Carbon reduction scenarios in the built historic environment: Final Report

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Executive Summary

To limit global warming a reduction in energy consumption and carbon emissions from the built environment is crucial. Despite pre-1919 buildings accounting for a large proportion of the existing building stock, the role of these buildings in contributing to sector energy and carbon reductions has previously been judged to be limited in most models due to low cost effectiveness. This has been justified by the difficulty in improving such buildings particularly those with heritage significance. However, this research aimed to evaluate the opportunity for pre-1919 buildings to contribute to climate change targets and therefore to critically challenge the previous assumption that they should be discounted.

Improving the energy performance of the pre-1919 building stock contributes to a number of benefits, from reducing carbon emissions to improving thermal comfort. However, any intervention for 'short-term' gains in energy efficiency should avoid loss of significance and negative unintended consequences such as reduced indoor air quality or condensation and damp. Although designated buildings such as those with 'listed' status are widely recognised to embody significance from a heritage perspective, pre-1919 buildings which have not been listed or are situated outside a conservation area may still represent value, particularly regarding aesthetics. Pre-1919 buildings can contribute to the local character of an area as well as representing inherent values, and can be considered heritage assets within the planning system.

The research included the identification of the existing evidence base regarding carbon reductions and a review of the assumptions used in previous models. It also incorporated a review of the scale and scope of the historic built environment. This informed the estimation of potential carbon reductions and associated costs, and the development of a carbon reduction roadmap to 2050. Two broad packages of measures 'low' and 'high' were developed, to improve the performance of five archetypal historic buildings, and consideration given to the avoidance of unintended consequences. The 'low package' of measures included loft insulation, secondary or double glazing, an alternative heating system, some wall insulation to rear extensions and/or rear elevations and some floor insulation. The 'high package' of measures included greater levels of insulation, greater levels of technologies such as solar photovoltaic panels, higher levels of air tightness. The exact measures in each package varied slightly across the five archetypes depending on the archetype parameters. The five pre-1919 archetypes, which included terraced and semi-detached properties are representative of 74% of the pre-1919 housing stock. Modelling suggests that approximately 15 million tonnes of operational carbon dioxide emitted annually by this building cohort could be reduced to almost zero by 2050. Savings derive from: substantial phased building fabric and air tightness improvements; a switch away from fossil fuel-based heating; and the decarbonisation of the national electricity grid. The estimate is based on assumptions about both the proportion of buildings retrofitted to the different energy efficiency levels, and the rate of increase in annual deployment over a 10-year period. Based on a 10-year period to reach stable deployment, a 25% reduction in annual carbon emissions by 2030 and 60% by 2040 was estimated for the modelled stock, including electricity grid decarbonisation.

Excluding grid decarbonisation, with a 10-year scaling up to a stable deployment level, it is estimated that 371 million tonnes of carbon dioxide (tCO_2) could be achieved, a saving of 123 million tonnes up to 2050. Sensitivity analysis indicated that if deployment stability was achieved within 5 years, an additional 67 million tonnes of carbon dioxide (tCO_2) could be saved. The additional savings in carbon emissions highlights the benefit of overcoming any practical issues for faster implementation in order to scale up deployment capacity within the shorter timescale.

Fabric improvements represented the greatest share of the carbon reductions achieved under our assumptions (40% weighted average). This was followed by the decarbonisation of the electricity grid (38% weighted average) and then carbon reductions delivered from fuel switching (21% weighted average). However, this pattern varied between low and high packages of measures, and between archetypes. For example, where the low package of measures was adopted, the greatest proportion of carbon reduction was achieved from the decarbonisation of the electricity grid. In contrast, where high packages of measures were adopted, proportionally the greatest carbon reduction was delivered by fabric improvements with the exception of Archetypes 1 and 2[1]. The contrast highlights the importance of electricity grid decarbonisation as a part of the strategy to deliver carbon reductions alongside fabric improvements. Greater reductions in carbon from fabric improvements may also be possible, particularly if a greater number of properties were retrofitted with the more efficient package of measures, or at a faster rate. However, interventions must be weighed/balanced in relation to heritage value and the impact of measures on the building fabric to avoid negative unintended consequences. Therefore enhanced reductions through fabric improvement is likely to require the research, development and innovation of measures and systems appropriate for the pre-1919 building stock, and the training of those specifying and installing these.

Any intervention will add to the existing embodied energy represented by pre-1919 buildings. Compared with operational energy, the embodied energy is a smaller proportion of the lifecycle carbon of a building. Pre-1919 buildings have existed for more than a century and will have gone through a number of cycles of repair, maintenance and refurbishment, adding to their total embodied energy. The more extensive the intervention, typically, the greater the embodied energy that is added. However, as operational energy requirements reduce, and decarbonisation of the grid accelerates, additional thought may be needed in relation to the

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[1] Archetypes 1 and 2 were both modelled as pre-1850s properties with more restricted 'high measure packages' applied than other archetypes due to assumed high heritage sensitivity.

specification of materials and measures to limit embodied energy gains arising from future interventions.

Understanding the potential to reduce the operational energy consumption and carbon emissions from the pre-1919 building stock is challenging from both a technical modelling perspective and in making assumptions about real-world implementation. The pre-1919 building stock is heterogeneous and data on the construction details, post-construction alterations and existing condition of pre-1919 buildings is not available. Energy models simplifying assumptions about consumption and building performance prejudicially affect historic buildings. There is a lack of clarity around the decarbonisation of the mains gas network on which a large proportion of pre-1919 buildings currently rely. Occupant behaviour is not predictable and improvements to building fabric may not result in expected energy demand reductions.

Of particular concern for pre-1919 buildings is the conservation of heritage values. Heightened consideration is needed around the risks of maladaptation, including in the context of future climate projections, and negative unintended consequences. Increased air tightness and inadequate ventilation, either in design or as a result of occupant behaviours, can not only reduce indoor air quality but also increase humidity levels and mould growth in buildings, and also limit a building's ability to combat summer overheating. This will have implications for the health of the building and its occupants.

Based on the existing literature, increased thermal performance does not necessarily result in overheating. The positioning of wall insulation can, however, affect whether the wall's thermal mass can be used to buffer potential summer overheating which, in conjunction with appropriate ventilation, may become increasingly important in the context of future climate projections. Further, the positioning of solid wall insulation may have implications for impacting on the aesthetic value of a pre-1919 building and reduce the rate at which moisture within the wall can evaporate. However these concerns, and the legislation that exists to avoid harmful interventions to buildings which are listed or in conservation areas, should guide rather than hinder efficiency improvements.

Previous research suggested that the decarbonisation of 90% of the UK stock to reduce carbon emissions has an average cost of £418/tCO_2e, with a cost uplift of 12% for 'heritage' buildings (Element Energy and UCL, 2019). In the present research, costs for the five archetypes modelled were variable. Where improvements were treated as standalone projects, additional costs included preambles, enabling works, professional fees, VAT and contingency. For high and low measure packages, this resulted in a mean cost of £457/tCO_2 based on a 30-year average carbon factor. Where improvements were incorporated into a wider home improvement project or at 'trigger points', costs were assumed to include only the cost of the measures and the enabling works, they reduced to a weighted average of £420/tCO_2 (including VAT), and £362/tCO_2 (excluding VAT).

The research formed a five week research project and, although the use of the full version of the Standard Assessment Procedure 2012 was used to avoid limitations in Reduced data SAP, there is scope for further refinement of the results that might identify greater energy and carbon savings. A wider range of interventions might be considered in more detailed analysis and through more complex modelling. Future updated versions of SAP where there is likely to be slight changes in assumed U-values might also result in higher estimated savings. Only five archetypes were modelled representing 74% of the current pre-1919 housing stock. Future research could be undertaken to explore the carbon reduction potential of remaining pre-1919 stock (domestic and non-domestic) as well as undertake further analysis based on regional variations, tenure, and household structures. The current available data on the number of buildings in conservation areas and the rigour of the data on precise numbers of listed versus non-listed buildings was limited, and further research on this area would support potential refinement of energy and carbon reductions, and the associated costs.

Further research around measures and technologies for energy and carbon reductions in the pre-1919 stock could include the effects of solid wall insulation, secondary double glazing, and ventilation strategies. Such research should consider implications for and strategies to mitigate future overheating risks. Additional research could also include heating strategies for the pre-1919 building stock including the role and suitability of heat pumps and heat networks, the potential risks and unintended consequences of these.

Acknowledgments

The project team would like to thank Historic England for their support and guidance during the project, particularly Adala Leeson, Iain McCaig, Hannah Fluck, Douglas Phillips, and Soki Rhee-Duverne. Thanks also goes to Bill Bordass for his comments and guidance, and to the UCL 3D Stock team led by Paul Ruyssevelt. The analysis used the UCL 3D Stock model as described on the UCL 3DStock website[2], with data kindly provided by Geomni, part of the Verisk group.

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[2] https://www.ucl.ac.uk/bartlett/energy/research-projects/2020/may/3dstock

1. Introduction

This project is concerned with developing forecasts for estimating the scale of carbon reduction and the associated abatement costs across the built historic environment. Historic England would like to gain a greater understanding about the carbon reduction potential of the built historic environment, including the identification of the potential challenges associated with maladaptation. This information is intended to contribute to the Climate Change Committee's Call for Evidence to inform the 6th Carbon Budget.

The study aims were:

1. To undertake a detailed literature review collating the existing evidence base regarding carbon in the built historic environment
2. To review the assumptions used to model the carbon impact and cost of domestic heritage properties in the current UK carbon targets
3. To review current estimates of the scale and scope of the built historic environment.
4. To refine assumptions regarding the scale, scope and cost of carbon reduction actions within the built historic environment used in existing models
5. To include consideration of heritage values and risks of maladaptation
6. To develop carbon reduction scenarios to 2050 for the built historic environment.

2. Methods

2.1 Literature review

The main element of the research was a literature review. The literature review incorporated academic peer-reviewed articles, research reports, and government and industry reports. Online databases such as Scopus were used to identify relevant articles, and websites of relevant organisations were visited. The study search strategy adopted a structured key word search to maximize the coverage of relevant disciplines. Where possible, sources were retrieved and assessed for relevance at title and then abstract level.

The literature review identified the existing evidence base regarding energy (by source) and carbon in the built historic environment (*aim 1*) and informed the review of assumptions made in the Element Energy and UCL (2019) model (*aim 2*). Using sources such as the Valuation Office Agency and the English Housing Survey, a review of the current estimates of the scale and scope of the built historic environment were undertaken (*aim 3*) to develop packages.

Common energy efficiency measures were identified using case studies in the existing literature, including from the Superhome Network[3] database. The Superhome Network database was filtered to include only pre-1919 properties which had been assessed by an official assessor (**Section 3.13, Table 11**). This informed the design of two packages of measures for modelling, designed to reduce energy consumption and carbon emissions (*aims 4 and 6*). These packages of measures were also informed by a review of the literature about maladaptation risks (*aim 5*) and were subsequently agreed with the steering group.

2.2 Cost estimates

Costs have been estimated for high and low refurbishment packages. A range of costs were initially identified in the literature from sources such as the SuperHome Network, the Energy Saving Trust, the Sustainable Traditional Buildings Alliance, and the Existing Homes Alliance to provide guidance. Costs for the packages in this research were estimated using the industry standard Spon's Architects' and Builders' Price Book 2020 and Spon's Mechanical and Electrical Services Price Book 2020, as well as the BEIS (2017a). The costs for heat pumps were taken from Spon's Mechanical and Electrical Service Price Book 2020. Costs have been scaled according to the size of the element and property for each of the five archetypes.

Spon's figures includes labour and materials, but excludes other costs. Therefore an uplift has been applied to the total to better reflect the costs involved with the retrofit works (**Table 1**). However, it should also be noted that costs are highly variable and figures should be treated as indicative only. Costs will vary based on factors such as:

- The current condition of each property

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[3] http://www.superhomes.org.uk/get-inspired/superhome-database/

- Market conditions[4]
- Contractor pricing
- Scale of each project (i.e. economies of scale)[5]
- Conservation status

Therefore future research would be necessary to provide much more robust costs of high performance carbon reduction refurbishments across the built historic environment, accounting for additional factors such as location and building condition. A sensitivity analysis on costs was undertaken (Section 4.12). This highlighted the opportunities for reducing costs, particularly in relation to the removal of VAT and by incorporating energy efficiency improvements as part of other building improvement works.

Table 1: Cost uplift assumptions

	Potential uplift		**Uplift applied**
VAT	5 – 20%	Some energy saving products are eligible for lower VAT rates (5%), but not all. For example, energy efficient boilers, secondary or double glazing do not currently qualify for a reduction in VAT (Gov, 2020).	10%
Professional fees	15%	Based on Spon's Architects' and Builders' Price Book	15%
Preliminary works	20%	Based on Spon's Architects' and Builders' Price Book	20%
Enabling works	25%	Based on Spon's Architects' and Builders' Price Book	25%
Contingency	12 - 20%	Due to the high level of uncertainty relating to existing housing, a high level of contingency has been applied	20%

Costs presented take no account of any grants, ongoing fuel savings or income from renewable energy exports. Further, the costs are assumed to be additional to the existing costs of ongoing maintenance and replacement, for example occasional replacement of the boiler. The costs do not specifically include the cost of the replacement of the heating distribution such as radiators, although enabling works have been provided as a proportion of the costs, which would also incorporate the decommissioning and removal of the existing heating system. Where heat demand is sufficiently low following fabric improvements, the

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[4] Costs are likely to reduce where around 100,000 energy efficiency improvement packages are retrofitted annually as the market matures. This has been seen with the fall in costs for the solar photovoltaic panel market, technology adoption supported by the Feed-in tariff incentive.

[5] Where multiple properties undergo a retrofit of a package of measures as part of a wider project, it is possible that cost savings could be achieved in comparison with the costs for a single property.

retention of existing radiators may be possible. In other situations, suitably-sized low temperature radiators may be necessary.

A report outlining a range of investments to decarbonise Bristol by the Centre for Sustainable Energy (2019) suggests some of the improvements could be partially funded by reassigned 'conventional' investments, such as anticipated replacement new gas boilers. The BEIS (2017b) estimates the annual market value for boilers across all buildings in the UK to be around £2.5 - £3 billion.

2.3 Model – Building archetypes and measures

Due to the heterogeneity of the pre-1919 building stock, the wide range of variables and extensive range of options for interventions, a desktop mid-case-scenario approach has been adopted for this research using archetypes. Although there are multiple factors which will impact on actual carbon and energy reductions achieved through interventions within the pre-1919 building stock, the approach adopted has attempted to provide an indication of what may be possible.

Building archetypes have typically not included heritage buildings (Mourão et al., 2019). There are exceptions to this such as the Energy Technologies Institute (2012) who defined three, out of nine, modelled archetypes as pre-1919 (converted flat, detached and mid-terrace). Therefore new archetypes had to be defined for this study.

Baseline archetype buildings were modelled using the SAP-certified software, JPA Designer 990 using SAP 2012 assumptions version 9.93 (July 2016) (BRE, 2016b). This uses the 'full SAP' methodology not the simplified RdSAP methodology used for energy performance certificates. SAP is the official methodology adopted in industry for calculcating building energy and environmental performance (BEIS, 2014). It was judged that SAP was an appropriate choice for the level of analysis given the number of archetypes and the research time constraints. More detailed modelling using tools such as PHPP would not necessarily produce better results since our starting assumptions are based on averaging large numbers of properties using limited data.

Each baseline archetype was adjusted until it met expected statistical energy use ranges (i.e. modelled energy use was compared against age banded gas use for pre-1919 houses). Data sources for energy consumption comparison included the National Energy Efficiency Data (NEED)[6] framework, supplemented by information from the English Housing Survey (EHS)[7] for floor area and energy performance certificates (EPC) rating. Due to time constraints, a

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[6] https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-consumption-data-tables-2019

[7] https://www.gov.uk/government/statistics/english-housing-survey-2018-to-2019-headline-report

single archetype (4) was mirrored for all four main orientations (south, north, east, and west) to identify the potential effect on space heating[8] and on electricity generation from solar photovoltaic panels. Regional climates have not been taken into account due to the research timescales.

Two improvement packages were run through the baseline archetypes with the results from the SAP summary sheet saved in PDF format for reference. Improvement packages (**Appendix 2 Tables 2.1 and 2.2**) were informed by the modelling and common measures adopted by the pre-1919 SuperHome Network examples. For example, where the model returned space heating intensity in excess of 100 KWh/m^2, an alternative heating technology was identified to deliver the necessary heating and domestic hot water demand. A central location (Sheffield) was adopted for the archetype models. Therefore the electricity generation calculated from the solar photovoltaic panels represents this location. Higher values are likely to be calculated if a more southern region were adopted, and lower values for more northern regions.

Two improvement packages[9] – low and high impact energy efficiency improvement, were developed per archetype. These were structured around lower and higher carbon savings, and the measures were selected to reflect potential requirements for pre-1919 buildings status as heritage assets within the planning system. Measures were also considered in relation to the nature of traditional construction, which performs differently to modern construction (e.g. permeable fabric). The high impact energy efficiency packages included a form of mechanical ventilation to reflect the assumed greater air tightness resulting from the works. Triple glazing is assumed to be only suited to pre-1919 housing which is not listed or in a conservation area.

Since the majority of operational carbon emitted in homes is from fossil fuel use for heating (Committee on Climate Change, CCC, 2015), options consistent with realistic national heating decarbonisation pathways were considered when developing the improvement packages. The UK Government is yet to publish a national heating strategy, but the CCC (e.g. CCC, 2016) and others have completed research in this area (e.g. Rosenow and Lowes, 2020). The chosen packages were agreed with the project steering group.

Energy use intensities (kWh/m^2/a) were recorded from the SAP summary sheets and tabulated in MS Excel for different applications e.g. space heating, hot water, lighting, fans, and pumps. These were split between fuel, heat and electricity. Energy use intensities were multiplied by an appropriate current carbon factor (e.g. BEIS emission factors). SAP 2012 carbon factors for electricity are outdated therefore the analysis further included a trajectory of future carbon

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[8] Due to changes in solar gain, for example.

[9] It should be recognised that the measures outlined are for the purposes of modelling only; in reality these measures may not be suitable for application to every building within the archetype. Therefore, a range of options and their appropriateness should be assessed for a building and its context on a case-by-case basis.

factors to show the effects of UK electricity grid decarbonisation[10] and estimated cumulative savings until 2050. Energy use intensities or carbon intensities were then scaled by total floor area for the properties related to each building archetype to give an estimate of total energy and carbon saving in all historic dwellings.

2.4 Calculating savings across the pre-1919 stock

Assumptions have been made about the proportion of the properties for each archetype that can be retrofitted with low and high efficiency packages. The assumed proportions of properties that would be retrofitted to the low and high level packages are outlined in **Appendix 4 Table A4.5**. Assumptions about proportions have been informed by data from the English Housing Survey and data provided by Geomni. Geomni's data included the proportion of listed buildings represented by each archetype[11]. In reality it may be possible to achieve a greater number of properties retrofitted with the higher level package of measures, increasing the carbon and energy savings realised. Future research to refine estimations of designated and non-designated pre-1919 buildings, including in and outside conservation areas, would support further investigation of their carbon reduction potential. However, a conservative approach was adopted to accommodate some flexibility and reflect the complex factors involved in retrofitting the pre-1919 building stock.

For the purposes of this research, deployment has been assumed to grow from zero in 2020 to a stable level, and continue until all properties in each archetype have been retrofitted over a 25-year period. The model assumes linear growth in retrofitting, although in reality, given the right policies, it is likely that growth would be exponential rather than linear. It has also been assumed that it would take 10 years to scale up the required rate of deployment in industry including increasing the necessary skills and supply chains.

For each year additional energy and carbon savings were calculated for the number of properties in each archetype assumed to have been retrofitted by that time, the remaining proportion were modelled using the archetype base case. The cumulative carbon savings take account of changes in carbon and fuel factors, and electricity was assumed to be carbon neutral by 2050. It was also assumed that no properties will be left on mains gas by 2050. In the case of the decarbonisation of the main gas network, it is expected that there would be no change in heating energy demand compared with the 'no gas' assumption adopted for this research, and therefore the final carbon and energy saving is expected to be broadly similar[12].

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[10] https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting

[11] It is recognised that the Geomni data is currently limited to a selection of urban areas, although data for additional locations are under development.

[12] The absolute energy consumption will be slightly different because the heat pump will less electricity to deliver the same amount of heat.

The Standard Assessment Procedure default settings were used for boiler efficiency for the existing heating systems in the model. This assumes an average 84% efficiency. In the modelling, where the space heating intensity of an archetype property has achieved less than 100KWh/m^{2}a[13], the property has been determined to be suitable for a domestic heat pump. Where the property exceeds this, a biomass heating system[14] has been used in the modelling. The ASHP coefficient of performance (COP) adopted for the modelling is 1.75, which is a conservative figure both at a domestic and heat network level. A greater carbon reduction from heat pump technology is likely to be achievable by using low carbon refrigerants, but this is not included in the present calculations.

Only properties judged to fall broadly into the five archetypes have been included in the scaling calculations. This is estimated to be more than two-thirds of the pre-1919 housing stock in England. For the remaining domestic properties, such as converted flats, and non-domestic pre-1919 properties, further research to identify energy and carbon savings is needed.

2.5 Main changes compared with other models

The approach adopted in this research has been different in comparison with other studies such as Element Energy and UCL (2019). Particular deviations from the assumptions made by Element Energy and UCL (2019) are outlined in **Table 2**. Additional assumptions pertaining to the present research are outlined in **Section 4** and **Appendix 3**.

Table 2: Primary changes in assumptions compared with Element Energy and UCL (2019)

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[13] There have also been recent developments of CO_2-based heat pump technology to produce high temperatures (up to 110˚C), which may provide future options for properties with higher space heating intensities.

[14] Biomass has been selected for the modelling but in reality the chosen heating system should be based on individual cases and their contexts. Embodied carbon is likely to vary for biomass systems, depending on where the fuel is sourced.

Element Energy Assumption	Treatment in this research	Rationale
Assumed 4.5% of the building stock (based on listing) is defined as 'heritage'	Data on total historic building stock included from sources such as the Department for Communities and Local Government, the Valuations Office Agency, the Department of Business, Enterprise, Industry and Strategy, the Building Research Establishment, and Historic England.	The concept of heritage extends beyond listed buildings to the wider pre-1919 stock.
Mix of solar thermal and photovoltaic systems	Photovoltaic panels only	In general, the use of solar thermal is not anticipated to be cost effective in comparison with technology such as solar photovoltaic systems, which could incorporate an immersion diverter for increased flexibility.
Hybrid heat pumps included	Hybrid heat pumps excluded	The aim is to achieve where possible an adequate thermal performance in the pre-1919 building stock to facilitate the use of heat pumps. Hybrid heat pumps are not established technologies and therefore difficult to estimate the potential for. It is also difficult to estimate consumer and installation prices.
Technology suggested as more feasible than energy efficiency measures	Technology and energy efficiency measures both considered as part of the strategy	The aim was to both improve the thermal performance of the fabric where possible in parallel with changes to the space heating technology

3. Review of Literature

3.1 Introduction

The IPCC (2018) report highlights that the built environment is an essential sector requiring a rapid and deep reduction in emissions to limit global warming to 1.5°C. However, between 2010 and 2019, global final energy use in, and direct emissions from, buildings grew (International Energy Agency, 2020). In the UK, buildings in 2014 accounted for 34% of total greenhouse gas emissions, and the residential sector was responsible for 64% of the emissions from buildings (Climate Change Committee, CCC, 2015).

