Trust. *https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf*

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*, 65–77. DOI: *https://doi.org/10.1007/978-3-319-75774-2_5*

Pracchi, V. (2014). Historic buildings and energy efficiency. *The Historic Environment: Policy & Practice*, 5(2), 210–225. DOI: *https://doi.org/10.1179/1756750514Z.00000000052*

Quidos. (2020). *Conventions (v 11.1) for RdSAP 9.92, 9.93 and 9.94*. Quidos.

Royston, S. (2014). Dragon-breath and snow-melt: Know-how, experience and heat flows in the home. *Energy Research & Social Science*, 2, 148–158. DOI: *https://doi.org/10.1016/j.erss.2014.04.016*

Shove, E. (2018). What is wrong with energy efficiency? *Building Research & Information*, 46(7), 779–789. DOI: *https://doi.org/10.1080/09613218.2017.1361746*

Shrubsole, C., Macmillan, A., Davies, M., & **May, N.** (2014). 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock: *Indoor and Built Environment*, 23(3). DOI: *https://doi.org/10.1177/1420326X14524586*

Sorrell, S., Dimitropoulos, J., & **Sommerville, M.** (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy*, 37(4), 1356–1371. DOI: *https://doi.org/10.1016/j.enpol.2008.11.026*

Sunikka-Blank, M., & **Galvin, R.** (2012). Introducing the prebound effect: The gap between performance and actual energy consumption. *Building Research & Information*, 40(3), 260–273. DOI: *https://doi.org/10.1080/09613218.2012.690952*

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

Tweed, C., & **Sutherland, M.** (2007). Built cultural heritage and sustainable urban development. *Landscape and Urban Planning*, 83(1), 62–69. DOI: *https://doi.org/10.1016/j.landurbplan.2007.05.008*

Wise, F., Moncaster, A., Jones, D., & **Dewberry, E.** (2019). Considering embodied energy and carbon in heritage buildings—A review. *IOP Conference Series: Earth and Environmental Science*, 329. DOI: *https://doi.org/10.1088/1755-1315/329/1/012002*

Wise, F., Moncaster, A., & **Jones, D.** (2021). Reducing carbon from heritage buildings: The importance of residents' views, values and behaviours. *Journal of Architectural Conservation*. DOI: *http://doi.org/10.1080/13556207.2021.1933342*

Wood, C., Bordass, B., & **Baker, P.** (2009). *Research into the thermal performance of traditional windows: Timber sash windows* (Research Report, pp. 1–35). English Heritage. *https://research.historicengland.org.uk/Report.aspx?i=16035*

Zagorskas, J., Zavadskas, E. K., Turskis, Z., Burinskienė, M., Blumberga, A., & **Blumberga, D.** (2014). Thermal insulation alternatives of historic brick buildings in Baltic Sea Region. *Energy and Buildings*, 78, 35–42. DOI: *https://doi.org/10.1016/j.enbuild.2014.04.010*

TO CITE THIS ARTICLE:
Wise, F., Moncaster, A., & Jones, D. (2021). Rethinking retrofit of residential heritage buildings. *Buildings and Cities*, 2(1), pp. 495–517. DOI: *https://doi.org/10.5334/bc.94*

Submitted: 11 January 2021
Accepted: 18 May 2021
Published: 14 June 2021

Buildings and Cities is a peer-reviewed open access journal published by Ubiquity Press.