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Rethinking retrofit of residential heritage buildings

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
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; Misirlisoy & Günço 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).
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; Rayston 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    | 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.    | 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.

**Case study elements**

- Site visits (24/02-17/03/2020)
- Semi-structured interviews
- Retrofit acceptability table
- Accompanied qualitative survey of building
- Quantitative survey: measurements; energy and building details
- Site visits audio recorded and transcribed

**Energy behaviour diaries**

- Winter diary February/March
- Summer Diary July/August

**Energy modelling**

- RdSAP model produced
- Energy bills and meter readings recorded and analysed
- SBEM models created for CS1, CS5 and CS14

**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.
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).

Table 2 Details of retrofits modelled in the 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 | Modelled for CS5 and CS14 only. CS1 currently do not heat their bedrooms |
| 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 |
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.
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.

![Figure 4: Level of clothing.](image)
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/m²/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/m²/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.

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 kgCO₂/kWh (BEIS 2019), compared with 0.5190 kgCO₂/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.
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 CO₂ 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 [...].
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.
(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).

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 MtCO₂/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
An 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 increasingly 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.
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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.

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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

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