A number of challenges are presented when estimating the impact of future energy efficiency improvements in the heterogeneous historic building stock. These include the lack of robust estimates of the number of historic buildings; uncertainty regarding stock profile such as forms of construction, materials used, condition; and lack of records regarding the presence and quality of energy improvements to the stock. There are further challenges relating to the impact of occupant behaviour on gains and the future cost of implementing energy efficiency improvements. Therefore the following literature review includes consideration of the profile and scale of the pre-1919 building stock with a focus on domestic properties. It presents a discussion of the predicted and measured performance of these buildings. The decarbonisation strategy of the pre-1919 building stock will include the decarbonisation of the national energy supplies, which is discussed in addition to common measures adopted in the literature for pre-1919 buildings. The wide range in the costs associated with intervention as presented in previous studies is outlined, before providing an overview of the main risks of maladaptation and unintended consequences arising from interventions.

In England, 21% of domestic and 32% of non-domestic buildings were constructed prior to 1919, contributing to a considerable proportion of the existing building stock. This section reviews information on the contribution of pre-1919 housing to the buildings stock, evidence about condition, location, occupation and construction. It collates evidence related to energy use and carbon in heritage building stock.

Despite decarbonisation of the electricity grid, further improvement in building energy efficiency is important. Integrated studies such as the Krakow Energy Efficiency Project in Poland indicate that investing in the decarbonisation of the heat network coupled with improving building energy efficiency is highly cost effective (Rosenow et al., 2016). Therefore this review considers both evidence on the retrofit of energy efficiency in pre-1919 housing and the decarbonisation potential for pre-1919 housing through adjustments in fuel choices and decarbonisation of the energy grid.

The review also considers aspects of heritage value, and other benefits of improving thermal efficiency in housing.

3.2 Energy and the buildings sector

Pre-1919 buildings represent a large proportion of the domestic and non-domestic building stock the UK (by number of property).

In 2017, there were 28.5 million domestic properties in the UK, with over 83% of these located in England (Piddington et al., 2020). Although direct emissions from UK residential buildings have reduced, the CCC (2015) report that the rate of this reduction has slowed. In 2017, the overall domestic sector in the UK consumed 28% of the national total final consumption (BEIS, 2020a). This made it the second largest consumer of energy after transport (40%) (BEIS, 2020a). The largest proportion (65%) of domestic energy consumption is attributed to space heating (**Figure 1**). A reduction in domestic energy consumption, particularly for space heating, therefore has the potential to have a significant impact on the total UK energy consumption (BEIS, 2020). Since 1970 the energy used to produce domestic hot water has reduced, despite an increase in the number of dwellings (Palmer and Cooper, 2014). Palmer and Cooper (2014) suggest this reduction reflects improved insulation (i.e. hot water cylinder insulation, pipe lagging), improved heating system efficiencies and an increase in electrical appliances such as showers that heat water separately.

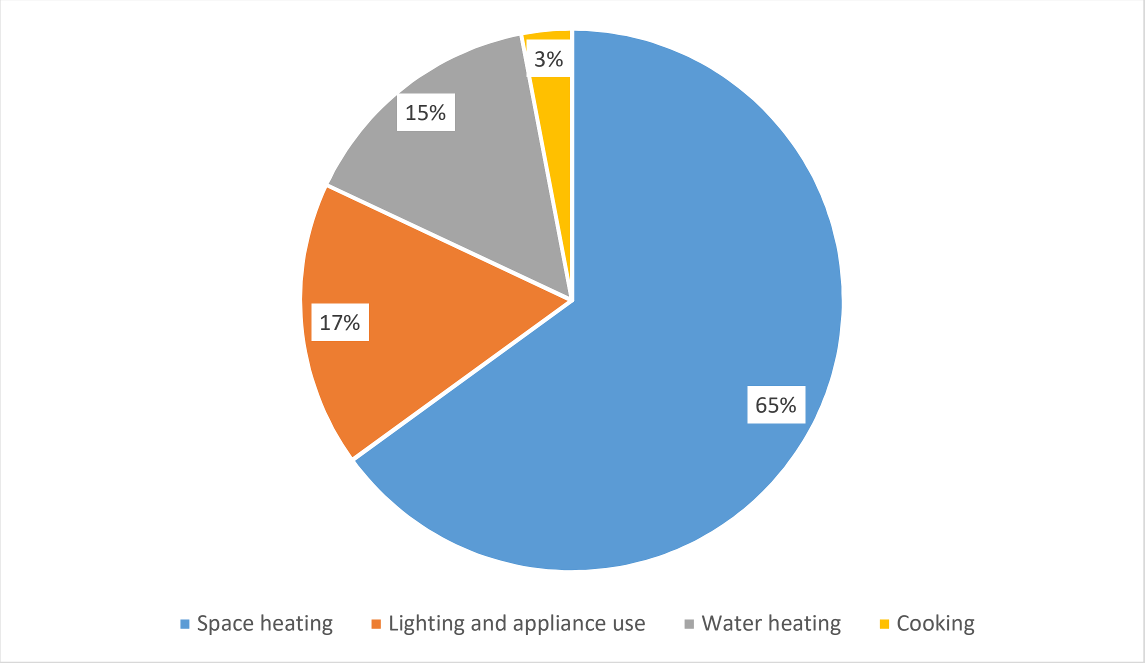

Figure 1: Domestic energy consumption by end use (BEIS, 2020a)

In relation to emissions, residential buildings accounted for 64% of total UK greenhouse gas emissions (CCC, 2015). The CCC (2015) report that emissions from buildings reduced by 21% between 2007 and 2014 reflecting the impact of high energy prices, improved energy efficiency and economic recession.

In England, the Valuations Office Agency (VOA, 2016) identified 466,530 non-domestic pre-1919 properties as of 31 March 2015, 32.2% of all non-domestic properties (1,448,780)

(**Figure 2**). In the non-domestic building stock, industrial buildings (the sector with lowest proportion of pre-1919 buildings) consume the second largest proportion of energy and emits the most carbon emissions (BEIS, 2018a).

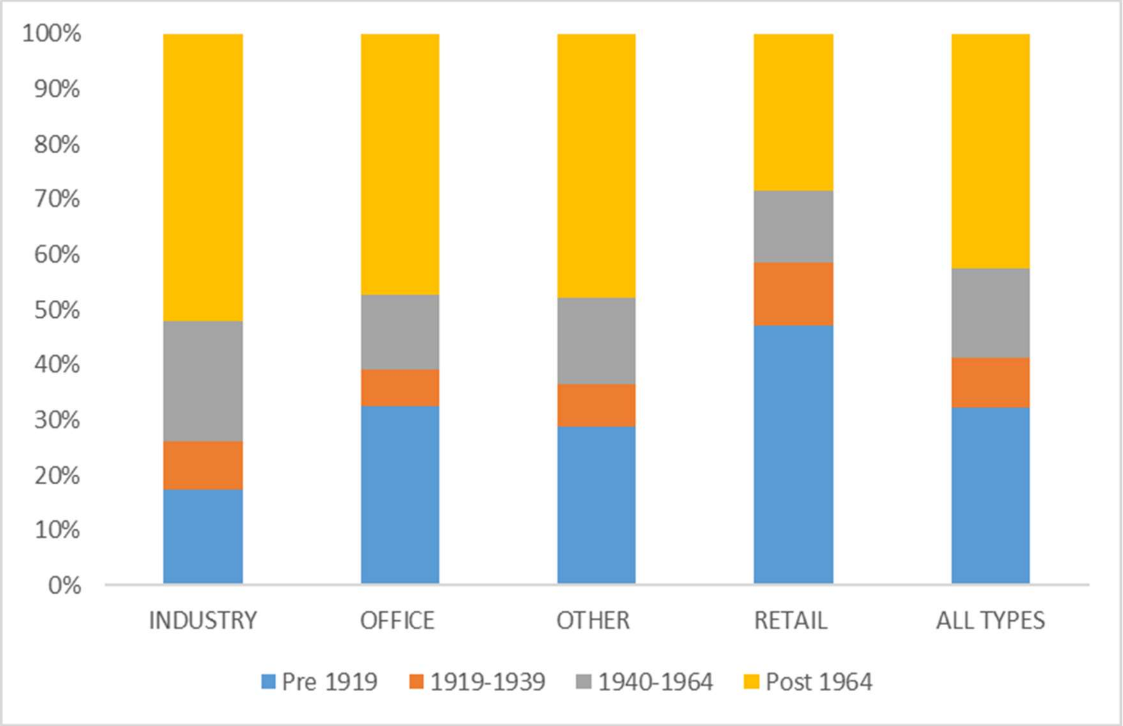

Figure 2: Number of non-domestic buildings in England by age and type (VOA, 2016)

There are over 5 million pre-1919 houses in England, accounting for 21% of the overall English domestic stock (Piddington et al., 2020; Valuation Office Agency, 2019; DCLG, 2019a) (**Figure 3**). The proportion of the pre-1919 housing stock varies slightly regionally, with greater proportions of pre-1919 dwellings seen in London, the North West and South West (**Figure 4**). This is also likely to vary within regions. For example, 30.5% of the housing stock in the city of Cambridge was constructed before 1919, but for East Cambridgeshire pre-1919 dwellings account for 18% of the wider housing stock (Cambridgeshire Insight, 2008).

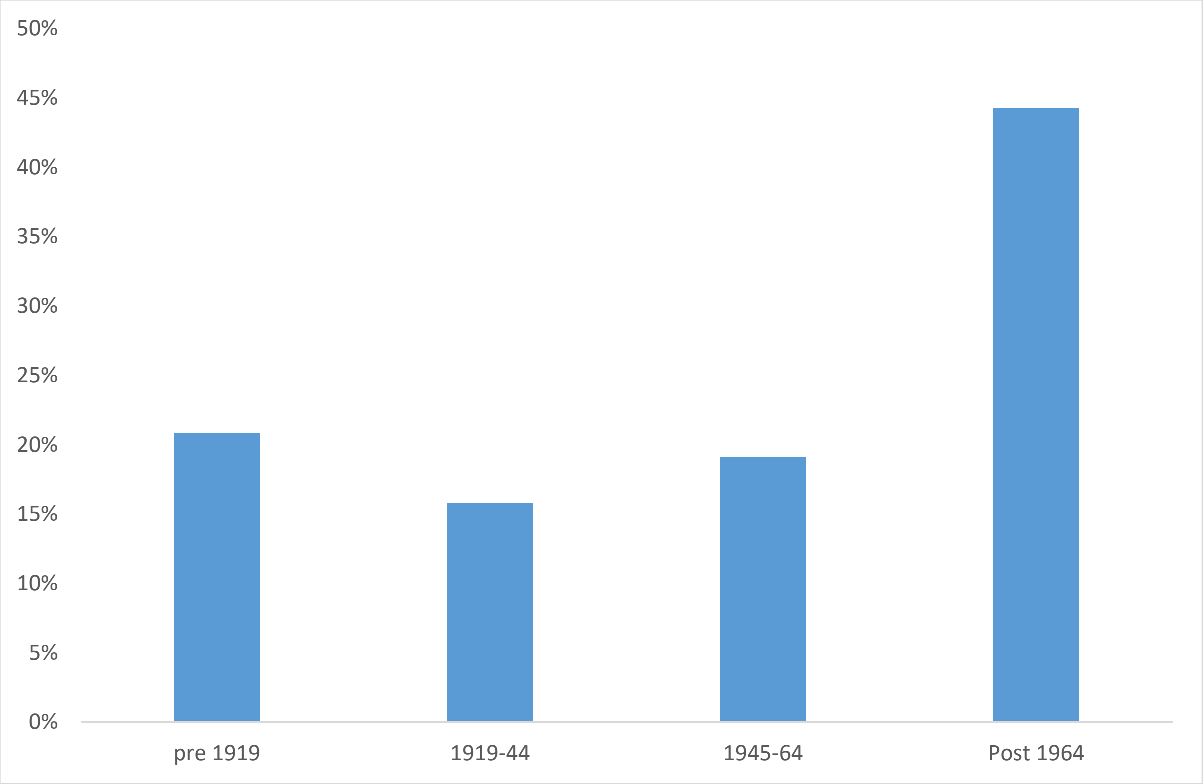

Figure 3: Overview of the age profile of the domestic building stock (%) (DCLG, 2018b)

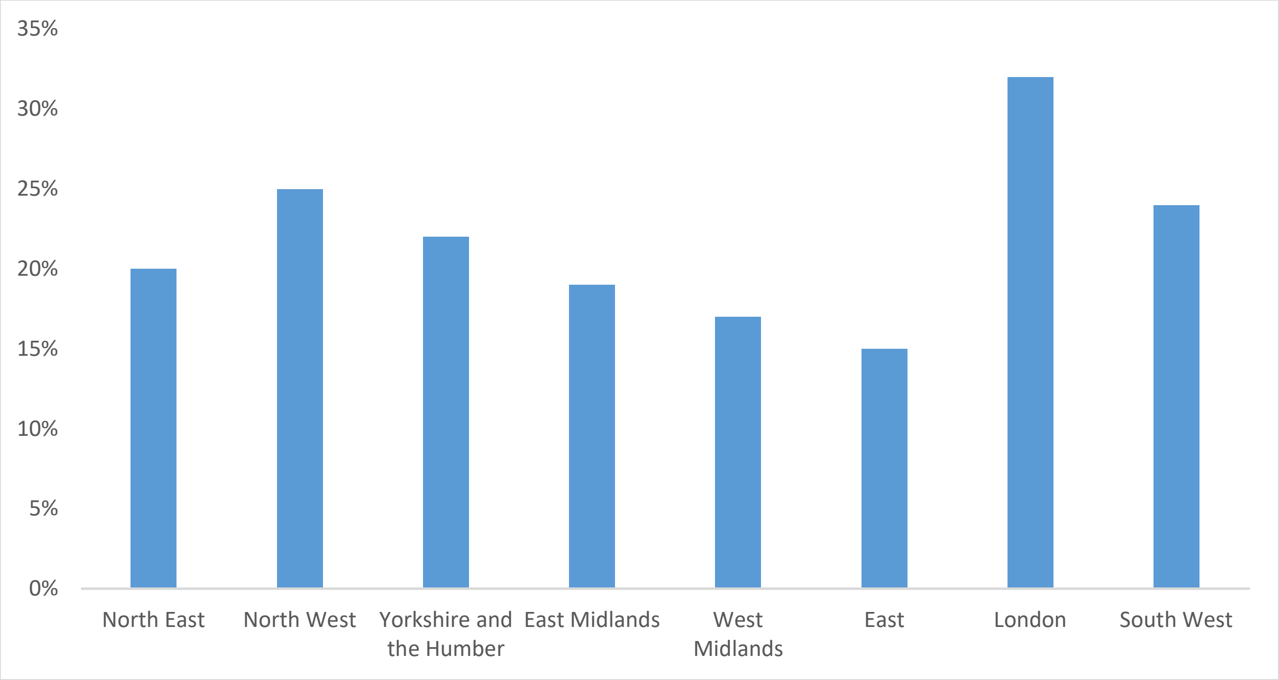

Figure 4: Proportions of pre-1919 domestic stock by region (VOA, 2015)

Based on the number of properties, dwellings account for 91.6% of the pre-1919 building stock (VOA, 2016), supporting findings of Whitman et al. (2016). Between 1991 and 2017, the number of pre-1919 homes decreased by 4% (BRE, 2020). Subsequently, the number of pre-1919 dwellings increased between 2018 and 2019. Heritage Counts 2019 identified that over 12% of 'new' housing in England in 2018-19 were conversions of pre-1919 non-domestic properties to domestic use (Historic England, 2020b). The types of pre-1919 dwellings changed since 2001 (DCLG, 2001; BRE, 2014) (**Figure 5**), particularly in relation to converted flats. These changes reflect not only demolitions but also conversions and changes of use (BRE, 2020).

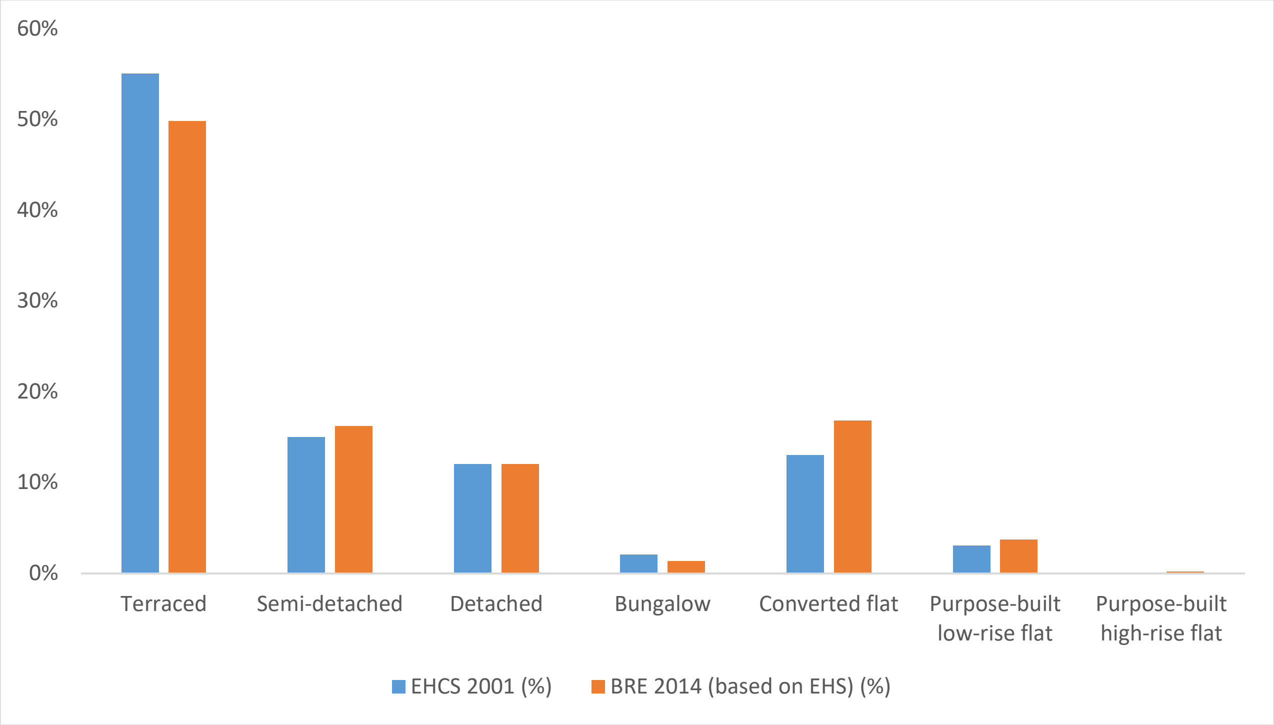

Figure 5: Types of pre-1919 dwellings (From BRE, 2014; and DCLG, 2001)

Based on the number of dwellings, terraces contribute around half of the pre-1919 housing stock (Whitman et al., 2016). More than three-quarters (78%) of dwellings constructed prior to 1919 are either terraced, semi-detached or detached. However, this distribution varies between periods of pre-1919 dwellings. Although terraces predominate the Victorian (50.5%) and Edwardian (58.5%) periods, detached houses (37.4%) is the main house type constructed prior to 1850 (Nicol et al., 2014) (**Figure 6**).

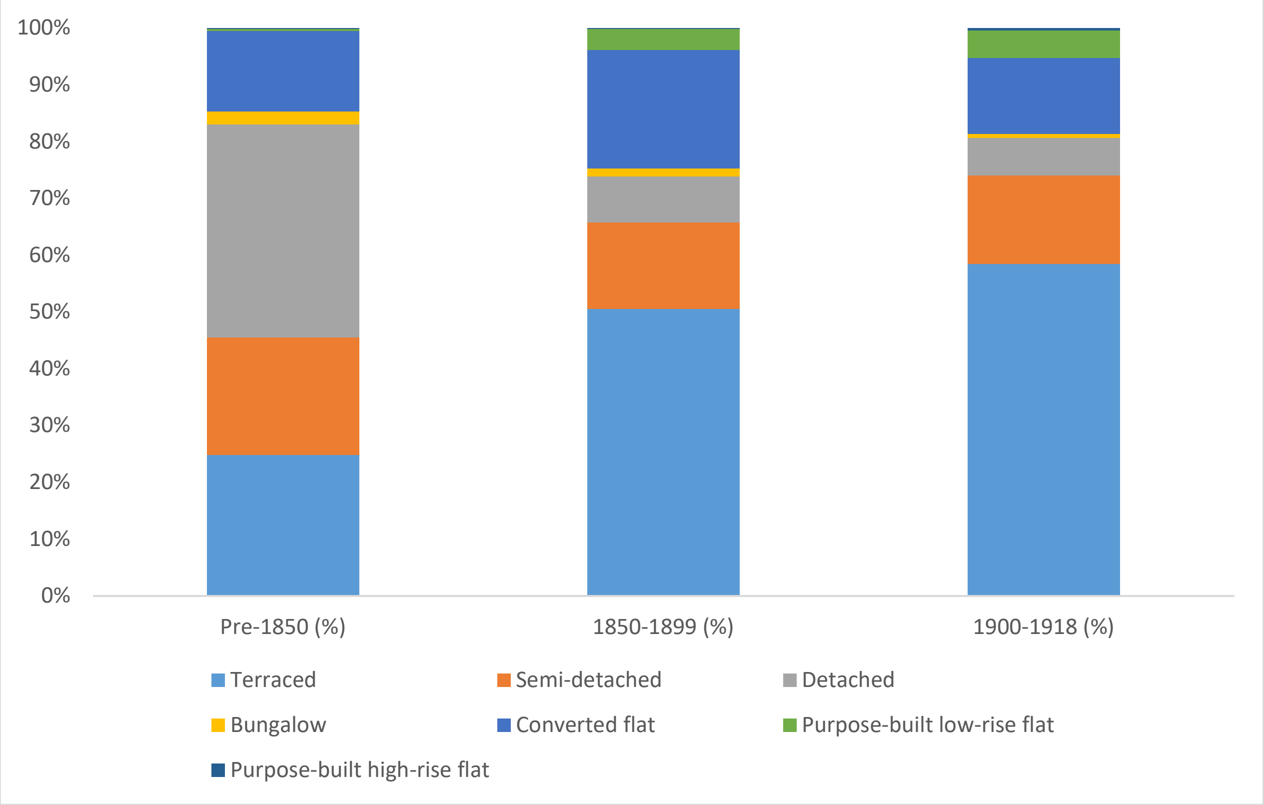

Figure 6: Types of pre-1919 dwellings by period (Nicol et al., 2014)

3.2 Other benefits of improving energy efficiency

Of all houses designated as 'non-decent' and, based on EPC rating, least efficient in England, 64% have been identified as likely to have been built prior to 1919 (DCLG, 2018). This age category has been identified as representing some of the least efficient buildings in England (Dowson et al., 2012), and 35% of pre-1919 properties have been identified as 'hard to treat' (DGLG, 2018a). However, this segment of the housing stock has lasted for more than a century. They also represent multiple values[15] and benefits, incorporate varying levels of embodied lifecycle energy and carbon. Additional benefits from heritage include contributing to a 'sense of place', adding to the character of an area (British Property Federation, 2013), add to local communities' knowledge and sense of identity, and can boosts social capital (Historic England, 2014).

The housing stock has been highlighted as requiring significant improvement to contribute to UK climate change objectives, as well as to improve its climate resilience to mitigate risks such as overheating (CCC, 2019). Improving the thermal comfort of housing has a number of additional benefits including a reduction in absences from work (38%) and school (50%),

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[15] Heritage values fall into four main groups: evidential value; historical value; aesthetic value; and communal value. The term 'significance' is a collective term for the sum of the heritage values embodied by a place (Historic England, 2008)

reduced childhood asthma, improved educational achievements, (Department of Health, 2010), reduced risk of heat- and cold-related deaths, reduced energy bills, and lower levels of fuel poverty[16] (CCC, 2019).

Fuel poverty has been associated with poor physical and mental health, and excess winter deaths (Thomson et al., 2017). The annual cost to the NHS of poor housing in England has been estimated to be between £1.4 and £2 billion (CCC, 2019) and the Department of Health (2010) estimated the annual cost of NHS treatment of winter-related disease in cold private housing to be around £859 million, and investing £1 to keep homes warm would save the NHS 42p. In a longitudinal qualitative study of mixed-tenure, low-income communities in Wales, it was found that improving energy efficiency of homes at risk of fuel poverty improved occupant well-being, thermal comfort, social interactions and the use of the indoor space (Grey et al., 2017). The improvements were also shown to alleviate financial stress.

The largest proportion of fuel poor households (16.7%) have been identified as residing in pre-1919 dwellings, interpreted by BEIS (2020b), reflecting both the average energy efficiency of pre-1919 dwellings and the higher than average floor area, resulting in higher fuel bills. Castaño-Rosa et al. (2019) found that dwelling size and type of household are important factors in relation to vulnerability to fuel poverty. Energy efficiency interventions can therefore reduce fuel poverty vulnerability. However, there are a number of other factors that can contribute to fuel poverty which are not associated with energy efficiency or inefficiency, such as the high cost of energy, low income, ill-health which are also associated with poverty more generally (Middlemiss, 2016). That is, improving the energy efficiency of dwellings will not necessarily resolve fuel poverty without considering the multiple factors contributing to a household being designated as 'fuel poor'.

3.3 Effect of tenure

Almost two-thirds (61%) of the pre-1919 housing stock is thought to be privately occupied (owner-occupied 21.3%; 39.7% private rented) (**Figure 7**) (DCLG, 2010a). Whilst tenure type has been identified as relating to energy consumption, Huebner et al. (2015) emphasises this is confounded by building characteristics, occupancy and energy patterns (e.g. working from home). Further, tenants may have less control over the type and operation of their heating system, and this may affect energy consumption (Kearns et al., 2019). In the private housing sector the DCLG (2014) estimates that 29% are solid walled dwellings compared with 13% in the social housing sector. Of all EPC F and G rated houses in England, the private

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[16] Thomas et al. (2017) highlight the difficulty in determining fuel poverty with a single metric. Previously defined as when a household spends more than 10% of their income on fuel bills (Swan et al., 2017), the Low Income High Costs (LIHC) indicator currently defines fuel poverty as when a household has fuel costs that are above the national median level. Therefore, were they to spend the amount required to heat their home to 'adequate temperature', they would have a residual income below the official poverty line. There are criticisms of the LIHC indicator, some arguing it has little value (Thomas et al., 2017). It is also worth noting that there have been significant adjustments in the distribution of fuel poor households since changing to the LIHC indicator to determine fuel poverty. For an analysis of this and a critique of the LIHC indicator, see Robinson et al. (2018).

rental sector contributes to 28% (DCLG, 2018a). The private rental sector also accounts for 19.4% of fuel poor households in England (BEIS, 2019b). Recent legislation is helping to drive improvements in the performance of the private rental sector.

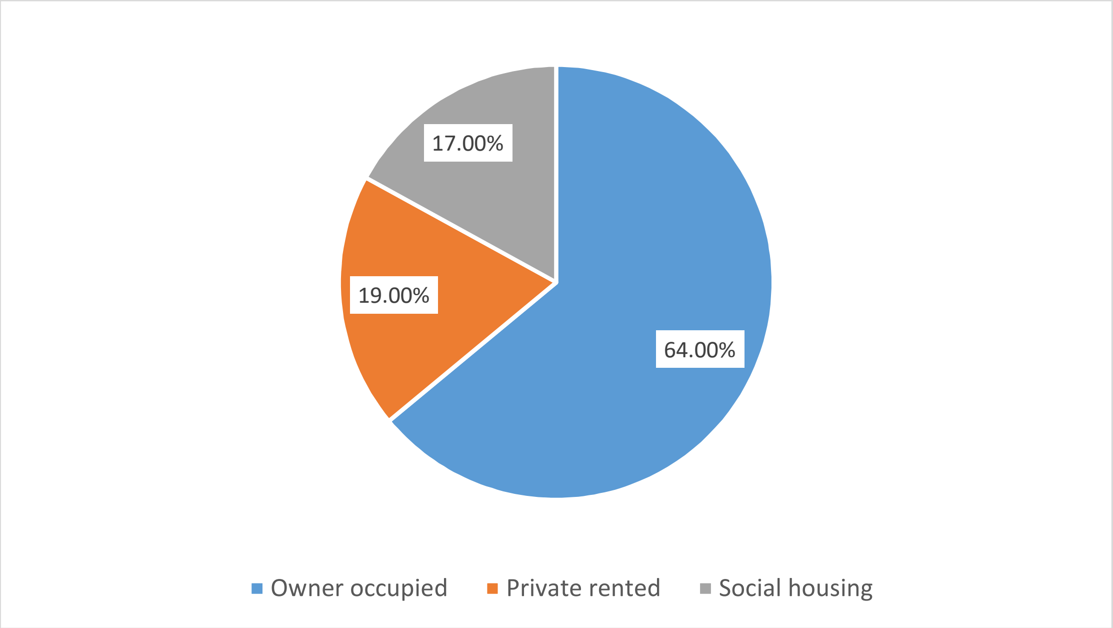

Figure 7: Tenure across pre-1919 housing stock (DCLG, 2019b)

As of 1st April 2018 the Energy Efficiency (Private Rented Property) (England and Wales) Regulations 2015 made it unlawful to lease property failing to attain minimum energy efficiency standards (MEES) as determined by a property's energy performance certificate rating, which is underpinned by Reduced Standard Assessment Procedure calculation (RdSAP). Unless exempt, where private rental properties fail to comply with MEES, local authorities can issue a compliance notice, publish information pertaining to the breach and issue a penalty of up to £5,000 (BEIS, 2017c). The aim of this standard is to reduce the proportion of calculated thermally inefficient, fuel poor housing.

3.4. Location of pre-1919 housing

When considering location types, pre-1919 dwellings are the predominant period in city centres (46.6%), villages or rural locations (44.3%), or other urban centres (39.4%) (DCLG, 2010b) (**Figure 8**). The proportion of city centre locations is much higher for pre-1919 housing than later periods of construction. However, almost 70% of dwellings constructed prior to 1850 are in rural locations (BRE, 2020). In relation to heating fuel, it is worth noting that homes in isolated rural locations or in village centres were less likely to be connected to a mains gas supply (DCLG, 2010a), with 84% of all pre-1919 houses and bungalows connected to mains gas compared with 87% of the English housing stock overall (DCLG, 2015a). Whilst 8% of households in England are heated by electricity, the second largest percentage after mains gas (Ofgem, 2015). For rural homes heating oil represents the largest source of fuel for heating after mains gas (Consumer Futures Unit, 2018). This is the same for pre-1850s homes (Consumer Futures Unit, 2018), although it is not clear whether or not this is due to a high proportion of pre-1850s properties being located in rural locations.

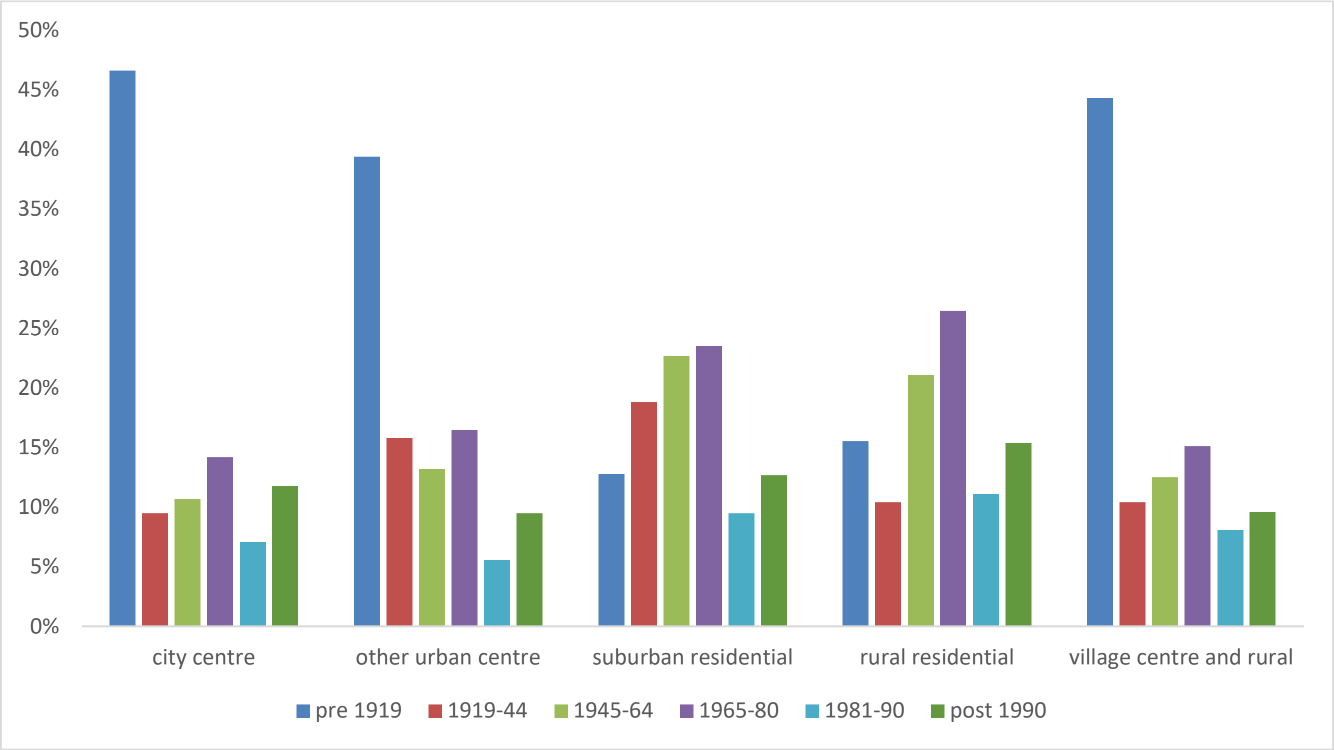

Figure 8: Location distribution for periods of housing in England (DCLG, 2010b)

Since changes have been made to how fuel poverty is calculated, the proportion of fuel poor households has reduced across all regions in England to differing extents (Robinson et al., 2018). Regions with the highest proportions of fuel poverty under the Low Income High Cost indicator are the West Midlands (15.2%), East Midlands (13.2%), North East (11.6%) and North West (11.3%). Previously the South West had a high proportion of fuel poor households, a region with a high percentage of Lower Social Output Areas[17]. Such areas have been more vulnerable to fuel poverty under the previous calculation methods, attributed to their lack of access to a range of fuel types and lower thermal efficiency of the buildings (Robinson et al., 2018). The current method of calculating fuel poverty is also less likely to recognise households as 'fuel poor' if the dwelling is under-occupied, more common amongst owner-occupied rural dwellings (Robinson et al., 2019).

3.5 Retrofit and modelling of Pre-1919 construction

The UK has the oldest housing stock in Europe (Roys et al., 2016). Generally, historic buildings and those of traditional construction are likely to perform differently in comparison with their modern counterparts. They are often viewed negatively in relation to energy efficiency, but their actual performance may, in part, reflect alterations and improvements made over the

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[17] Lower Social Output Areas is a geospatial statistical unit. It relates to small areas and is intended to improve the reporting of statistics relating to those areas.

lifespan of the building as well as a divergence from assumptions made in energy calculations and occupant behaviours. Pre-1919 buildings have usually been built using traditional construction, most commonly solid masonry walls (Historic England, 2015) (**Figure 9**). Suspended timber floors are the predominant floor type (Pelsmakers et al., 2019a), three-quarters of pre-1919 housing having a suspended timber floor across all or part of the ground floor (Pye and Harrison, 2003). Across the UK, it is estimated that 10 million suspended floors are uninsulated (Pelsmaker et al., 2019b).

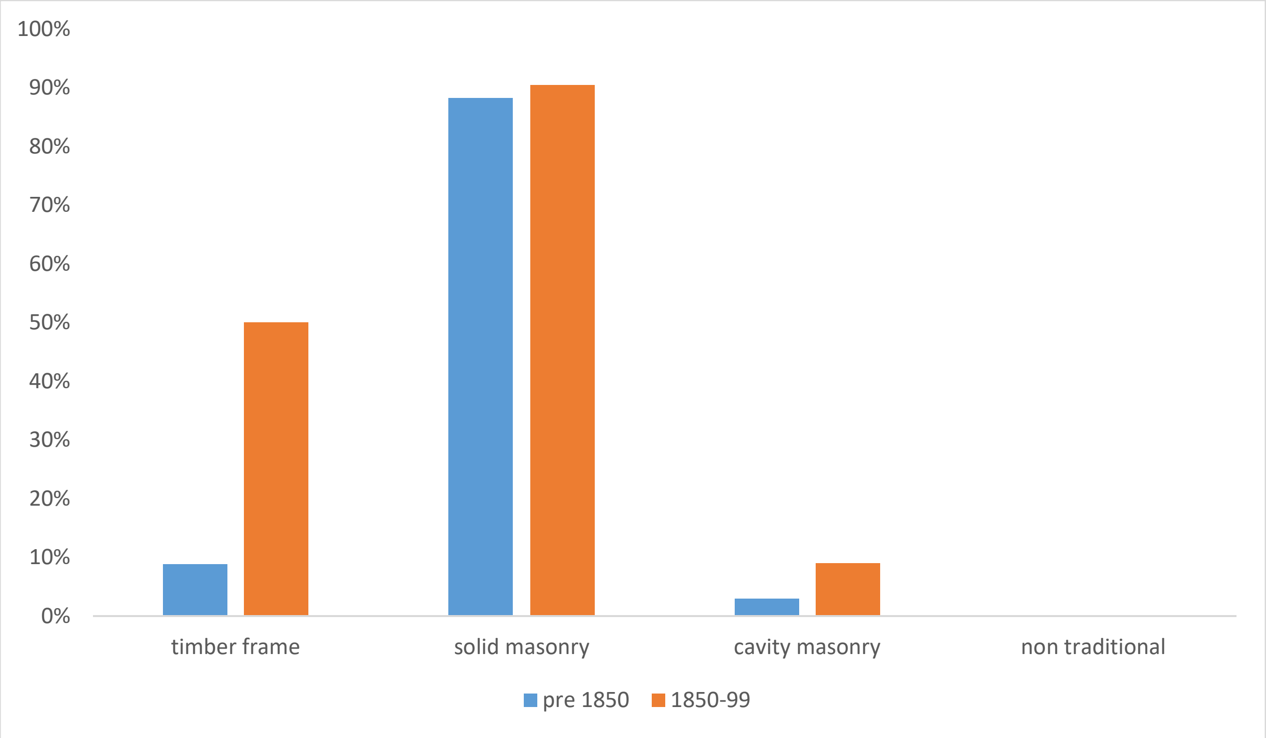

Figure 9: Wall construction types in the pre-1919 English housing stock (DCLG, 2010b)

Whilst a range of walling materials have been used to construct pre-1919 buildings, the predominant material used is brick, with an estimated 70% of solid walls 9-inches thick (Li et al., 2015). The most popular wall finish for pre-1919 walls is pointed brickwork (68.5%) but around a fifth (22.8%) of pre-1919 walls have a rendered finish (DCLG, 2010). For properties constructed prior to 1850, masonry walls are commonly more than 9-inches thick (DCLG, 2010). The thickness of the wall needs consideration in relation to the thermal mass as a thermal buffer, but also in the appropriateness and location of solid wall insulation (Hall et al., 2011).

Solid walls can act as a heat store (Historic England, 2015), providing the opportunity to regulate internal temperatures. However, they are considered a challenge for UK energy and buildings policies (Li et al., 2015), as solid walled buildings can be classed as 'hard to treat', referring to the difficulty in applying 'standard' energy efficiency measures such as cavity wall insulation (Sunikka-Blank and Galvin, 2016). 'Hard to treat' walls can also include pre-1919 cavity walls which may be unsuitable for retrofilling with insulation, and would limit options to internal or external wall insulation.

Pre-1919 housing tends to have larger usable floor areas (**Figure 10**) and to be constructed with permeable materials (Webb, 2017) which readily allow for the ingress and egress of moisture without causing damage to the building (Historic England, 2015). Therefore, consideration is needed to avoid inhibiting this absorption and evaporation of moisture by modern interventions, which could cause damage to the building. Further, where moisture becomes trapped and causes a building component such as a wall to remain damp, this will increase the thermal conductivity of the component, increasing the rate of heat transfer (Walker and Pavia, 2016). For example, there is evidence that, based on in-situ U-value measurements, the wet thermal conductivity of traditional brick walls can be 1.5 to 3 times greater than the dry thermal conductivity (Rhee-Duverne and Baker, 2013).

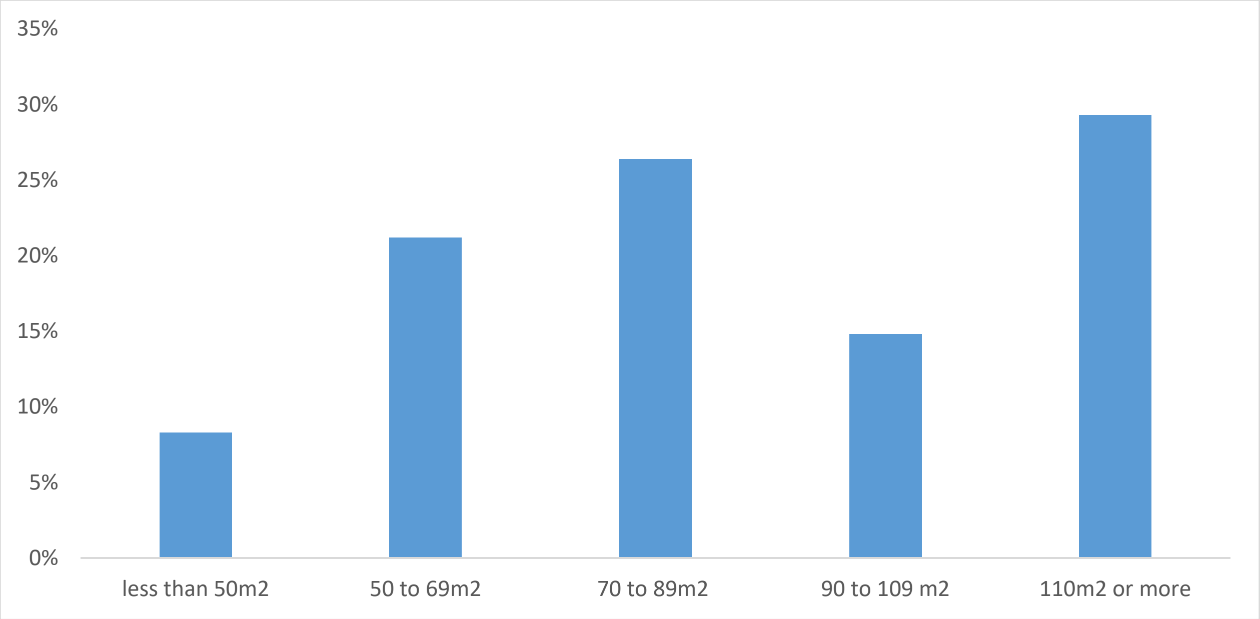

Figure 10: Total usable floor area in the pre-1919 English housing stock (DCLG, 2010b)

There are different assumptions made about the thermal performance, energy demand, energy intensity and emissions relating to traditional buildings. Based on their calculated operational energy usage, pre-1919 properties average 23 fewer points in the Standard Assessment Procedure (SAP) compared with post-1990 properties (DCLG, 2015b). As highlighted by Whitman et al. (2016), EPC, which are based on SAP, are modelled using a number of assumptions rather than measured data. Therefore, such energy ratings do not provide a reflection of actual energy use and does not reflect the wider sustainability of a property. This is a particular issue for all properties assessed with Reduced data SAP (RdSAP).

As with energy models generally, SAP has been identified as having a number of limitations (Summerfield et al., 2011) particularly in relation to historic buildings, including in relation to assumptions about U-values and air tightness (Whitman et al., 2016). In relation to all buildings, it is also worth noting that SAP only considers 'regulated loads', excluding energy consumption and carbon emissions arising from small power plug loads (Dowson et al., 2012), such as appliances.

RdSAP is a simplified version of SAP typically used for existing buildings to enable a calculation of the energy performance of such structures in the absence of complete information (Jenkins et al., 2017), and 'full SAP' is usually applied to newly constructed properties and is more detailed than RdSAP (Ingram et al., 2011). RdSAP has been criticised for using unrepresentative information in the model and has been shown in previous research to predict higher energy demand than full SAP (Ingram et al., 2011), disproportionately disadvantaging pre-1919 buildings. Research also indicates that multiple EPC assessors have been found to produce different results for the same property, with pre-1919 buildings experiencing the greatest difference in rating outputs (Jenkins et al., 2017). Despite assessors being required to undertake the same training, an EPC verification process, and software improvements. This may highlight the importance of the assessor knowledge but also the range of unknowns relating to aspects such as the diversity in construction and the existing building fabric. 'Full SAP' can be applied, and is preferable to apply, to existing buildings where an assessor has access to the additional data required. Access to this information may be difficult with pre-1919 buildings, and may support an argument for in-situ U-value measurements to be taken. However, this is likely to increase the time and cost involved in producing an accurate assessment of the energy performance of a building, and the required assessor knowledge. It also indicates the potential for the development of technology to support a more accurate energy performance assessment using in-situ measurements.

It is unclear to what extent the pre-1919 building stock has been 'improved[18]', particularly in relation to energy efficiency. However, 60% of all pre-1967 housing in England is reported to have had some form of major improvement since construction, 15% having been completely renovated (Piddington, 2020). Given that dwellings typically undergo a major refurbishment every 50 years (Simpson et al., 2016), in the context of the pre-1919 housing stock this is hardly surprising. In the pre-1919 housing stock the most common improvements have been identified as the reconfiguration of internal space (31.5%), an extension for amenities (31.1%) and a complete refurbishment (25.7%) (DCLG, 2010) (**Figure 11**).

There may, therefore, be a large opportunity for energy efficiency improvements at the point of general building improvements or extensions. In the wider housing stock, this has been associated with 'trigger points'[19] and 'consequential improvements'[20]. In relation to EPC recommended improvements, boiler upgrades have been suggested for 78% of the pre-1919

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[18] Here 'improved' is taken to mean increased thermal performance of the building fabric and/or improved efficiency of building services.

[19] Trigger points: salient events such as a boiler breaking down or life events such as moving house that result in works being undertaken and thereby provide an opportunity for improving home energy efficiency (Wilson et al., 2015; Fawcett, 2014)

[20] Consequential improvements whereby homeowners are required to undertake additional energy efficiency measures when undertaking other home improvement works (Simpson et al., 2016).

housing stock, followed by increasing loft insulation (37%) and improved heating controls (32%) (DCLG, 2009 – EHCS, 2007) (**Figure 12**). BRE (2008) suggests that the most common thicknesses of loft insulation in pre-1919 housing are 50 – 99mm and 100 – 149mm.

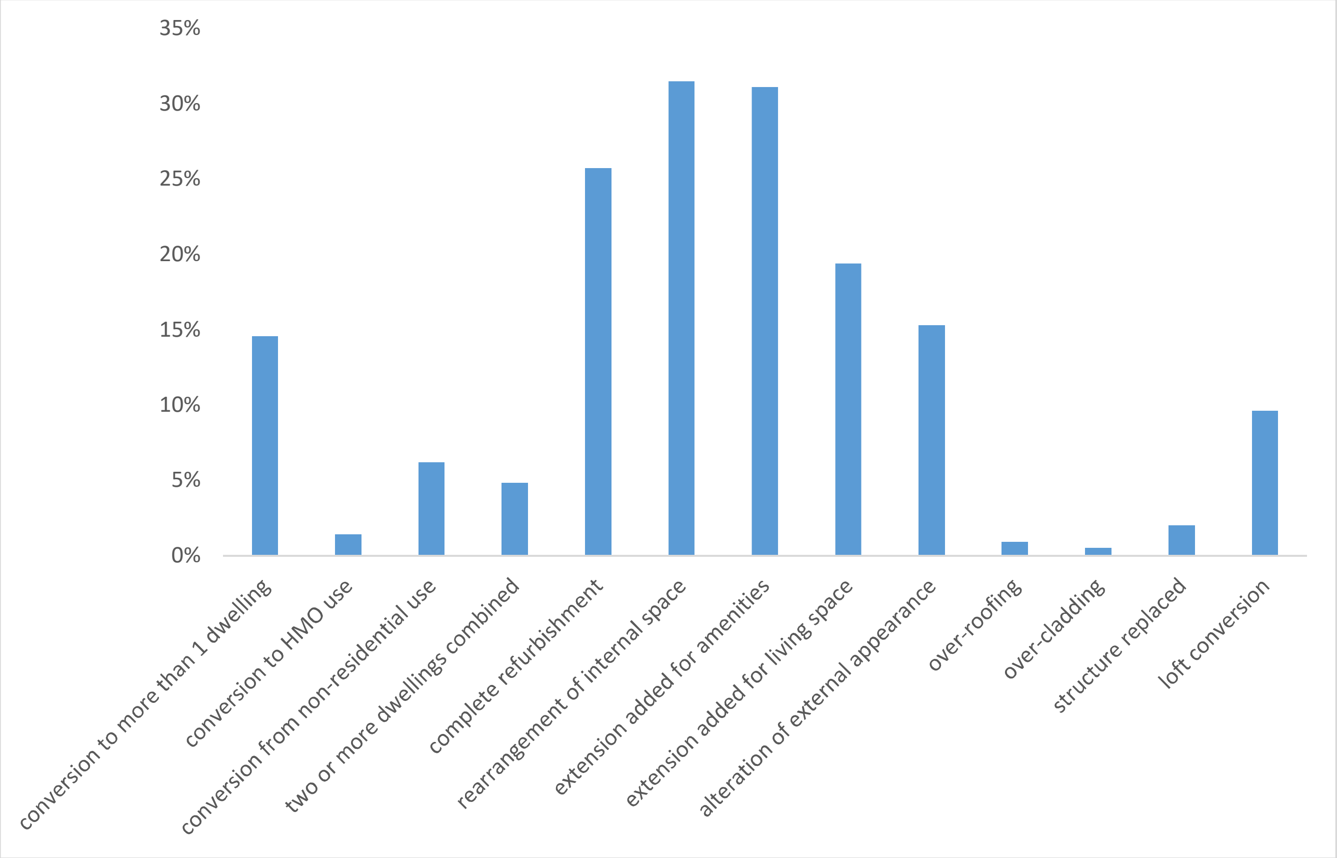

Figure 11: Common improvement measures in the pre-1919 housing stock in England (DCLG, 2010b)

It is worth noting that, based on EPC recommended measures, the pre-1919 housing stock generally appears to have lower proportions of measures recommended than homes from other periods of construction, although it is unclear whether this is due to the measures having already been installed or due to their judged inappropriateness. Further, caution is needed when considering recommended measures such as cavity wall insulation for pre-1919 housing as indicated in **Figure 12**, as this measure is unlikely to be appropriate for the majority of early cavity walls as these tend to perform differently from their modern counterparts (Historic England, 2012).

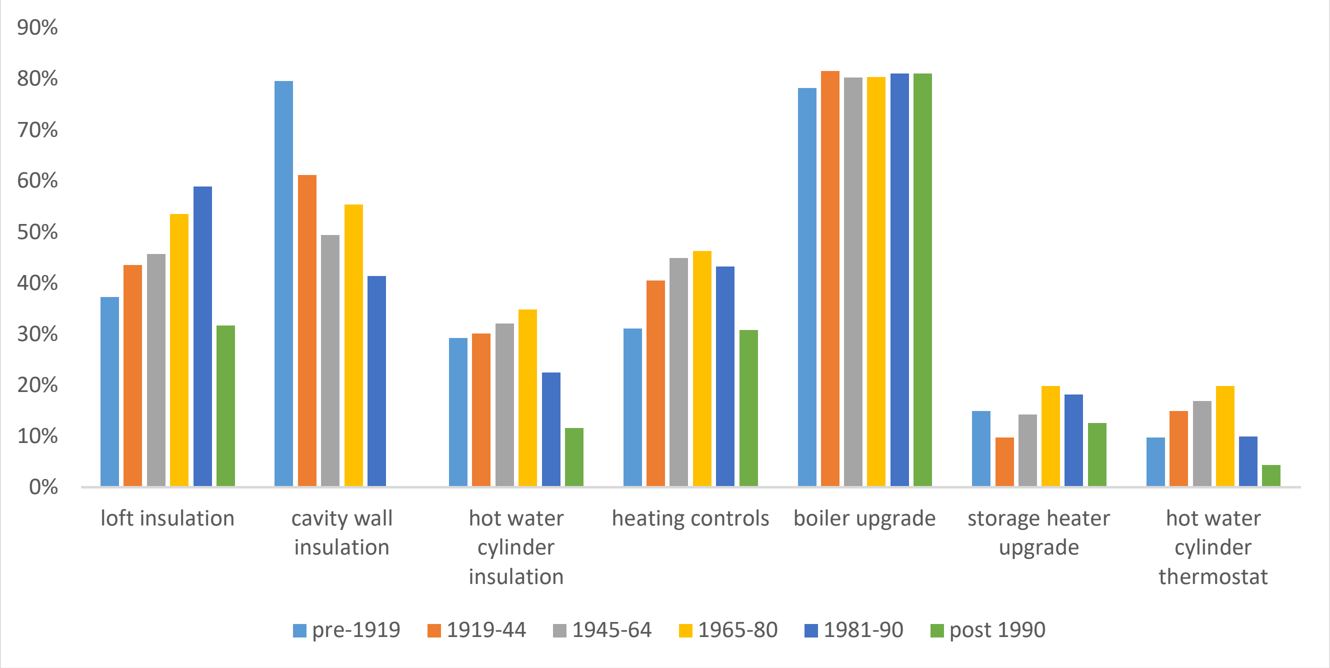

Figure 12: EPC recommended measures by construction date (DCLG, 2009)

Using the Homes Energy Efficiency Database for Norfolk, Foulds and Powell (2014) identified pre-1900 dwellings to have a strong correlation with complete single glazing, no loft insulation and no wall insulation. This supports findings by the DCLG (2010) that a higher proportion of dwellings constructed prior to 1919 were likely to be single glazed, and the most common frame material for single glazing in pre-1919 housing is timber (32.4%). However, half of pre-1919 dwellings have been estimated to have PVCu double glazing installed (DCLG, 2010) (**Figure 13**).

In addition to the lack of a regulatory requirement for energy efficiency at the time of construction, Fowler and Powell (2014) suggest single glazing and a lack of insulation may be attributable to building conservation constraints (supporting the findings of more recent research (e.g. Hilber et al., 2019; Kaveh et al., 2018)), and lack of access to components (supporting findings by Gillich et al. (2019)). Indeed, replacing existing single glazed windows can unacceptably alter a building's appearance and therefore secondary glazing may be the preferred option for listed buildings or those in conservation areas (Historic England, 2016), particularly on front elevations.

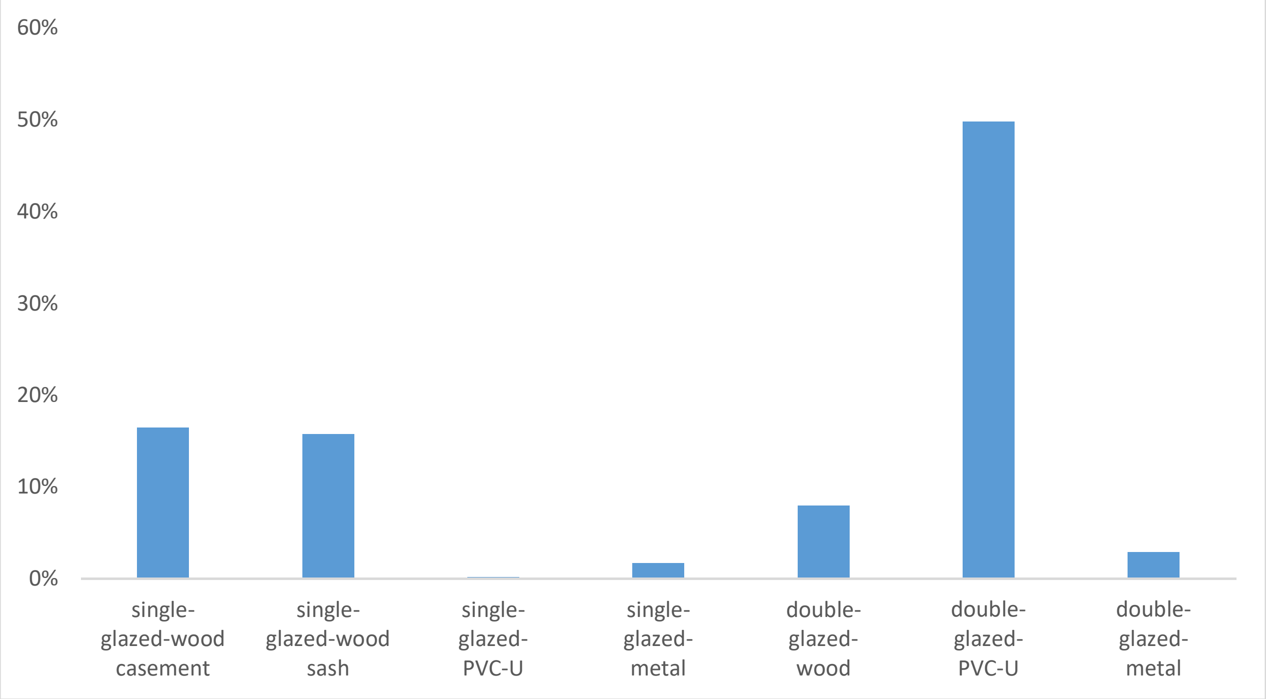

Figure 13: Glazing types in pre-1919 English housing stock (DCLG, 2010b)

The preceding section suggests that improving the thermal and energy efficiency of the historic building stock represents multiple challenges (Whitman et al., 2016), including the calculated thermal efficiency of historic building fabric, the suitability of measures for traditional buildings, and risks resulting from maladaptation. The calculated thermal efficiency poses a particular issue when attempting to calculate the possible energy and carbon reductions possible from intervention due to the variety of variables associated with the heterogeneous pre-1919 building stock.

3.6 Heritage value

The National Planning Policy Framework (DCLG, 2019c) states:

> "*Heritage assets range from sites and buildings of local historic value to those of the highest significance, such as World Heritage Sites which are internationally recognised to be of Outstanding Universal Value. These assets are an irreplaceable resource, and should be conserved in a manner appropriate to their significance, so that they can be enjoyed for their contribution to the quality of life of existing and future generations*"

Historic buildings are assets which have been determined to possess three attributes (Webb, 2017), and therefore require protecting:

> **Age** – usually more than 50 years, although buildings can be listed from 30 years from construction.

Integrity – the property's physical characteristics from a historic period(s) should have been retained

Significance[21] – the property must be of special architectural or historic interest

Listing protects against the loss of character or the special architectural or historic interest embodied by an asset. The older and rarer a building is, the more likely it is to be considered to be of 'special interest' (Department for Digital, Culture, Media and Sport, 2018). Of the pre-1919 building stock, buildings dating before 1700 which retain a significant amount of their original fabric are likely to be of special interest. Buildings constructed from 1700 to 1850 that retain a significant proportion of their original fabric are also likely to be considered to be of special interest, although some selection for designation is necessary. Due to the large number of surviving buildings erected between 1850 and 1945, progressively greater selection is required.

Heritage buildings contribute to local character and their inherent values may result in them becoming legally protected (Cabeza et al., 2018). In the UK, buildings and areas of special interest can be protected under the Planning (Listed Buildings and Conservation Areas) Act 1990. Protected buildings are those which are 'listed', or located within a designated conservation area or World Heritage Site (BSI, 2020). The legislation aims to manage changes to listed buildings or unlisted buildings within a conservation area, protecting against damage to or loss of significance (Rispoli and Organ, 2018).

Designated historic buildings are a sub-set of historic building stock. Sunikka-Blank and Galvin (2016) argue that, even when a building is not deemed significant and is undesignated, there is aesthetic value for properties and streets which lie outside of statutory protection. For those constructed prior to 1919, the performance of undesignated and designated traditionally constructed buildings will be the same where all other factors are the same (i.e. building services, features, interventions, occupancy). Therefore there is scope to adopt a similar approach to enhance the performance such buildings. The benefit of designation, however, is that it affords greater opportunity for positive management of sustainable decisions relating to changes. This can help avoid issues such as inappropriate interventions which can undermine the longevity of the fabric or structure.

Whilst there is no agreed absolute number of heritage buildings, it is known that there are approximately 600,000 listed buildings across the UK (Historic England, 2020a; Welsh Government, 2018; British Listed Buildings, 2018; and Nidirect Government Services, 2018). Of this, 400,000 listed buildings are estimated to be in England - Grade I (2.5%), Grade II* (5.8%), and the remaining are Grade II (Historic England, 2020a). Of the pre-1919 building stock a large proportion of pre-1840 buildings are likely to be listed but buildings constructed between 1840 and 1919 are less likely to be listed (Whitman et al., 2016). Unlisted pre-1919

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[21] Significance also derives from a building's setting, as well as its physical presence (Historic England, 2020c).

properties not located within a conservation area, will not normally have the same level of legal control as their listed and conservation area counterparts. However, their construction is usually similar and their appearance may be equally important to maintaining the character of the locality. Although the exact number of unlisted pre-1919 properties across England is not currently known, there is ongoing research in this area (UCL Energy Institute, 2020).

Conservation areas are designated based on an area's special architectural or historic interest (Historic England, 2019). There are approximately 10,000 designated conservation areas in England, forming special protection of the character or appearance of a designated area (Historic England, 2019). Whilst no definitive estimate of the number of buildings in conservation areas currently exists, Bottrill (2005) used typical housing density for a particular local authority and the size of the conservation area (hectare) to estimate that there are over 1.2 million dwellings in conservation areas across England, Scotland and Wales. Of this, she estimates 1,093,529 dwellings are located within conservation areas in England. The existing literature does not, however, appear to provide any estimation of non-residential buildings in conservation areas. The overlap of listed buildings in conservation areas is also unknown, although Boardman (2007) suggests this may be considerable.

Legislation governing building conservation is perceived to reduce opportunities to increase the energy efficiency of listed buildings, or those which are located within conservation areas, by limiting changes and/or adoption of measures or systems to those appropriate to the character of a property (Hilber et al., 2019; Kaveh et al., 2018). Measures such as external wall insulation can particularly affect the character of heritage properties and therefore it may not be possible to install such measures on the grounds of the significant visual impact it is likely to have, although there are some exceptions when external insulation can improve the external appearance. However, there are opportunities to use measures that compliment such buildings, and opens the potential for innovative approaches (Pigliautile et al., 2019; Zagorskas et al., 2014), although care is needed in applying innovative measures to avoid negative unintended consequences.

Fouseki and Cassar (2014) argue that any intervention project should seek to give at least equal importance to heritage values as energy priorities, if not more, and interventions should be positioned within the framework of the Burra Charter. They highlight that to achieve a balance between comfort, cost-effective energy technologies and heritage preservation, there needs to be a dialogue, compromise and negotiation between professions. It is possible to successfully undertake interventions without compromising the significance of heritage buildings through such dialogue, informing the specification of methods and materials employed (Organ, 2019).

3.7 The performance of the pre-1919 stock

British Standards (BS 7913 2003 - section 4) states that '*understanding the significance of a historic building enables effective decision-making about its future*'. Understanding of the performance of historic buildings is improving, and there is a recognition that the thermal performance of the fabric of these buildings is often better than predicted (Li et al., 2015; Agbota et al., 2014; Rye and Scott, 2012; Baker, 2011), while newer buildings can often be worse (Li et al., 2015). This includes a performance gap between designed and measured performance in 188 new low energy housing (Gupta and Kotopouleas, 2018). The difference between actual and predicted energy savings is known as the energy performance gap. This will be discussed in further detail in Section 3.8. Gupta and Kotopouleas (2018) found that better detailing and workmanship were crucial in addressing the performance gap in new low energy housing, particularly in relation to air permeability and 'thermal defects' detected in the building fabric. Based on analysis of 471 dwellings in the BRE database, Stephen (2000) found that the mean air tightness of properties constructed prior to 1900 is 12 - 13 air changes per hour (arch) at a pressure of 50 Pa, this research indicating air leakage rates increased in the 1920s, although buildings in the sample constructed after 1980 achieved the lowest air leakage rates. Stephen (2000) also noted that solid masonry walls achieved a lower mean air leakage rate than cavity walls, although worse performance relative to timber-framed brick clad buildings, and large panel systems.

There is a general assumption that the historic building stock has a higher energy use per unit area when compared with their modern counterparts (Moran et al., 2012; Whitman et al., 2016). An association has been identified between energy consumption and floor area (DECC, 2013), although in reality energy consumption is affected by multiple factors such as number of occupants, the level of thermal efficiency, occupant behaviour, and so on. While pre-1919 housing has been identified as typically having a higher level of energy consumption than average of all dwellings, DECC (2013) notes that this is lower than the 1919 – 1944 housing stock across all floor areas and that the age of a property has less influence on energy consumption than other attributes such as household income and property size. Research based on the analysis of household energy use questionnaires from pre-1919 dwellings in a conservation area in Bath has shown that lower than average levels of energy consumption from historic housing have been achieved when the property has been retrofitted with energy efficiency measures (Moran et al., 2012). Although the research does not consider types of tenure, it does suggest that income, household age, number of rooms and low energy lighting were not significant predictors of energy consumption in pre-1919 housing.

It has been suggested that, when considered across their lifecycle, accounting for their embodied energy (Crockford, 2014; Power, 2008), the energy profile of pre-1919 buildings is better than that of new buildings (Cultural Property Technical Committee 346, 2015). Therefore, to continue to enjoy that advantage and avoid what Akande et al. (2016) call 'environmental obsolescence', improving the energy efficiency of historic buildings is important, provided such improvements do not lead to negative unintended consequences.

3.7.1 U-values

A U-value of 2.1 W/m^{2}K has been previously assumed for traditional solid walls in calculations such as RdSAP. Existing research has shown that modelled U-values for solid walls have generally been poorer than in-situ measurements (Li et al., 2015; Watson, 2015; BRE, 2014;

Hulme and Doran, 2014; Rhee-Duverne and Baker, 2013; Stevens and Bradford, 2013; Rye and Scott, 2012). In a sample of 34 different walls, research by Rye and Scott (2012) highlighted that 77% of the sample had calculated U-values in excess of the in-situ measurement. That is, the thermal performance in-situ was better than predicted.

Strong evidence exists showing that the thermal performance of solid walls is better than 2.1 W/m^{2}K (BRE, 2016a). In light of the increasing evidence relating to walls, the assumed U-value for walls has since been reduced in RdSAP (BRE Group, 2019). Although the assumed U-value for solid walls constructed prior to 1975 is now 1.7 W/m^{2}K (BRE Group, 2019), there remains evidence that the actual U-value of a number of solid walls will be lower. However, there does not appear to be agreement in the literature about an alternative standard U-value.

The accuracy of U-values can be improved by providing more information about the layers and materials used within a wall, but this can be difficult to determine (Rye and Scott, 2012). It is also worth noting that research on U-values by Historic Environment Scotland (Baker, 2011) has highlighted that the thickness of a solid wall will affect its actual U-value. For example, in-situ measurements of a 600mm thick solid wall had a U-value range of 0.8 to 1.6 W/m^{2}K, and stone walls 300mm thick ranged from 1.1 to 1.5 W/m^{2}K. Whilst this indicates greater thermal resistivity is associated with thicker walls, because non-invasive measurements were taken it is unclear to what extent the wall composition including the materials and moisture content were considered in the research.

In research commissioned by the government, the BRE (2014) undertook in-situ U-values of 118 solid walls and 159 cavity walls. Both 'standard' and 'non-standard' solid walls were found to have a mean average measured U-values of 1.57 W/m^{2}K and 1.28 W/m^{2}K respectively (median values were 1.59 W/m^{2}K and 1.28 W/m^{2}K respectively). Although the non-standard solid walls were observed to have a wider range of U-values, this was interpreted as reflecting the diversity of walls within this group (i.e. range of widths and materials). Similarly, measured U-values for uninsulated cavity walls were found to be better than assumed. Li et al. (2015) suggest a mean average U-value of 1.3 W/m^{2}K for solid walls[22]. In their research they note that the distribution of measured U-values for solid brick walls and the mean average were similar to that of solid stone walls. However, they also highlight that some solid walls exceeded a U-value of 1.3 W/m^{2}K. This corresponds with Rye and Scott (2012) who calculated an average of 1.31 W/m^{2}K for 39 pre-1919 solid walls constructed of permeable materials. An argument therefore exists in favour of in-situ measured U-values rather than an assumed one (Rye and Scott, 2012), particularly when attempting to more closely predict potential energy savings from refurbishment.

More accurate representation of solid wall U-values is likely to improve their EPC rating. In Li et al.'s (2015) research, they suggest a change from 2.1 W/m^{2}K to 1.3 W/m^{2}K would result in a third of solid wall buildings moving by a whole EPC rating band, and a reduction of 6% in

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[22] No median value is reported in Li et al.'s (2015) publication. It is unclear from Rye and Scott's (2012) report whether a mean or median value is presented as the 'average' U-value.

calculated heat loss from solid walled homes. It is worth noting that where the measured U-value of a component is better than predicted, it may reduce the calculated energy savings and may also increase the payback period of installed measures such as insulation.

In relation to solid walls, underestimating their existing thermal performance presents a number of issues. It provides the potential for inaccurate reporting of the thermal performance of a building (Li et al., 2015), misinforming occupants and having possible financial ramifications for landlords in the private rental sector through legislation such as the Minimum Energy Efficiency Standard. Further, it is unlikely that the predicted energy and cost savings based on RdSAP will be realised, particularly in the case of solid wall insulation (Watson, 2015) resulting in an energy performance gap.

Some initial evidence about floor U-values indicates that, when in-situ measurements are taken across an uninsulated suspended timber floor, the actual U-value is worse than assumed in models, and in reality heat flow through a floor is likely to be higher than predicted (Pelsmakers et al., 2019a). Although further research on the heat loss of ground floors is required, if the thermal transfer of ground floors is greater than predicted, across the estimated 10 million uninsulated floors in the UK (Pelsmakers and Elwell, 2017), scaled up this could result in considerable potential for saving energy. Whilst insulating floors can be disruptive and considered to be only economically viable during a refurbishment (Dowson et al., 2012), this economic viability may improve where the pre-insulated thermal performance is poorer than estimated by models.

Limited research appears to have been undertaken on in-situ roof U-values. In their study of a 1970s detached dwelling in East Anglia, Elwell et al. (2017) noted that the thermal performance of the cold pitched roof was poorer than estimated. This may have been associated with under-insulated areas, particularly at the eaves, and ventilation.

Although the proportion of heat loss from windows will vary depending on the size and number of windows in each building, usually windows will account for a proportionally smaller surface area than other external components such as walls (Historic England, 2017a). They are generally assumed to account for 10% - 20% of building heat loss (Historic England, 2017a). Although there are exceptions, typically windows are small relative to wall areas so the cost of replacement double glazing will seldom be covered by energy savings within the lifetime of the insulated glazed units. In-situ measurements of single glazing have identified a U-value of around 5.5 W/m^{2}K (Baker, 2008), and window performance can be affected by thermal bridges and edge effects (Historic Environment Scotland, 2010), including in double glazed units (Cuce, 2018). In addition to the potential loss of the historic and aesthetic value of the original glass, Dowson et al. (2012) confirms that based on the payback period alone, replacing single glazing or early forms of double glazing may not be justifiable. Historic Environment Scotland (Baker, 2008) suggest that secondary glazing can reduce heat transfer through a window by 63%. Window coverings such as curtains, blinds and shutters are a lower cost intervention than secondary glazing and are likely to have a lower embodied energy. According to Historic Environment Scotland (Baker, 2008), timber shutters can reduce heat transfer through a window by 51%, a modern roller blind by 22%, and curtains by 14%. In recent research, window coverings have been shown to improve the U-value of single glazing and a reduction in heat transfer through the glazing of between 4% and 68% depending on the material (Fritton et al., 2017). When applied to single glazing, well-fitting shutters have been shown to have a slightly better U-value (1.92 W/m^2K) to low emissivity secondary glazing (1.96 W/m^2K) (Fritton et al., 2017). This is in-line with Wood et al.'s (2009) report for Historic England on the performance of traditional sash windows. Using two methods of measuring the in-situ U-value (i. glass only; ii. glass and frame) Wood et al. (2009) found that heat loss could be reduced using window coverings such as reflective roller blinds (i. 37%; ii. 38%), heavy curtains (i. 39; ii. 41%), well-fitting shutters (i. 64%; ii. 58%), low-emissivity secondary glazing (i. 63%; ii. 58%) and low-emissivity secondary glazing with well-fitting shutters (i. 73%; ii. 62%). In Baker's (2017) report on metal-framed windows, a heat loss reduction resulting from the use of heavy curtains (63%) was similar to the use of low-emissivity secondary glazing (68%) when compared with single glazing alone when taking U-value measurements through the glass and frame. Although this improvement in thermal performance only occurs when the window covering is closed, and is highly dependent on occupant behaviour, it may represent a lower cost, less invasive option to improving the thermal performance of windows. Such measures also have the potential to improve occupant comfort. However, it is not currently possible to model such improvements in SAP. Therefore it has not been included in the model assumptions, although

3.8 The energy performance gap

Buildings that have a calculated poor energy performance have been shown to consume less energy than predicted, whilst buildings with a high energy rating consume more energy than predicted (Cozza et al., 2019). Referring to the difference between predicted and actual energy performance (Pasichnyi et al., 2019; Zou et al., 2018), the energy performance gap is thought to have a variety of causes (Gillich et al., 2019), and is considered to be a 'major issue' (Green et al., 2019a) which needs to be addressed to reduce uncertainty about energy savings and performance. At a conceptual level, the main consideration is the failure to sufficiently acknowledge the distinction between energy efficiency and energy demand; whilst energy efficiency may increase, energy demand and consumption may continue to rise (Gillich et al. 2019).

The causes of the energy performance gap reported in the literature include a lack of understanding about how buildings perform in operation (Bordass, 2020; Bordass et al., 2004), the inaccurate energy models used to predict energy consumption (Pelsmakers et al., 2019a) or the assumptions used for the algorithms when calculating predicted energy use (Sunikka-Blank and Galvin, 2012) relating to assumed U-values, expected air change rate, and standardised internal temperatures (Cozza et al., 2019). The actual energy use of efficient buildings tend to be underestimated, while the models overestimate it for other buildings (Cozza et al., 2019), such as pre-1919 properties. The energy performance gap can be influenced by variations in the design and construction stages (Zou et al., 2018). Cuerda et al. (2020) have also highlighted the huge influence of occupancy, particularly in relation to behavioural patterns, in their mixed-methods research based on two dwellings in Madrid, Spain[23].

Based on a case study of two dwellings, Gupta and Chandiwala (2010) found that, to support a reduction in the gap between actual and modelled consumption, taking occupant preferences into consideration is important when selecting interventions for low-carbon domestic refurbishments. This included considering occupants' perception of comfort, energy behaviours and expectations. This was found to positively engage occupants and influence their behaviours post-refurbishment.

3.9 Occupants, behaviour and energy

Activities and occupancy patterns will also influence energy consumption within buildings. Indeed, factors such as location, orientation, building fabric, construction, building services, and the occupants will influence operational energy use (Historic England, 2018). The way these factors interact it known as the 'building performance triangle' (Historic England, 2018). In non-domestic buildings, there are a number of factors affecting operational energy. This extends beyond the physical characteristics of the building such as the thermal performance of the external fabric, geometric shape, plan depth and surface-to-volume ratio, but also to the activities within the building (Evans et al., 2017). The type of activities that take place within the building will determine the heating and cooling demand, electrical and lighting use, and occupancy levels and patterns (Evans et al., 2017).

Occupant behaviour can have a significant impact on energy consumption, and energy behaviours are highly variable due to factors such as occupant culture, upbringing and education (van Dronkelaar et al., 2016). Bergman and Eyre (2011) emphasise the need for a cultural-behavioural shift in the way households consume energy in parallel with improving the efficiency of homes, and Santangelo and Tondelli (2017) suggest that behavioural changes can be better effected when "a discontinuity occurs in the household context" such as renovation works.

There is some evidence to suggest that occupant behaviour may have a stronger impact on energy savings than physical intervention considered to be acceptable for listed buildings (Ben and Steemers, 2014). Clear, direct feedback about the impact of behavior on energy use to occupants has been linked with energy demand reductions in housing generally (Bergman and Eyre, 2011).

Occupant energy behaviour has been studied for at least four decades (e.g. Socolow, 1978) showing behaviour can cause large variations in energy use. In recent studies, Gram-Hassen (2013) found domestic energy consumption could vary by a factor of three in similar buildings

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[23] Dwellings were both located in the same neighbourhood, identical original construction, with a similar socio-demography of the occupant. One of the dwellings had been refurbished between 2009 and 2011 to include double glazing, floor insulation and external wall insulation.

with similar occupants, and Sunikka-Blank and Galvin (2012) found energy consumed for heating could vary by more than a factor of six in properties with the same thermal rating.

The prebound effect and rebound effect may also have an impact. Where occupants in less efficient buildings modify their behaviour to be more economical with their space heating (Sunikka-Blank and Galvin, 2012). When improving the thermal efficiency of a home, this can result in a 'prebound effect'. This occurs where, prior to energy efficiency improvements, a building consumes less energy than predicted by models such as RdSAP. Estimated to be 30% lower than predicted before a refurbishment (Sunikka-Blank and Galvin, 2012). Energy savings from retrofit are then lower than predicted, for technical reasons and because the occupants abandon their modified behaviours that were keeping consumption below the assumed rates.

A 'rebound effect' is another phenomenon resulting in lower energy savings than predicted. Also known as 'Jevons Paradox', the rebound effect occurs when the energy savings resulting from an improvement in a building's thermal or energy performance is consumed by additional energy use such as increased internal temperatures or increased appliance use (Sunikka-Blank and Galvin, 2012). Alternatively, financial savings on fuel bills may be spent on goods or services with negative environmental implications, such as increased travel (Shove, 2018), or heated conservatories (Chu and Oreszczyn, 1991).

The interactions between warmth, health and energy demand are similarly complex. Inadequate warmth in housing has been shown to have a detrimental effect on the physical and mental health of occupants (Collins and Dempsey, 2019; Thomson et al., 2017). This is particularly the case for vulnerable groups including the elderly, children, and those with chronic health conditions (Public Health England, 2014). Further, increasing internal temperatures of colder homes is likely to reduce the risk of health issues relating to cardiorespiratory conditions (WHO, 2018). Naturally this would increase the energy consumption of homes with inadequate indoor temperatures if energy efficiency was not improved.

Based on an analysis of evidence by the World Health Organisation (WHO, 2018), 'adequate warmth' is defined as 18°C for all rooms, and 21°C for living rooms. These are the temperatures assumed in SAP calculations. However, there is limited evidence on exact optimal indoor temperatures and there are calls for reflecting on whether lower temperatures or the heating of single rooms should be considered as an alternative heating strategy (Shove, 2019). There is a risk of placing strain on social interactions within the home by adopting a strategy which only heats a limited number of rooms within a property (Grey et al., 2017). Public Health England (2014) have suggested that negative health conditions start at around 18°C for healthy adults who are sedentary and wearing minimal clothing, indicating that there could be scope to reduce standard temperatures for households with healthy adults if behavioural changes were adopted alongside in-home thermal performance improvements. Although in the UK cold dwellings in the winter are currently identified as a more significant issue than overheating, based on current projections of a higher frequency of extreme summer temperatures (Met Office, 2019), the risk posed by overheating in buildings and associated health effects is likely to increase.

Thermal comfort can be achieved through an 'adaptive approach' whereby occupants modify and adapt their behaviour to obtain thermal comfort (Albatayneh et al., 2017). This approach can include controlling natural ventilation by opening and closing windows, utilizing shutters or closing curtains to mitigate summer overheating, and selecting suitable clothing for the context. Whilst such an approach could help to reduce energy consumption, it is difficult to model these adaptive behaviours when calculating potential reductions from adapting buildings. Behavioural changes are potentially an inexpensive approach to reducing energy consumption. It is estimated that turning a thermostat down by 1°C could achieve 90% of the energy savings predicted from cavity wall insulation (DECC, 2012).

In owner-occupied properties, decisions about energy efficiency measures and the appropriation of efficient technologies has been shown to diverge from concepts such as Rational Choice Theory. Indeed, homeowners do not always consider if they can make "expenditure decisions that would make good financial sense in terms of enhancing" property value (Munro and Leather, 1999, p.519). Instead works are performed to create a 'home', enhance thermal comfort and due to perceived necessity (Aune, 2007; Munro and Leather, 1999) such as replace a defective boiler.

Traditionally energy policy has focused primarily on cost and competition and assumed a rational consumer (Aune, 2007). However, this takes a limited view. Similarly, information deficit whereby it is assumed people will act based on increased awareness has also been shown not to apply to the context of home improvements and technology appropriation. Christie et al. (2011) demonstrated that homeowners who had not adopted efficient technologies already had complete information and were aware of their decisions. Similarly in behavioural research, although information is recognised as important, alone it is unlikely to result in sustained energy consumption changes (Santangelo and Tondelli, 2017). To be useful, information needs to be from a trustworthy, credible source (Santangelo and Tondelli, 2017) and framed in a way that appeals to what occupants value (i.e. utility bill savings, comfort, reducing environmental impact) (Organ, 2015).

The concept of home is emotionally-laden (Wilson et al., 2013), although this does not necessarily result in irrational decisions. Rather, it leads to decisions that may be difficult to predict when using traditional decision-making theories (Levy et al., 2008). Indeed, in research of owner-occupiers in Bristol found the adoption of home energy efficiency measures and technologies were not purely economically motivated, neither were they solely environmentally motivated; rather owner-occupiers were influenced by multiple, and sometimes conflicting, factors (Organ, 2015).

In their study of middle-income owner-occupied households in Cambridge, Sunikka-Blank and Galvin (2016) highlight that people do not base their thermal retrofit decisions on apparently rational and economic considerations, as suggested in theories such as Expected-Value Theory which includes theories such as Rational Choice Theory (Organ et al., 2013). The authors suggest decisions can be formed based on economic and environmental aspirations, guided by homeowner perceptions about what has 'aesthetic value'. This may result in perceived compromises between retaining aesthetic features and improving the thermal or energy performance of a dwelling. This may be even more pronounced in properties with recognised inherent aesthetic heritage value.

3.10 UK decarbonisation strategy – heating and electricity

Given the proportion of energy used providing heating and hot water to our buildings, the decarbonisation of space and water heating[24] is critical (Rosenow and Lowes, 2020). However, this will require a stable electricity grid and any low carbon heating system, whether heat pumps, hydrogen or others will have implications on national energy infrastructure (Gillich et al., 2019), such as repurposing the national gas grid with hydrogen (Renaldi and Friedrich, 2019). On a micro-generation scale, technologies such as solar photovoltaic panels are likely to be capable of producing a proportion of annual energy demand in historic housing, research suggesting that across five case studies of pre-1919 houses in the city of Bath, roof-mounted photovoltaic panels were able to contribute on average to 56% of electricity consumed based on ordinary energy use patterns (Moran and Natarajan, 2015), with remaining energy coming from other sources such as the national energy networks. Therefore, investment in the national energy networks will be necessary to continue to decarbonise (Ofgem, 2020).

3.10.1 Heating

Currently only 5% of the energy used for home space heating is from low carbon sources (Ofgem, 2020). Alongside a drive to reduce the demand for heating through improved thermal performance across our building stock, there are two main pathways for national 'heat decarbonisation' in the UK (BEIS, 2018b; Imperial College London, 2018):

1. **Electrification,** with most houses heated via individual, shared or communal heat pumps - mostly air source heat pumps[25].

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[24] By increasing the thermal performance of pre-1919 buildings, hot water is expected to form an increasing proportion of energy consumption by end use, although unless a dwelling achieves nearly zero energy demand, space heating is expected to remain the largest proportion by end use.

[25] There are currently an estimated 160,000 heat pumps in the UK (CCC, 2019). Hybrid heat pumps which use a gas or hydrogen boiler to back up the heat pump, are technically feasible but have additional complexity and additional cost. Therefore, other forms of heat pumps such as air source, are expected to be the preferable option. The performance of hybrid heat pumps has been reported to be highly dependent on the control settings, and user adjustment of these have been identified as a major reason for manufacturers being called out to resolve system issues (BEIS, 2016b). Further, heat pumps require refrigerants, and the most common of these are hydrofluorocarbons, which have a global warming potential substantially greater than CO_2 (DECC, 2014).

2. **Gas/hydrogen,** with the national gas grid converted to a mixture of fossil gas, biogas and hydrogen (which itself is a mix of low and high carbon sources).

Both pathways represent a range of considerations relating to carbon emissions, national infrastructure and building energy (**Table 6**). In addition, when considering the adoption of hydrogen, inefficiencies are likely to be introduced through converting electricity into hydrogen and then into heat (Camden Council, 2019). Although they will have some application, particularly in rural areas, other technologies such as biomass and solar thermal are unlikely to be suitable for widespread adoption across the pre-1919 building stock due to external and internal space constraints, and planning constraints. Micro-generation technologies are likely to be more appropriate when installed in locations hidden from main views or adjacent structures (Ross and Zasinaite, 2017). Heat networks can use heat from multiple sources, can fit into these and other pathways. Whilst uncertainties exist around the future mix of heating technology, electrification will have a significant role (Rosenow and Lowes, 2020).

In the UK existing heat networks are predominantly gas-fired CHP (Foxton et al., 2015). However, heat networks are likely to only be cost-effective for a limited proportion of properties, but could suit up to 20% of the traditional stock (Element Energy and UCL, 2019). In 2015, 2% of the heat demand for buildings was provided by 2,000 heat networks (Ofgem, 2015). It is estimated that, by 2050, heat networks have the potential to deliver 20% (Foxton et al., 2015) to 43% of heating demand in buildings (Ofgem, 2015), and represent a cost effective option for areas with high heat densities such as cities (Ofgem, 2015).

The national gas grid forms significant national infrastructure, so the government will be reluctant to endorse an approach which will phase out such infrastructure. In practice, a combination of low-carbon gas and electricity is likely to be adopted. Both pathways are likely to require investment in national energy infrastructure, but the least cost option will need heat loss from buildings to be reduced to avoid substantial end user cost rises (Rosenow and Lowes, 2020).

The CCC (2016a) highlight that heating in buildings needs to transition away from gas boilers to non-hydrocarbon sources such as electricity, heat networks, and hydrogen or biomethane. In their later report, the CCC (2019) suggest that domestic space heating could come from heat pumps and, for heat-dense areas such as cities, from low carbon heat networks[26].

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[26] An example of a ground source heat pump for a heat network in a rural setting is the Swaffham Prior Renewable Heat Network project in Cambridgeshire. The village has a mixture of historic and modern buildings. The network is expected provide heat to 180 homes with an estimated cost of £3 million (Bioregional, 2017). A planning application for the project was submitted in July with an intended installation start date in 2021 (Heating Swaffham Prior, 2020).

An example of a heat network in a city location is the Bunhill waste heat system in Islington. The 1MW heat pump recovers low-grade waste heat from the London Underground (Northern Line) and uses this to provide space and water heating for 500 dwellings (Heat Pump Technologies, 2019).

Table 6: Considerations pertaining to the electrification and gas/hydrogen pathways for heat decarbonisation

	Electrification	**Gas/hydrogen**
Carbon	Pro: National electricity grid is decarbonising and so this is a route to zero carbon. Con: Will increase electricity demand and in the short-term may lead to higher use of gas and possibly other fuels to generate electricity.	Pro: Biogas and green hydrogen (produced with renewable electricity) can decarbonise the gas supply. Con: a) There is currently limited availability, and uncertainty whether they can meet current demand. b) It is likely to be largely fossil fuel based for quite some time. CCS has been mentioned as partial solution.
National infrastructure	Will lead to higher electricity demand and could need major grid reinforcements, particularly if limited energy efficiency improvements are made to buildings.	Major infrastructure changes needed to accommodate substantial quantities of hydrogen. Impacts on farming industry (some positive) and land use.
Building energy use/cost	Without improvements to fabric thermal efficiency and air tightness of many buildings, it is likely to lead to higher operational costs. Electricity is 3-5 times the price of gas, the "efficiency" of heat pumps is 2-4 times that of gas boiler. Radiators would most likely need changing in many properties.	Highly unlikely that any mix of biogas/hydrogen/CCS will be as cheap as current or even recent gas prices. Therefore without fabric/air tightness improvements, energy costs will rise. Radiators probably compatible but boilers will need to change.

However, the CCC have also stated that using heat networks is limited to a 20% saving in total building heat demand (CCC, 2016a), and biomethane potential is limited to around 6% of current gas consumption (CCC, 2019).There is considerable uncertainty around the use of hydrogen for space heating (CCC, 2016a): some authors suggest it could be considered as a source of energy for supplementary heating or in a hybrid heating role (Rosenow and Lowe, 2020). However, it seems unlikely to make sense for each dwelling to be connected to a hydrogen supply for only occasional use.

3.10.2 UK heating strategy – impact on carbon modelling

In the present research, from a technical perspective, our approach is to attempt to reduce the heat demand to a level where low-temperature heating (i.e. <55°C output temperature) is possible, although stored domestic hot water is likely to need to be at least 60°C to avoid the growth of Legionella bacteria (HSE, no date). Low-temperature heating[27] such as domestic heat pumps will result in a better co-efficient of performance, and therefore greater energy and carbon savings can be achieved (Jenkins et al., 2009). This will involve fabric and air tightness improvements. This level should be compatible with cost-effective heating such as heat pumps, heat networks or gas/hydrogen boilers. Given that there is no 'one-size-fits-all' solution for the building stock generally, and the pre-1919 stock more specifically, this approach avoids the need for the researchers to choose which technology is 'best'.

For carbon calculations, we have assumed that heat pumps will be the predominant technology. This is largely because there is no current strategy for the decarbonisation of the gas network, whereas there is a current strategy for the electricity grid up to at least 2030. Therefore any carbon factors we estimate for the gas network would be highly speculative. In reality it is likely that a range of technology for heating and hot water will be deployed across the pre-1919 building stock, selection based on the context.

For some archetypes and retrofit strategies, it may not be possible for practical or heritage reasons to achieve a heat demand appropriate for low-temperature radiators. In these cases, a combustion based approach could be more appropriate - i.e. heating by gas or hydrogen, or potentially biomass in rural areas. For those instances, a second modelling iteration will be performed after discussion of the most appropriate approach. District heat networks may also be suitable, particularly where there are high heat densities, for example in cities.

3.10.3 Electricity

The carbon emissions factor used for mains electricity in the UK has been falling as a result of changes to the energy sources (Bordass, 2020). Since 2012, carbon emissions from the National Grid (covering Great Britain only) have decreased by two-thirds since 2012, with 40% of electricity generated from coal in 2012 to 67 consecutive days without coal in 2020 (**Figure 14**).

This carbon intensity is expected to reduce further over the next 120 years (NHBC, 2012, p.6). The Committee on Climate Change and National Grid are both targeting <100 g/kWh by 2030 to meet national carbon budgets. The impact of this is:

a) Based purely on average annual carbon emissions, resistive electric heating is lower carbon than all fossil fuels;
b) Gas CHP is no longer a "low carbon" technology unless it burns Hydrogen or a synthetic low-carbon fuel, such as ammonia (not in individual dwellings) or possibly biofuels;
c) Heat pumps are substantially lower carbon than fossil fuels, including natural gas.

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[27] Some district heating networks in Scandinavian countries are intended to operate at lower temperatures (30 – 70°C) (Yang et al., 2016) although in the UK heat networks using heat pumps will typically supply hot water for space heating at 80°C (Tunzi et al., 2018).

However, a switch towards resistive electric heating or use of heat pumps without thermal improvement of buildings would lead to a large increase in demand for electricity, potentially leading to increased fossil fuel use (gas) to meet this demand. Electrification of transport is also accelerating dramatically and Government has pledged to end sales of new petrol/diesel vehicles by 2035. Reversible vehicle-to-grid connections (in buildings that have off-street parking) could help to smooth electricity demand peaks and fill in the troughs.

Despite this, a large-scale switch to heat pumps over the coming decades is not seen as an insurmountable problem by National Grid, with 60% of homes heated by heat pumps by 2050 as one of their four Future Energy Scenarios[28]. Although to accommodate improvements to the national electricity grid, Ofgem (2020) highlights that there will be a need for consumers to change the way they use electricity in relation to the supplies available.

It is important to note that, where energy prices fall this will likely have an impact on the return on investment ('payback period') of energy efficiency improvements, more so in the context of rising external temperatures (Neroutsoua and Croxford, 2016). More expensive measures may, therefore, become unviable based on capital costs alone. In reality, the payback period will relate to actual energy savings and, as highlighted by Historic England (2017b) the capital cost of the improvement works, with large capital costs typically taking longer to payback.

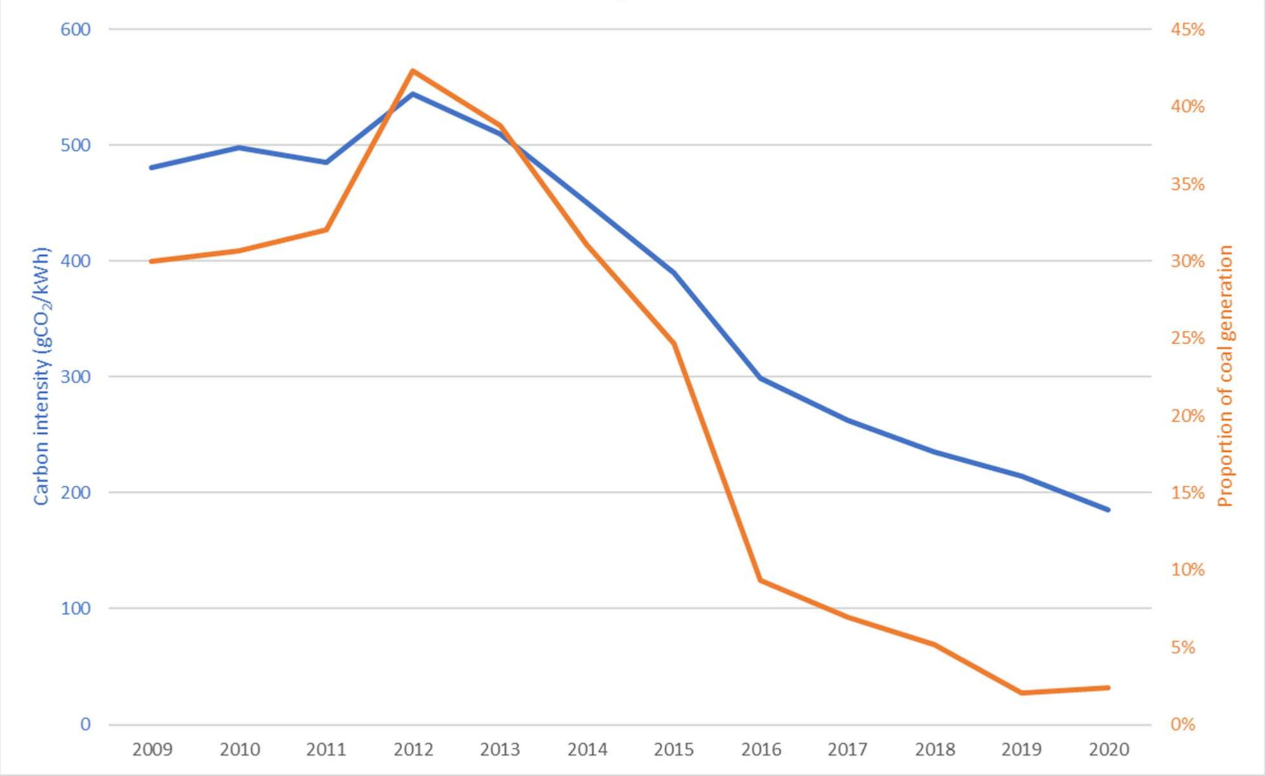

Figure 14: Carbon intensity of National Grid (National Grid ESO, no date-a)

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[28] http://fes.nationalgrid.com/

3.11 Operational and embodied energy and carbon

In residential and office buildings, there is evidence that shows that operational energy accounts for 80 – 90% of lifecycle energy and embodied energy[29] 10 – 20% (Ramesh et al., 2010), although it is not clear whether these findings are applicable to pre-1919 buildings. There are difficulties in calculating actual lifecycle embodied and operational energy due to the range of variables. In new construction, research has estimated that operational carbon accounts for 74% - 80% of a 60-year lifespan of a building (Iddon and Firth, 2013) based on the minimum designed service life for a modern house (NHBC, 2012). The average lifespan of a typical UK house is 120 years and relates to the building envelope, superstructure and substructure (NHBC, 2012).

Operational energy is energy used by the occupant for space and water heating, cooling, lighting, mechanical ventilation and appliances (Azari, 2019). Approximately 80% of energy consumption for space and water heating is provided by natural gas (Watson et al., 2019). Given the large proportion of domestic energy used for heating, weather conditions significantly affects energy consumption in the housing stock, which will create particular problems if dependency on electricity increases.

In comparison with operational energy or carbon, embodied energy and carbon is associated with less frequent events such as the construction of the building, on-going material or component replacement (Iddon and Firth, 2013) and periodic refurbishment. However, interpretations of embodied energy do not always incorporate energy relating to building maintenance although this will gradually increase the amount of embodied energy in a building (Fuertes, 2017). The frequency of material or component replacement will depend on the estimated lifespan of a component (**Table 7**), as well as the quality of the materials, design level of a component, workmanship, indoor (e.g. internal position in an area with variable humidity such as a bathroom) and outdoor environment (e.g. coastal), in-use condition and maintenance levels (Rauf and Crawford, 2015).

Table 7: Examples of assumed service life components or technology (Source: NHBC, 2012)

Component or technology	Estimated lifespan
Building envelope, superstructure and substructure	120 years
Windows	40 years
Boiler	12 years
Hot water cylinder	30 years
Mechanical ventilation heat recovery	15 years
Solar thermal panels	30 years
Flooring finishes (e.g. carpet)	10 years

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[29] Existing embodied energy can be considered to have already been 'spent' (Historic England, 2020b; Menzies, 2011), although maintenance or improvement works will contribute further embodied energy.

The proportion of embodied energy or carbon relative to operational energy or carbon will also depend on behavioural aspects such as occupant energy consumption behaviours, the types of materials selected, as well as the building location, local climate and fuel source used (Dixit, 2017). This makes it difficult to generalize in terms of the proportions of embodied energy and operational energy in buildings.

Embodied energy is the amount of energy required to process and supply a material to a construction site (Hammond and Jones, 2008). That is, it is the amount of energy used to extract the raw material, process it, and transport it for use on site. Similarly, the emissions related to these processes over the lifespan of a material or component is described as the embodied carbon (Hammond and Jones, 2008). However, embodied carbon[30] is not well understood and, due to a variety of uncertainties, is difficult to measure (Historic England, unpublished). Energy and carbon lifecycle analyses can vary in terms of the extent to which the material lifecycle is captured. For example, these can include a cradle-to-grave, cradle-to-gate and cradle-to-site[31] (Crishna et al., 2011). This can impact on the reported embodied carbon, as highlighted by Crishna et al. (2011) in their study on the embodied energy and carbon of dimensioned stone (**Table 8**). In comparison, general concrete is reported to have an embodied carbon of 130 kg/CO_2/tonne (cradle-to-gate) (Crishna et al., 2011). These figures vary further when considering the country of origin of the material, the distance to site, and the type of transport used. In addition to this, the literature on embodied carbon and energy is limited, particularly in relation to elements such as heating and heating distribution systems.

Table 8: Comparison of results from embodied carbon lifecycle analyses of dimensioned stone (Source: Crishna et al., 2011)

Stone type	Embodied carbon (kgCO_2e/tonne)	
	Cradle-to-gate	Cradle-to-site
Sandstone	64.0	77.4
Granite	92.9	107.5

Although embodied carbon and energy within historic buildings can be assessed through lifecycle analysis, Jackson (2005) suggests that figures estimating embodied carbon and energy in historic buildings are likely to be underestimated. However, as highlighted by Menzies's (2011) in her report for Historic Environment Scotland, such embodied energy and

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[30] Described in the BRE Green Guide to Specification as the measured in kilograms of CO_2 equivalent to the greenhouse gases arising from a square metre of the material over a 60-year period. This includes manufacture, installation and final demolition (Anderson et al., 2009).

[31] 'Cradle-to-gate' includes upstream processes (i.e. raw material extraction through to when the finished product leaves the factory gate) It excludes transport of material to the building site. 'Cradle-to-site' includes the processes from 'cradle-to-gate' plus transportation of the finished product to the construction site, construction or assembly processes on-site, and wastage disposal. In addition to this process, 'cradle-to-grave' also includes activities relating to operation and maintenance, renovation and refurbishment and retrofit (Dixit et al., 2013).

embodied carbon will not contribute to a reduction in their current and future energy consumption and carbon emissions – it represents energy and carbon that have already been 'spent' (Historic England, 2020b). Despite this, the use of durable materials and construction details with long lifespans can reduce the refurbishment cycle of existing buildings, requiring less energy and carbon over time (Menzies, 2011). Further, although embodied energy will not contribute to current and future energy consumption and carbon emission reductions, the retention of pre-1919 properties has multiple advantages. For example, when compared with demolition and rebuilding, refurbishing existing buildings avoids large amounts of waste resulting from demolition (Plimmer et al., 2008) and the associated emissions (Historic England, 2020b). When compared with new build, Plimmer et al.'s (2008) research highlights that existing buildings offer 'good value', with faster project timescales (Power, 2008) and potentially being less costly to refurbish and maintain compared with new build (Power, 2008). Historic properties represent embodied energy and carbon, but also aesthetic qualities that contribute to the identity of an area (Plimmer et al., 2008). Further, there are well-reported socio-political issues associated will demolition, particularly mass demolition and the refurbishment of existing buildings would help avoid such issues (Power, 2008).

The amount of embodied energy associated with a building refurbishment typically increases with the depth of a 'low energy refurbishment'; that is, where a refurbishment includes increasing amounts of insulation and energy systems to reduce operational energy, the amount of cumulative embodied energy from the new materials will increase. This has been shown in Neroutsoua and Croxford's (2016) research comparing the low energy refurbishment of a Victorian house to two different standards.

The embodied carbon of a building or refurbishment can be reduced by selecting materials with lower embodied carbon. This includes how materials are transported to site, with embodied energy found to be considerably higher when transported by air compared with transporting it by road, rail or ship (Historic Environment Scotland, 2011). Natural building materials typically have a lower energy and lifecycle impact in comparison with petroleum-based materials (Bastien and Winther-Gaasvig, 2019). For example, timber framed windows have a lower amount of embodied carbon than PVCu window frames (Iddon and Firth, 2013; Historic Environment Scotland, 2010). Similarly the type of inert gas in double or triple glazed windows will impact on the embodied energy and carbon. Historic Environment Scotland (2010) identified inert gas as accounting for a significant proportion of embodied energy due to the energy needed to extract these gases, xenon gas as having higher embodied energy than alternative inert gases. For Historic Environment Scotland research, slim profile double glazed units had been specified due to historic preservation requirements and although this meant lower U-values for the units, the smaller cavity between the glazing panes resulted in a smaller volume of inert gas. Therefore, the slim profile double glazing had a lower embodied energy than conventional double glazing. The embodied energy was further reduced where timber frames were specified, and reduced further where it was possible to retain the original window frames (Historic Environment Scotland, 2010). It is worth noting that, where glazing is replaced, there may be concern in the loss of the historic glass which can have a less uniform reflection than the flatter modern glass (Ginks and Painter, 2017). Further, the performance of multi-paned glazing filled with inert gases depends on the unit seals remaining intact to ensure the gases are retained (Historic Environment Scotland, 2013a).

A similar situation regarding embodied energy arises in relation to insulation materials. For example, expanded polystyrene has a higher embodied energy (88.6MJ/kg) compared with wood fibre board (20MJ/kg), although the density of expanded polystyrene is lower than wood fibre board. It is worth noting that, when embodied energy is calculated based on a functional unit (1m^2) rather than weight, Hill et al. (2018) suggest that where cellulose-based fibre board insulation such as wood fibre is produced using energy from non-renewable sources, there is a large range in embodied energy, and it can be considerably higher than other insulation materials.

The thermal conductivity (K-value) of expanded polystyrene (0.028 W/mK) is lower, and consequently more thermally efficient, than wood fibre (0.08 W/mK) (Neroutsoua and Croxford, 2016) (see **Table 9**). Indeed, measured thermal conductivity of insulation composed of natural-based materials such as sheep wool, flax fibre, and hemp fibres are generally higher than conventional thermal insulators (Jerman et al., 2019). Therefore, for the same thickness of insulation applied to a wall, a lower reduction in U-value will be achieved with wood fibre, and the carbon emission reduction achieved will be less. There may need to be a compromise between operational carbon emission reduction and embodied energy reduction. However, natural materials such as wood fibre have additional advantages such as being hygroscopic[32]. Such a characteristic may contribute to improved internal environments and increased building longevity (Bastien and Winther-Gaasvig, 2019) through the reduction of moisture-related defects (McCleod and Hopfe, 2013). Hygroscopic materials have been identified as having the potential of being particularly suited to historic buildings (Jerman et al., 2019) due to their typically vapour permeable fabric.

Embodied energy is typically found to represent a lower proportion of a building's total lifecycle energy than operational energy and emissions (Dixit, 2017). However, as the energy efficiency of buildings increases, if all else is equal, embodied energy will represent an increasing proportion of lifecycle energy (Dixit, 2017).

In a refurbishment to reduce the operational carbon emissions of a Victorian terrace by 60%, Heritage Counts 2019 estimated that the construction-related embodied energy the refurbishment equated to 2% of the building's total emissions across a 60-year period (1.2 tCO_2e) (Historic England, 2020b). In comparison, demolition and the construction of a new home, embodied emissions were estimated as 23.9% of an equivalent building's total emissions over a 60-year period (Historic England, 2020b) highlighting the benefits of upgrading rather than replacing historic structures.

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[32] A property of a material whereby the material will absorb and release atmospheric moisture to reach an equilibrium with the surrounding air (Pelsmaker et al., 2019b)

Table 9: Example of materials and their embodied energy and carbon

Measure/ material	K value (W/mK)	Embodied energy (MJ/m^2)	Embodied carbon (kg CO_2/kg)	Source
Expanded polystyrene	0.028	Not stated	2.5	Neroutsoua and Croxford (2016)
Polystyrene		109.2	4.39	Historic Environment Scotland (2011)
Mineral wool	0.044	Not stated	1.2	Neroutsoua and Croxford (2016)
		16.6 MJ/m^2	1.28	Historic Environment Scotland (2011)
Wood fibre	0.038 – 0.43[33]	Not stated	0.12	Neroutsoua and Croxford (2016)

3.12 Possible carbon reductions

Recent reports published by Element Energy and UCL (2019) for the Committee for Climate Change, and by Cardiff University (Green et al., 2019a) for the Welsh Government, explore the potential for reducing the carbon emissions from the existing housing stock. Whilst Element Energy and UCL (2019) focused on improvements to heating and hot water provision, cooking, lighting, and appliances, Cardiff University presents findings based on 40 case study buildings and a questionnaire (Green et al., 2019b). Although neither report focused on heritage buildings in detail, they highlight the need for incentives and regulation to help drive changes, and stability within energy policy to aid certainty in the market. Cardiff University (Green et al., 2019a) estimate that home carbon emission reductions of between 50% and 80% can be achieved at a capital cost of £300/m^2 to £400/m^2. In contrast, Element Energy and UCL (2019) suggest that decarbonizing 90% the UK housing stock to achieve a total carbon emission abatement of 72% has an average cost of £418/tCO_2e, and 12% higher cost for hard-to-treat heritage buildings, of which Element Energy and UCL designate to account for 3% of the building stock. In relation to improving energy efficiency, both studies highlight the additional constraints heritage buildings pose. However, the range in costs could be interpreted as reflecting not only the number of variables in estimating improvement costs for heritage buildings, but also the level of uncertainty in relation to aspects such as the existing condition. The condition of a building before a refurbishment will determine whether the installation of energy saving measures can be considered economical (Neroutsoua and Croxford, 2016).

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[33] Updated from 0.08 W/mK reported in Neroutsoua and Croxford (2016) to 0.038 – 0.043 w/mK from Greenspec (2020).

In *PAS 2035:2019 - Retrofitting dwellings for improved energy efficiency - Specification and guidance*, the BSI (2020, p.10) states:

> *"[…] it is not appropriate to attempt to achieve the same level of emissions reduction from every domestic building, because the same target applied to every dwelling might result in significant damage to some older, traditionally constructed buildings…rendering them unhealthy places to live…and damaging our architectural heritage".*

PAS 2035:2019 also encourages a 'fabric first' approach to improving the performance of existing housing. Whilst this is generally accepted in industry as an appropriate approach, this can be problematic for heritage buildings. Issues may include the lack of reversibility of some measures, and the risk of damaging protected values. Measures such as internal wall insulation may also reduce the use of a building's thermal inertia, reducing a wall's ability to act as a thermal buffer against overheating and increasing the risk of it suffering from prolonged penetrating damp and frost attack. This reduction in the wall's thermal inertia can also result in an increase in the heating season. Previous research has shown that buildings perform better where they included higher thermal mass in living rooms in addition to solar shading and adequate ventilation (CIBSE, 2005). However, whilst high thermal mass has been identified as beneficial to combat overheating, in cold climates it has been identified as increasing the energy requirement of a building (Reilly and Kinnane, 2017).

In contrast to a 'fabric first' approach, alternative approaches which could be considered. Curtis (2012) suggests taking an 'occupant behaviour first' approach, an approach previously adopted by Historic Environment Scotland. The hierarchical approach prioritises occupant energy behaviours, followed by improving the efficiency of heating and lighting systems. Only then should fabric improvements be considered followed by technologies such as solar panels and heat pumps, which will only be appropriate in some projects (Curtis, 2012). By prioritising occupant behaviour, such an approach may help to avoid adding unnecessary amounts of embodied energy through significant intervention, but behavioural change is known to be influenced by multiple factors (Pothitou et al., 2016) and is difficult to negotiate and change. Behavioural change may also not result from improvements as this will be affected by a range of factors including habit (Walker et al., 2014).

The existing literature has indicated that a range of carbon and energy reductions are possible from the existing building stock (**Table 10**), including pre-1919 buildings, listed and non-listed. In relation to carbon reductions, a summary of some of these reported reductions are shown in Table 8. There has been additional research undertaken by Parity Projects (Historic England, 2017b) which modelled four improvement scenarios for four solid walled houses in Reading, Berkshire ranging from low to high cost intervention packages. In this project the carbon savings achieved ranged from 10% (House 2, low cost package) to 66% (House 2, high cost package with internal wall insulation).

Table 10: Examples of the range of real-world carbon savings reported in literature

Source	**Carbon reduction (%)**	**Description**
Green et al. (2019)	50 – 80%	Review of 40 real-world cases from previous projects
Historic England (2020)	60%	Real-world case (Victorian terrace)
Gupta and Gregg (2015)	75%	Real-world case (Victorian semi-detached)
Hartless and Staden (2013)	53 – 81%[34]	Real-world cases
Makrodimitri (2010)	76%	Real-world case (Victorian semi-detached)
SuperHome Network (no date)	72%[35]	Real-world cases

Hartless and Staden (2013) highlight that it is possible to achieve carbon reductions up to 50%, compared with the carbon emissions prior to a refurbishment, for under £5,000. For reductions in excess of 60% more expensive measures such as solid wall insulation and microgeneration technologies are necessary. Parity Projects found that achieving a carbon reduction in excess of 40% is unlikely in solid walled housing without solid wall insulation (Historic England, 2017b). Further, it will be essential for an improvement in industry understanding and skill to deliver substantial improvements in the performance of the pre-1919 stock (Kaveh et al., 2018; May and Rye, 2012).

Importantly, in relation to the pre-1919 building stock there is no 'one-size-fits-all' solution (Green et al., 2019a), although there are some commonly adopted measures which can be identified in the literature. For example, **Table 11** present the common measures identified across 65[36] pre-1919 buildings in the Superhome Network. It is worth noting that it is unlikely that technology such as solar photovoltaics or solar thermal would be able to meet demand for domestic heating and hot water in the UK and therefore should be viewed as supplementary forms of heating and hot water (Herrando and Markides, 2016). Local authorities such as Camden Council have assumed air source heat pumps as the default technology in their work on carbon scenarios (Camden Council, 2019). They assume this

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[34] When only considering those pre-1919 houses in the sample which underwent a higher level of energy intervention.

[35] Mean average based on all 'Superhome Assessor' assessed pre-1919 domestic properties, excluding flats and properties which achieved a reported ≥100% carbon reduction, with a median value of 70%. When incorporating flats, this mean average increased to 74%, with a median value of 72%.

[36] Properties selected based on pre-1919 construction date and the carbon reduction of each property selected had been assessed by a Superhome assessor

technology will run on electricity, which is decarbonising, and avoids relying on a national strategy of decarbonising the main gas network. Heating technology that burns solid fuel such as woodburning stoves and biomass boilers have considerations such as sourcing and storage of fuel. Further, even when smokeless, woodburning stoves contribute to the particulate PM2.5[37], which is emitted from burning solid fuel. The BMJ (2016) suggests that a single smokeless log-burning stove can emit more PM2.5 than 1,000 petrol cars annually, and this has implications for health and the environment.

Limitations exist regarding the extent to which buildings deemed to have architectural heritage can be insulated, particularly where such interventions are irreversible (BSI, 2020). Whilst there are planning constraints relating to listed buildings or those in conservation areas, Gillich et al. (2019) suggests that 69% of the total domestic solid walled area is suitable for partial or complete insulation. However, in the case of solid wall insulation, there will also be planning constraints in relation to buildings which are listed or in conservation areas, which may restrict the adoption of this type of measure across the pre-1919 building stock.

In 2015, an estimated 4% of all domestic solid walls in England were insulated (Hansforth, 2015). This had increased to an estimated 10% of solid walls by 2017 (DCLG, 2019b). The median reduction in gas consumption resulting from solid wall insulation is estimated to be 18.9% based on calculations by the BEIS (2020). Although this is often an expensive and intrusive measure, the CCC (2016b) highlight the need for increased uptake rates for solid wall insulation. However, internal wall insulation in particular can be highly disruptive to occupants, representing a major barrier for homeowners (Dowson et al., 2012). Disruption has been found to be a barrier to other improvement measures such as mechanical ventilation heat recovery (MVHR) systems which requires high levels of air tightness (Banfill et al., 2019).

Furthermore, there is not currently sufficient skill within the construction industry to achieve a sufficiently high level air tightness (Kaveh et al., 2018). Recent research has shown that in a large sample of new dwellings, MVHR is beneficial over natural ventilation where the air tightness is less than $3m^3/m^2h$ at 50Pa (Crawley et al., 2019). Mechanical ventilation will introduce further considerations including maintenance requirements and operating costs, space requirements, quality of installation workmanship and future breaching of air tightness (e.g. penetration of the fabric for new services). Previous research by Bell and Lowe (2000) on energy efficiency improvements in local authority dwellings in York, predominantly constructed in the 1930s and 1950s, included installing MVHR technology. The research found that introducing unfamiliar technology such as MVHR can result in sub-optimal use by occupants although this can be potentially improved with appropriate system design and occupant advice (Bell and Lowe, 2000).

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[37] Particulate matter with a diameter of up to 2.5 μm (European Environment Agency, 2015).

Table 11: Summary of most common measures across 65 pre-1919 Superhome buildings

Measure type	Measure	Frequency in sample (of 65 cases)	Proportion of sample (%)
Appliances and lighting	Low energy lighting/light bulbs	59	90.8
Insulation	Loft/Roof insulation	55	84.6
Glazing	Double glazing	47	72.3
Insulation	Floor insulation	47	72.3
Water efficiency	Water saving devices	46	70.8
Low carbon technology	Solar thermal panels	44	67.7
Draught proofing	Draught proofing	42	64.6
Appliances and lighting	Low energy appliances	42	64.6
Heating	New condensing boiler	41	63.1
Low carbon technology	Photovoltaic panels	37	56.9
Low carbon technology	Wood-burning stove	36	55.4
Insulation	Internal wall insulation	33	50.8
Other	Heat recovery unit or mechanical ventilation recovery unit	22	33.8
Insulation	Hybrid/combination solid wall insulation	16	24.6
Insulation	External wall insulation/insulating render	9	13.8

3.13 Costs

Pre-1919 homes account for 36% of the 4.5 million non-Decent[38] Homes in England (DCLG, 2019a). It is estimated that £9,991 would be needed for each non-decent pre-1919 property to improve to a 'Decent Home' condition (DCLG, 2019a). There are considerable gaps in the available data to determine the technical feasibility of improvement measures at a reasonable cost (Gillich et al., 2019) and there are costs uncertainties relating to air tightness works and the cost of transporting products (Neroutsoua and Croxford, 2016). However, there have been a variety of costs reported over the last decade that relate to upgrading the energy efficiency of the domestic stock (**Appendix 1 - Tables A1.1 and A1.2**). These range from total costs for whole house refurbishment (e.g. SuperHomes Network, no date; Hartless and Staden,

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[38] For a home to be considered 'decent' under the Decent Homes Standard it must: (1) meet the statutory minimum standard for housing based on the Housing Health and Safety System (no Category 1 hazards); (2) provide a reasonable degree of thermal comfort; (3) be in a reasonable state of repair; and (4) have reasonably modern facilities and services. This is in line with the Homes (Fitness for Human Habitation) Act 2018.

2013; Existing Homes Alliance, 2010) to cost of a construction detail (e.g. Neroutsou and Croxford, 2016) to the cost of individual measures or unit cost (e.g. BEIS, 2017; Historic Environment Scotland, 2015; Sweett Group, 2014). For example, a recent Historic Environment Scotland (2020) case study provides a total unit cost of £98/m^2 for installing double glazing, insulation (walls, floors, and roof), and low energy lighting, the reinstatement of fireplaces, installing a new opening and repairing plasterwork.

The costs reported in the literature have been derived from databases of actual project costs (e.g. Superhome Network and the Historic Environment Scotland case studies). In addition to aspects such as location and level of intervention, costs will also be influenced by the inclusion of non-standard or bespoke products; products from further afield; immature supply chains; the standard of the final finish; and poorly designed products or systems which require remedial works (Sweett Group, 2014). Reported costs will also be affected by the date the works were undertaken. As noted in Historic England (2017b), costs also vary between contractors. Further, it is not always clear from the literature whether the costs reported include ancillary costs such as scaffolding (Historic England, 2017b), consultants' fees, the cost of building repairs, only the cost of efficiency improvements and technology adoption, or a combination. In reality, costs will vary between each home including regional variations in prices, building condition, size, types and extent of measures installed, and discounting rates over time.

3.14 Maladaptation, unintended consequences and 'lock-in' effects

Maladaptation, unintended consequences and 'lock-in' are terms that are adopted in the literature in relation to energy improvements in buildings. Juhola et al. (2016) highlight the difficulties around defining the term 'maladaptation', describing the concept as 'elusive' and requiring subjective judgement. However, they suggest it refers to adaptation that has failed to "reduce climate-related risk, or that generate negative consequences for others" (p.135). The term acknowledges the diverse effects of intervention.

In contrast, unintended consequences are not always 'maladaptive'. Rather these are unexpected benefits and/or negative effects resulting from action. It can include the effect of an action which is contrary to the original intention (i.e. the intervention makes the problem worse) (Agbota, 2014). Davies and Oreszczyn (2012) suggest that negative unintended consequences can be broadly categorised as impacts relating to population health; deterioration of building fabric and/or building contents; and economic, social and cultural viability.

According to Bergman and Eyre (2011, p.342), the concept of lock-in derives "from critiques of neoclassical economic assumptions". The literature defines 'lock-in' effects in a number of ways. Reyna and Chester (2015) suggest it refers to committing to a particular pathway which is difficult to diverge from (Reyna and Chester, 2015). Urge-Vorsatz and Herrero (2012) suggest that 'lock-in' refers to the "the unrealised energy and carbon saving potentials that result of the installation of below state-of-the-art energy efficiency technologies in buildings". Therefore undertaking a sub-optimal intervention may require future improvements to "capture the remaining potential" (Urge-Vorsatz and Herrero, 2012, p.88). However, it can also mean when the adaptation of a property is based on current rather than future climate risks. When considering behaviour, current socio-technical structures, including habits, norms, worldviews, regulations and institutions which support existing patterns of behaviour, a change to a radically different technical or behavioural system can be difficult (Bergman and Eyre, 2011). 'Lock-out' is generally taken to occur when partial refurbishment or improvements in building performance will result in reducing the likelihood of further energy savings from additional improvements for the next 30 - 40 years (i.e. until the next renovation) (Fawcett, 2014). For the purpose of this research, the primary focus was on negative unintended consequences.

Improving the energy performance of our historic building stock contributes a number of benefits. This ranges from contributing to carbon reduction targets to improving internal comfort, particularly important as thermal comfort expectations change (Pendlebury et al., 2014). Any improvements, however, must avoid loss of heritage significance and other manifestations of negative unintended consequences such as condensation and damp. Short-term gains in energy efficiency should not compromise the long-term significance of built heritage (Rispoli and Organ, 2018). Unsuitable improvements can result in the reduction in the durability and lifespan of materials including the existing fabric. This can result in an increased frequency in interventions (Menzies, 2011) and, therefore, increase a building's embodied energy. Indeed, the value of heritage buildings is largely derived from their durability as well as their reflecting those who built and altered their physical form over the lifespan of the structure (Forman, 2015). Intervention to improve the performance of such buildings should avoid compromising such inherent values.

Improvements need to be undertaken with the understanding that the physical characteristics of built heritage is different from modern construction (Webb, 2017). Instead, improvements should enhance the climate change resilience of heritage assets (Fluck, 2016), undertaken with the understanding that the physical characteristics of built heritage is different from modern construction (Webb, 2017) to avoid issues of maladaptation and unintended consequences. There are unintended consequences, positive and negative, that can potentially be instigated from making alterations to heritage buildings in the process of improving their energy efficiency performance (Organ, 2019; Agbota, 2014), necessitating much greater consideration about the suitability of the measures and alterations for each particular building and their context to avoid maladaptation and unintended consequences.

Measures such as solid wall insulation particularly impact the aesthetics of a building. This can pose a risk to those buildings deemed to have heritage value where appearance is often of importance (Agbota, 2014). Whilst external wall insulation may alter the external appearance of a building, internal wall insulation can result in the need to remove features such as cornices, skirting boards or paneling (Agbota, 2014). Adopting insulating lime renders for heritage buildings which would normally be rendered can avoid visually impacting on building aesthetics externally. However, preliminary research undertaken by Govaerts et al. (2017) has indicated that insulating lime renders containing perlite may increase the moisture content of a wall, particularly during the winter period, which will reduce the thermal resistance of the wall. Measures such as secondary glazing have less potential to impact on the visual aesthetic of a building have been identified as having the potential to reduce the amount of natural daylight entering the building (Agbota, 2014), which may increase the need for electric lighting.

The long-term success of improving the thermal performance of traditional buildings relies on measures which will not negatively affect the building fabric (Historic Environment Scotland, 2018). How a building behaves and handles moisture changes when a building is altered. This needs to be sufficiently understood to avoid facilitating defects such as mould growth, timber decay (Historic Environment Scotland, 2018), damp, poor indoor air quality, and poor building performance (Handforth, 2015). In extreme situations, this can also lead to structural damage (Hansforth, 2015).

The BRE (2016a) identify 126 possible unintended consequences resulting from solid wall insulation, which they condense into 29 consequences. Of these, they identify 19 common risks, which can be further summarised into 8 issue areas relating to:

1. Moisture (humidity, condensation, damp) and resulting issues (e.g. fungal attack, insect attack, mould);
2. Air tightness and ventilation (e.g. reduced indoor air quality, increased radon concentrations, reduced removal of moisture);
3. Impact on aesthetics;
4. Potential impact on property value (uncertainties around changes in aesthetics, reduced usable floor area);
5. Disturbance of occupants and neighbours during installation;
6. Risk of increased maintenance requirements (e.g. lower sturdiness of the wall surface following installation of solid wall insulation);
7. Reduced daylighting leading to increased energy consumption for electric lighting; and
8. Potential increased fire risk.

Of these, (1) and (2) are likely to have the greatest impact on occupant health and wellbeing. Preliminary research by Sharpe et al. (2019) suggests that whilst more research is needed, there may be an association between households with increased energy efficiency and increased hospital admissions for respiratory conditions, arising from reduced ventilation rates. Caution is needed in improving the energy performance of buildings and systems within them to avoid instigating health and wellbeing issues in an attempt to resolve others. This appears to be particularly the case when considering the ventilation strategy for a property.

Existing studies such as Element Energy and UCL (2019) include ventilation strategies to avoid issues such as increased condensation as a consequence of energy efficiency improvements.

The management of moisture in buildings is closely related to indoor air quality and the health of the building occupants (Bastien and Winther-Gaasvig, 2018). Therefore it is important to consider how changes to the performance of the building will impact on the moisture levels within the fabric and in the indoor space. Dry walls, for example, have been shown to have a better thermal performance than damp or wet walls (Curtis, 2012), so intervention to improve the thermal performance of a building should avoid increasing moisture levels in walls.

Historic Environment Scotland (2013b) found mould to be growing in the roof space of a home constructed in 1872 of traditional materials. This was as a result of high relative humidity arising from a combination of insufficient ventilation and changes in the dew point due to reduced attic temperatures. Ventilation dilutes and removes internal pollutants and helps to maintain appropriate relative humidity levels (Banfill et al., 2019). Improving the air tightness of buildings is recognised as important in contributing to reductions in energy and carbon emissions in dwellings (Whitman et al., 2019; Banfill et al., 2019) but failing to provide sufficient ventilation can result in a reduction in the removal of indoor-generated particles, radon and moisture, and therefore a reduction in indoor air quality (Milner et al., 2015). This is likely to have an adverse effect on occupant health (Milner et al., 2015). Relative humidity levels should be maintained at between 30% and 70% and where this exceeds 80%, mould growth rapidly increases (Banfill et al., 2019). Strategies to maintain suitable relative humidity levels may include establishing natural or mechanical ventilation strategies.

Controlled ventilation can be provided through trickle vents in windows, extractor fans in areas such as kitchens, utilities rooms and bathrooms which have high humidity, or mechanical ventilation systems such as a mechanical ventilation and heat recovery (MHVR) system or a decentralised mechanical ventilation (dMEV). It is recognised that it is likely to be difficult to achieve sufficiently low permeability levels in many existing dwellings required for MVHR (Milner et al., 2015) and other more cost-effective methods of achieving energy efficiency should be given priority (Banfill et al., 2019). In the refurbishment of a Victorian end terrace as part of the Technology Strategy Board’s Retrofit for the Future project, MHVR was installed as part of a whole house strategy to reduce carbon emissions (Gupta and Gregg, 2015). However, this was deemed to be a more expensive technology, adding £6,117 to the refurbishment costs and the target air tightness level was not realised, raising questions about the appropriateness of the technology for this refurbishment. However, controllable ventilation should be considered as part of the wider refurbishment strategy to ensure adequate indoor air quality and humidity levels are maintained. This is also an important consideration in relation to occupant interaction with controlled ventilation. In new housing, occupants have been found to close trickle vents to control external noise, and turn off dMEV systems due to noise generated by the system (Aecom Limited, 2019). This resulted in reduced ventilation and unacceptable levels of humidity, bio-effluents (e.g. carbon dioxide), and volatile organic compounds. The Aecom (2019) report questions the adequacy of the ventilation requirements under Approved Document Part F of the Building Regulations for newly constructed housing, and this may indicate the need for caution where attempting to achieve similar air tightness and ventilation levels in pre-1919 properties.

There also needs to be consideration given to the compatibility of measures with the permeable building fabric. Where 'breathable' insulation is used, this may not provide the same level of thermal resistance for the same thickness of material compared with 'non-breathable' insulation (Greenspec, n.d.). Additional considerations might include the thermal conductivity of the insulation material, the environmental impact resulting from its manufacture, acoustic properties, availability, cost (Changeworks, 2012), aesthetic quality, durability and maintenance, and fire resistance (Galatioto et al., 2017).

Improving the envelope of traditionally constructed buildings can result in severe changes in moisture migration, leading to surface or interstitial condensation (Herrera and Bennadji, 2013). This can subsequently lead to deterioration of the fabric and mould growth. Adequate ventilation is important to reduce the risk of surface condensation and mould growth, as well as manage relative humidity and internal pollutants.

Around 20% of all homes are estimated to overheat in the current UK climate (CCC, 2019). The projected increased frequency of extreme temperatures in the future and an aging population are likely to result increased deaths resulting from heat (Taylor et al., 2018). Green et al. (2019a) highlight that the perception of increased thermal performance and airtightness increases the risk of overheating is not necessarily true. However, it is also recognised that utilising the thermal mass of the building fabric (Green et al., 2019a; Ji et al., 2019) and appropriate ventilation (King and Weeks, 2016) can reduce actual overheating risk. In the context of current climate projections, mitigating overheating risk in buildings is important. The Met Office (2019) suggests that by 2050 'hot summers' could be 50% more common, with temperatures exceeding 30°C for two or more consecutive days. This has an implication for public health and for potential overheating in buildings. The projected rise in temperatures is higher in South East England and less in the north and west (Met Office, 2018).

In pre-1919 housing, research that compared two Victorian houses found that the 'low energy refurbished' property was not subject to a greater amount of summertime overheating than the unrefurbished property (Makrodimitri, 2010). However, the study found that floors which had greatest exposure to solar gain were subject to greater overheating. Night-time ventilation and the use of shutters, blinds or curtains have been suggested to be an effective passive strategy for reducing overheating (Elsharkawy and Zahiri, 2020).

Using a ventilation strategy to reduce overheating is likely to require engaging with occupants to facilitate any necessary behavioural changes. Consideration may need to be given to aspects such as security risks (i.e. when opening windows on the ground floor at night to enable cooling) (King and Weeks, 2016), and this may prevent occupants from leaving windows open at night (Mavrogianni et al., 2017). Where pre-1919 buildings have traditional shutters, it may be possible to return these into working order or use internal curtains and blinds to support occupant behavioural strategies to reduce overheating in homes (Mavrogianni et al., 2017). In research which modelled the impact of climate adaptations, the use of external shutters from 9am until 6pm during summer months resulted in an estimated reduction in heat-related mortality by 37% - 43% for conditions representative of weather conditions in the 2030s, 2050s and 2080s (Taylor et al., 2018). Conversely, keeping windows closed led to an estimated heat-related mortality increase of 29% - 64% (Taylor et al., 2018).

This, however, relies on occupants adopting such strategies, which has been shown to not always be the case (Mavrogianni et al., 2017). In research on a retrofitted 1960s apartment tower block, overheating in the apartments could be avoided through occupant actions (i.e. opening windows) when external temperatures were lower than internal temperatures and using internal shading devices such as blinds (Baborska-Narożny et al., 2017). The use of mechanical ventilation was also identified as contributing to this wider strategy adopted by study occupants to reduce overheating, particularly to reach a compromise in avoiding the need for solar shading (e.g. blinds or curtains) and allow daylight to enter the apartment (Baborska-Narożny et al., 2017). Although the study was of 1960s dwellings, the findings may be of relevance to pre-1919 properties.

In relation to maladaptation issues arising from improvement measures, solid wall insulation is a common focus in the existing literature. Whilst there is no one-size-fits-all strategy, Hansforth (2015) highlights the importance of considering factors such as the archetype, heritage status, the location (e.g. coastal) and whether there is existing damp. Indeed, prior to installing solid wall insulation, the condition of the wall should be assessed to ensure that there is no damp and, in the case of internal wall insulation, brick pointing or the render is in a satisfactory condition. This is to avoid penetrating damp from occurring (Weeks et al., 2013). External wall insulation can enhance the weather protection to the wall but it will alter the external appearance (Weeks et al., 2013), and in so doing may damage the heritage value of the building. Wall thickness is likely to be a further consideration: wall thickness and sorpity affects the amount of water stored within the wall structure. These characteristics can also affect the rate of drying out, as can anything impeding evaporation from the surface, such as vegetation (Hall et al., 2011).

There are different advantages and risks for external and internal wall insulation (Hansforth, 2015). Solid wall insulation will alter the thermal responsiveness of the building, depending on the location of the insulation. External wall insulation reduces solar gain and therefore the internal temperature swings, as well as retaining the use of a building's thermal mass (Weeks et al., 2013). In contrast, internal wall insulation will increase the responsiveness to the heating system, but will increase internal thermal swings (Weeks et al., 2013).

External wall insulation systems generally have good insulation continuity, but internal wall insulation systems have unavoidable breaks at partitions and floors. To some extent, both systems will be subject to thermal bridging[39], but particular consideration should be given to the detailing around junctions (Weeks et al., 2013). At party walls, recommendations from

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[39] An increased heat flow compared with the adjacent parts. These points are at greater risk of condensation and mould growth.

the Retrofit for the Future programme suggest internal wall insulation should return along the party wall by 500mm to reduce thermal bridging and potentially reduce noise disturbance. However, findings from the BRE (Weeks et al., 2013) suggest that insulating the party wall for up to 1 metre along the wall is not 'worthwhile'. If the party wall is insulated, the BRE (2013) found the uninsulated neighbouring property will experience a greater risk of condensation. Thermal bridging at this junction was found not to significantly improve even where all adjoining properties were insulated.

Research has shown that whilst the drying of a solid wall with external wall insulation depends predominantly on the vapour permeability of the insulation, internal wall insulation can lead to lower masonry temperatures and a rising moisture content of the wall (Künzel, 1998). This is a particularly important consideration in the context of regional climates and future climate projections. For example, regions such as North West England is considered to have some of the wettest places in the UK (Met Office, 2016), and therefore internal insulation impeding drying out of solid walls through reduced wall temperatures would be ill-advised in the context of future climate projections.

Between 2008 and 2017, there was a 17% increase in rainfall from 'extremely wet days', with the proportion varying regionally (Met Office, 2019). This total rainfall from extremely wet days is currently anticipated to increase. Internal wall insulation will result in much of the wall being colder than before (Weeks et al., 2013), which may increase the risk of frost action. This form of solid wall insulation will also typically provide a greater barrier to moisture, increasing the need for controlled ventilation to maintain internal humidity levels. Further, unless moisture is prevented from moving through the insulation lager by installing a vapour control layer behind the plasterboard, the risk of interstitial condensation[40] increases.

In relation to building heating systems, where water temperatures fall below 60˚C[41] this can increase the risk of Legionella (Agbota, 2014). This could be a risk for low-temperature heating systems such as heat pumps, which would therefore be required to maintain stored hot water at 60˚C (Vatougiou et al., 2018). To avoid this, an electric immersion can be used to raise the temperature once a day. This can be achieved by the heat pump or by an immersion heater in hot water cylinders. For heat pump technology, this highlights the advantage of adopting hybrid heat pumps which is an electric heat pump combined with a boiler (usually gas) with the ability to switch between the two sources of heating and hot water (i.e. electricity and fossil fuel). The boiler is used to reach higher temperatures, usually required for domestic hot

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[40] Interstitial condensation forms within an element such as an external wall, floor or roof when warm air, which carries greater amounts of moisture, moves outwards from the inside of the building. The warm air meets the 'dew point' within the structure and condenses at that point (Collins and Dempsey, 2019).

[41] 60˚C is the recommended hot water storage temperature to prevent the growth of Legionella bacteria (Legionella pneumophila). The bacteria favour temperatures between 20˚C and 45˚C. If inhaled via water droplets, Legionella bacteria can lead to Legionaires' Disease, a potentially fatal type of pneumonia (HSE, no date).

water (BEIS, 2016a). However, without the decarbonisation of fuel sources such as the mains gas, the use of fossil fuels will increase the carbon emissions associated with hybrid systems in comparison with 100% electricity-powered heat pumps.

4. Modelling Assumptions and Data

4.1 Grid carbon factors for modelling

SAP excludes electricity use for appliances (for non-electricity heated properties), only including electricity used for pumps, fans and lighting. However, we are assuming a switch to heat pumps in many cases, so the electricity grid carbon factor is important. The current version of SAP uses a carbon factor from 2012 (519 gCO_2/kWh), which is extremely misleading in light of the progress made in the last decade. SAP 10.1, due to be approved in Building Regulations in 2020, uses a carbon factor based on a future grid intensity which will likely be achieved in the mid-2020s (136 gCO_2/kWh). This makes sense given that SAP is often used for new builds, and new homes approved under SAP 10.1 may not be completed until 2023 at the earliest.

For this modelling the following has been assumed:

- 'Current' emissions are based on the latest published grid carbon factor (2018) = 233 gCO_2/kWh
- Grid carbon factor at 2030 = 100 gCO_2/kWh
- Grid carbon factor at 2050 = zero (in line with national net-zero carbon target). Likely to be a pessimistic projection[42].
- Any interim or average factors needed will be calculated using a straight line between these points.

4.2 Overview

Based on the existing literature (e.g. DCLG, 2001), the UCL 3D Stock model (UCL Energy Institute, 2020) and data provided by Geomni, part of the Verisk group (Geomni, no date), archetypal buildings were developed (**Appendix 2 Table A2.2**), representing the predominant housing in the pre-1919 housing stock (74%). Based on an initial seven archetypes, these were further refined due to the similarities exhibited between the Victorian and Edwardian archetypes baseline characteristics. This resulted in five building archetypes. The archetypes were assumed to be in good condition. Due to a lack of agreement on alternative standard U-values, default U-values in SAP 2012 were assumed in the modelling. This has the additional benefit of enabling comparisons to be more easily drawn between other studies adopting SAP as the energy calculation.

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[42] There is no target date for a zero carbon electricity grid but it is estimated that the UK will be 90% to 'zero carbon' by 2030. Therefore 20 years to achieve the remaining 10% appears pessimistic.

The archetypes may also be representative of quasi-domestic commercial properties, although it is recognized that such properties are likely to have different energy consumption patterns comparative to domestic properties, relating to the types of activities and the equipment within these buildings. To construct the archetype models the information in **Appendix 4 Table A4.4** was identified.

The literature review highlighted a wide range of considerations relating to the profile and performance of the pre-1919 building stock which accounts for over 5.5 million domestic and 466,530 non-domestic buildings in England, or 21% and 32% of the domestic and non-domestic building stocks, respectively. All archetypes were assumed to have solid walls - Archetypes 1 and 2 were modelled with 500mm thick solid stone walls, and Archetypes 3 – 5 were modelled with 215mm thick solid brick walls, based on BRE (2016b). Base case U-values were sourced from SAP Appendix S at 1.7 W/m^{2}K (solid brick walls) and 2.0 W/m^{2}K (solid stone walls) (**Appendix 4 Table A4.3)**. Post improvement u-values were obtained from the same source and cross checked against calculated values from software package Ubakus (following BS EN ISO 13370). The airtightness for all base case archetypes was assumed to be 12m^3/m^2.hr taken from averages suggested by the literature for the type and age band of construction (Johnston et al., 2004). This figure is broadly similar to the mean airtightness of UK dwellings of 13 arch @50Pa identified by Stephen (2000), with a mean airtightness of 11 arch @50Pa for properties constructed prior to 1920, and 12 arch @50Pa for properties constructed prior to 1900. The figures adopted in the present research were confirmed by the energy modellers' own experience from small samples of field testing in Oxfordshire (q50 methodology[43]) but can vary based on the specifics of a project, particularly the number of chimneys and whether these are blocked off. Improved airtightness values were estimated from the energy modellers' own experience doing field testing, and influenced by the assumed number of chimneys, envelope area and building typology. These improved values were cross-checked against assumptions in the SAP software package (BRE, 2016b) which estimates infiltration based on a number of user set parameters (draught proofing, floor types, number of chimneys and flues). Surface areas of windows were based on SAP Appendix S (BRE, 2016b) for the relevant construction and age band and evenly distributed across available aspects. Simple building geometry was used and based on average expected building depths as suggested by the literature (Croyden Council, 2011; The University of the West of England, 2009; Allen and Pinney, 1990). The front door was orientated due south. A subsequent sensitivity analysis of different orientations suggested only minor effects of less than 1% for the base case and less than 2% for the high impact scenario. This second, higher value is due to the use of solar optimised glazing, comprising coatings that improve the g-value and result in better solar transmission. Assumptions such as floor areas, number of storeys and storey height, and boiler efficiency were based on comparisons with statistical data and/or relevant averages in the literature. The exception was Archetype 1 where the base case boiler

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[43] Calculated output from an air pressure test. 'q50' calculates the volume of air passing through each m^2 of building envelope. This is expressed in m^3/(h.m^2) @ 50Pa. An alternative measure would be to measure the air leakage rate (n50), where airflow at a controlled pressure differential is divided by the gross internal volume of the dwelling. This is expressed in air changes per hour (ach) (Gillott et al., 2016).

efficiency was adjusted to reach the expected SAP score and fuel energy use based on real world comparisons.

SAP defaults were assumed for boiler efficiencies in the modelled archetypes. Whilst detailed seasonal efficiency data was not available, the SAP derived efficiencies take into consideration aspects such as the year of manufacture, whether a boiler is condensing or not, the type of heating controls and whether there is a fan-assisted flue. For the present reseach, the boiler efficiency would be based on winter efficiency. A similar limitation is present for heat pumps in relation to seasonal COP. The COP default in SAP has been adopted for the research, but is likely to be conservative, with opportunities to realise better performance in practice.

Based on two energy efficiency measures packages – a low level energy efficiency measures package and a high level energy efficiency measures package (**Appendix 4 Tables A4.1 and A4.3**)[44], for all pre-1919 terraces, detached and semi-detached houses (74% of pre-1919 housing), it has been assumed that there will need to be deployment of at least 129,895 of these packages annually until 2050. It is assumed that there would be a scaling up period between 2020 and 2030. A further estimated 46,350 properties would need to be upgraded annually for the remaining stock not modelled in the present research (domestic and non-domestic). However, no cost estimates, or energy and carbon savings have been included as these are outside the parameters modelled. For the archetypes included in the modelling, costs were developed as outlined in section 2.2. However, as previously noted, further research should be undertaken to develop transparent and robust costs for energy efficiency works in pre-1919 properties.

In terms of decarbonisation of 74% of the pre-1919 housing stock, the deployment of the packages modelled could reduce carbon by 25% by 2030, 60% by 2040 and 99% by 2050. Based on a sensitivity analysis, if deployment figures were adjusted to include higher levels of deployment, the extent of carbon reduction by 2030 and 2040 would increase, and conversely slower deployment would reduce carbon savings. For example, if 250,000 retrofits were achieved annually, reductions in carbon emissions for the pre-1919 housing stock would be 39% by 2030. It is assumed that between 2020 and 2030 there will be a need to increase industry skill and supply chains to deliver such measures, and therefore deployment of measures in the first ten years is less than the 129,895 annual retrofits needed. It is worth noting that for all archetypes modelled, the airtightness has been assumed to be no better

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[44] The 'low package' of measures adopted for the five archetypes modelled broadly included loft insulation, secondary or double glazing, an alternative heating system and, where deemed appropriate, some wall insulation to rear extensions and/or rear elevations and some floor insulation. This depended on on the archetype parameters. The 'high package' of measures broadly included greater levels of insulation, greater levels of technologies such as solar photovoltaic panels, higher levels of air tightness.

than $5m^3/m^2/hr$. Greater savings may be possible with better airtightness. However, as outlined in **Section 3.15,** there are risks associated with inadequate ventilation. This is in addition to the challenges of achieving and maintaining high levels of airtightness in existing buildings.

Figure 15 shows the weighted average SAP score per year based on the archetype, deployment rate of energy efficiency packages, and the proportions of properties being retrofitted to low and high level packages. By 2050 it is expected that Archetype 5, for example, will achieve an average SAP score of around 90. This is partly due to the higher proportion of properties expected to be retrofitted to the higher level package. Conversely, the lower proportion of Archetype 1 properties expected to adopt the high level package is due to the assumed greater proportion of dwellings in this category with heritage value[45], and the rural location affecting appropriate fuels for heating has resulted in the SAP score for this archetype remaining comparatively low. SAP calculations are currently heavily weighted in relation to the cost of the fuel source, and due to the higher cost of biomass relative to natural gas, and the resulting high environmental impact rating for this archetype for both packages of measures, the SAP score of Archetype 1 appears to be particularly affected by the selection of biomass heating.

Figures **16 and 17** highlight the overall reductions in space heating demand and intensity across the five archetypes modelled. It is worth noting that, although overall space heating demand is greatest for Archetype 1 (pre-1850 detached stone dwelling in a rural location), the base case for Archetype 4 (Victorian/Edwardian semi-detached dwelling) has the highest space heating intensity across the five archetypes modelled. The largest reduction in both space heating intensity and space heating demand based on the archetype base cases is for Archetype 5 (Victorian/Edwardian small terrace), followed by Archetypes 3 and 4 (Victorian/Edwardian small terrace and semi-detached).

Grid decarbonisation is an important component in delivering carbon reductions, representing 12% to 39% of carbon reductions across archetypes (**Table 12**). The breakdown of carbon savings between fabric improvements, fuel switching and grid decarbonisation is presented in **Table 12**. This is further discussed in Sections 4.3 to 4.7. When focusing on the carbon reductions generated from fabric improvements alone, the savings ranged from 21% reduction in carbon emissions (Archetype 1, low package) to 54% reduction in carbon emissions (Archetype 2, high package), with a mean average carbon reduction of 39% across both packages, or 34% and 44% for low and high packages of measures respectively.

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[45] Data from Geomni suggests that the proportion of listed pre-1850 properties is higher than later construction dates.

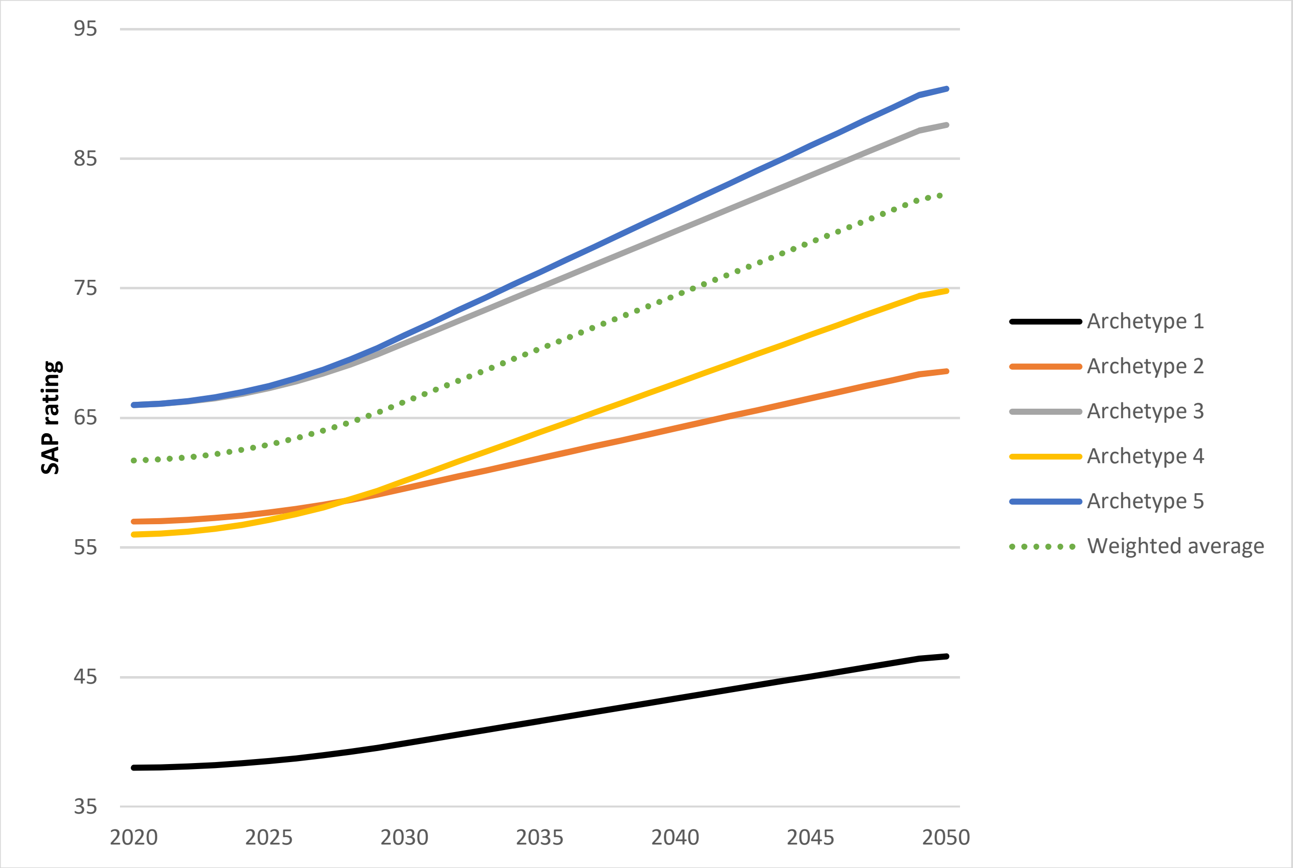

Figure 15: Weighted average SAP ratings per archetype based on phased deployment of packages of measures

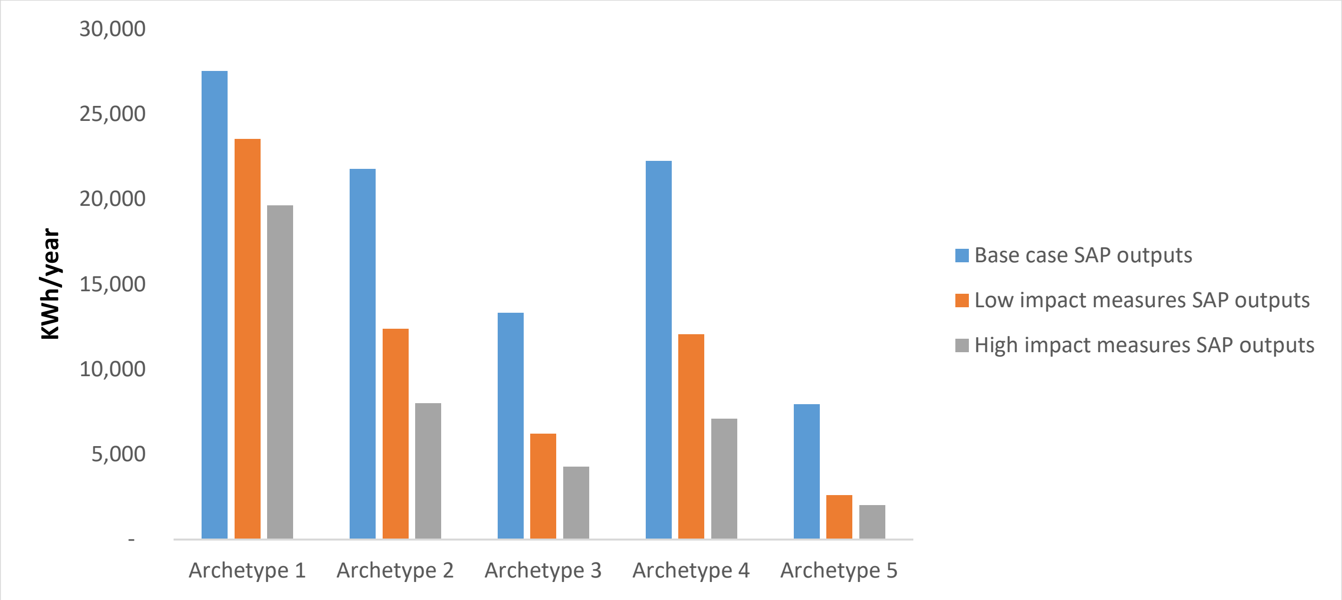

Figure 16: Archetype space heating (KWh/year) demand for base case, low impact package and high impact packages

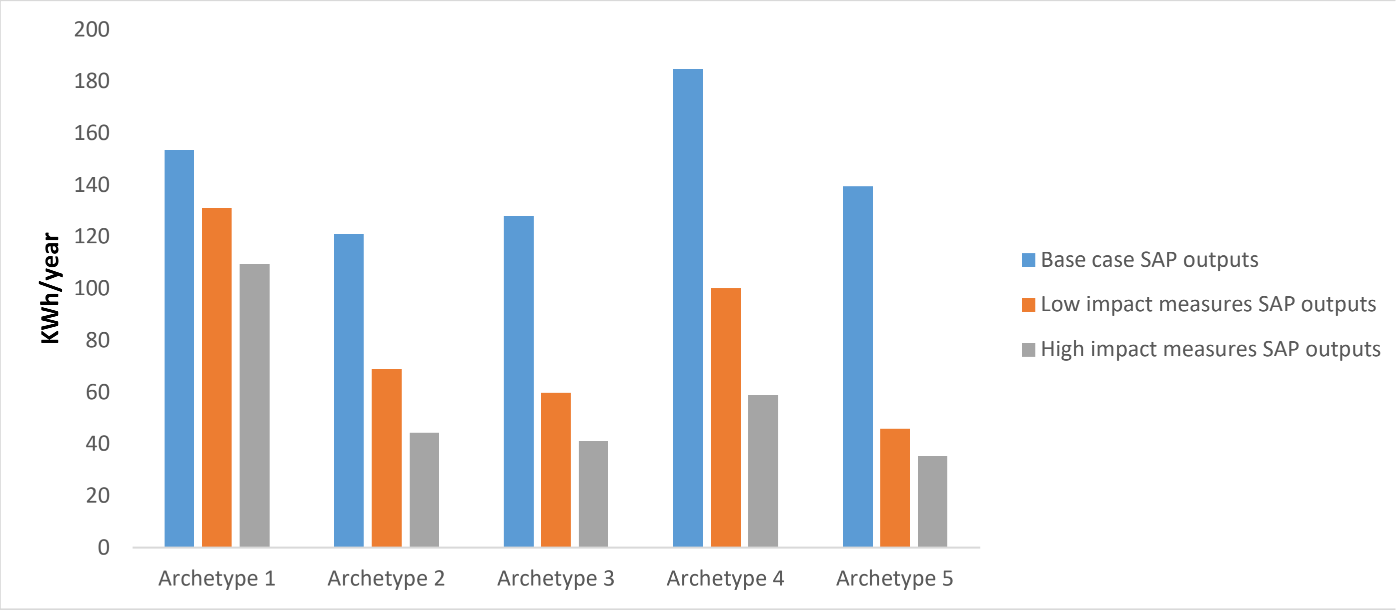

Figure 17: Archetype space heating intensity (KWh/year) for base case, low impact package and high impact packages

Table 12: Carbon saving breakdown by archetype

Archetype	Carbon savings from fabric improvements (%)	Carbon savings from heating fuel change (%)	Carbon savings from grid decarbonisation (%)
1 (low package)	21%	62%	12%
1 (high package)	31%	53%	12%
2 (low package)	42%	20%	38%
2 (high package)	54%	15%	32%
3 (low package)	34%	21%	46%
3 (high package)	43%	16%	40%
4 (low package)	33%	22%	44%
4 (high package)	50%	15%	35%
5 (low package)	39%	19%	41%
5 (high package)	44%	17%	39%
Weighted averages	**40%**	**21%**	**38%**

4.3 Archetype 1: Pre-1850 detached (stone, rural)

Archetype 1 represents one of the oldest buildings modelled. A three storey modelled building, it is heated by an oil boiler with radiators and incorporates a rear extension. The average floor area adopted for the model was 179m^2, making this archetype the second largest by floor area modelled. When scaling up for this archetype, it has been assumed that 80% of dwellings would be retrofitted to the lower package and the remaining 20% to the higher package of measures, as outlined in **Appendix 4** (**Table A4.6)**.

The base case for this property had the highest fuel consumption (37,094 KWh/year) when modelled in SAP 2012, and similarly the highest domestic hot water energy consumption (4,179 KWh/year). It has the highest carbon emissions of the five archetypes modelled (15,969 $kgCO_2$/year). This is partially due to the property being heated by oil rather, which has a high carbon factor (**Figure 18**). In relation to space heating intensity, the base case was calculated to require 173 KWh/m^2 annually.

The carbon intensities from the modelled outputs are based on SAP 2012 and not updated to current carbon factors. Therefore the carbon intensities in for the modelled archetypes should only be used for comparison purposes within the archetypes modelled. Carbon emission intensity for Archetype 1 was 89 $kgCO_2/m^2$ annually based on SAP 2012[46]. Archetype 1 achieved a SAP rating of F(38). For sense-checking purposes, the modelled SAP score was compared with real-world examples of oil-heated pre-1900 detached properties within the Cotswold District Local Authority. These real-world examples achieved a mean average SAP score of F(40).

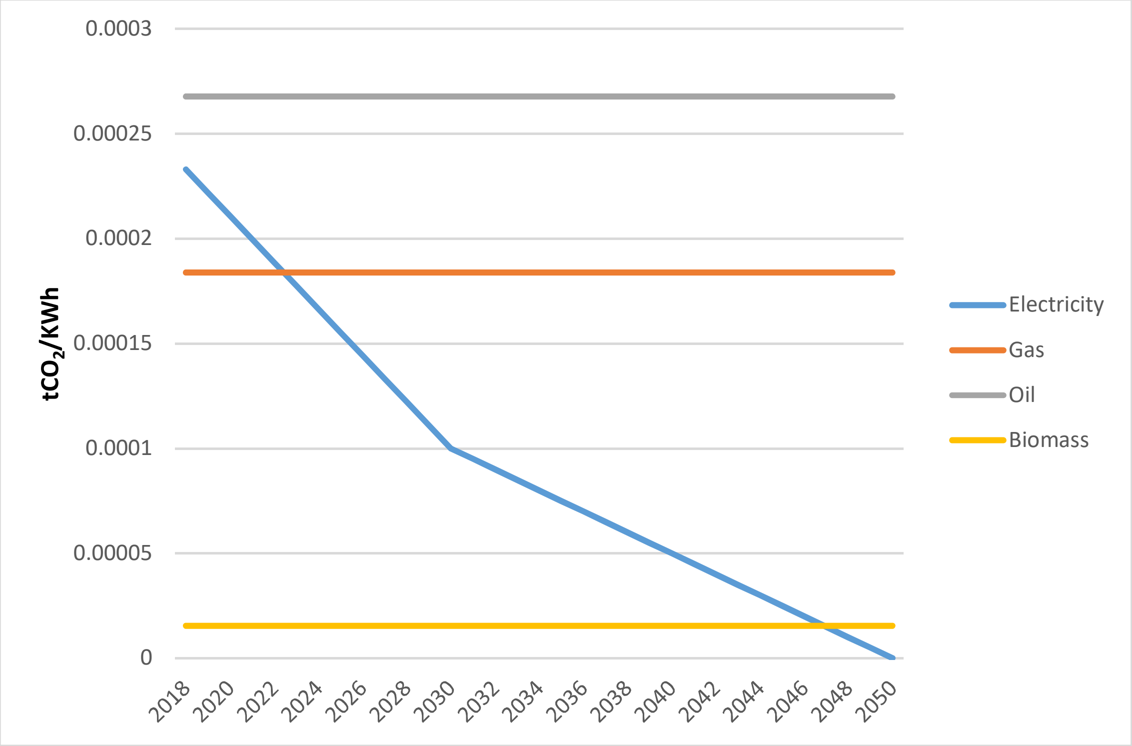

Figure 18: Carbon factors (tCO_2/kWh) for fuel sources[47]

Following intervention with the low package of measures, fuel consumption reduced (33,603 KWh/year), and domestic hot water energy consumption also reduced (3,682 KWh/year). Carbon emissions reduced to (5,345 $kgCO_2$/year). Space heating intensity and carbon

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[47] Based on current fuel projections for decarbonisation

emission intensity both reduced (131 KWh/m^2/year and 30 kgCO$_2$/m^2/year, respectively). The improved SAP rating was E(43), which remains low relative to other archetypes. The cost of the low level measures package was estimated to be around £125/tCO$_2$ based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £115/tCO$_2$.

Installing a higher package of measures, fuel consumption reduced further (28,053 KWh/year), and domestic hot water energy consumption reduced (3,682 KWh/year). Carbon emissions reduced to (5,128 kgCO$_2$/year). Space heating intensity reduced (109 KWh/m^2/year), although the carbon emission intensity reduced only slightly compared with the low package of measures (29 kgCO$_2$/m^2/year). The inclusion of a solar photovoltaic system in this property for the high level package of measures was estimated to produce 3023 KWh annually. This higher package of measures for Archetype 1 was 18 points higher than the low package of measures (D61), and 23 points higher than the base case. The cost of the higher level measures package was estimated to be around £212/tCO$_2$ based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved was estimated at £202/tCO$_2$.

Due to the property space heating intensity remaining above 100 KWh/m^2/year, it was decided that a domestic heat pump would not satisfy the heating needs of this archetype. Due to the rural location of this archetype, it was expected that in most cases, it would not be possible to connect to a heat network. However, it was assumed that there may be sufficient space to accommodate a biomass boiler. The fuel in the low and high package of measures was therefore changed to biomass for the purposes of the model.

The running costs for Archetype 1 reduce between the base case and packages of measures (**Figure 19**). The negative figure for 'renewable energy' represents the production of energy and possible export of this energy, assuming 50% of this would be exported to the main electricity grid at 5p/KWh. The greatest impact on running costs appears to relate to electricity.

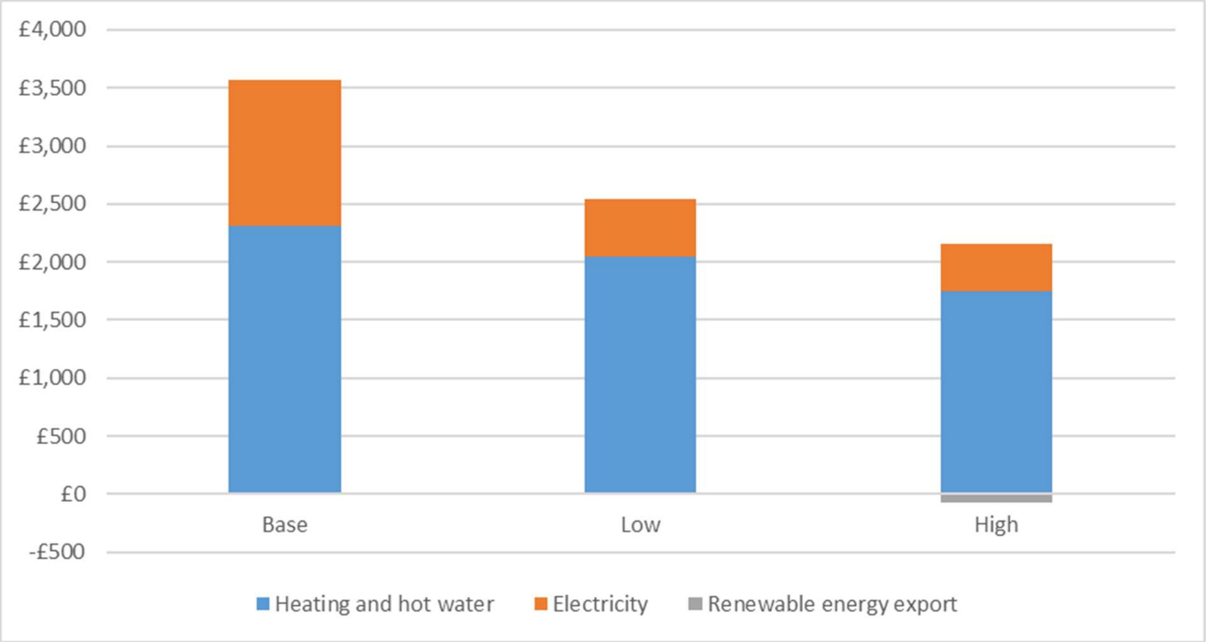

Figure 19: Archetype 1 running costs

Figure 20 shows the carbon savings for Archetype 1 relating to fabric improvements, fuel switching and from grid decarbonisation. For Archetype 1 the heating system was modelled as a biomass boiler rather than a heat pump. Therefore the saving realised from grid decarbonisation is lower than other archetypes. The breakdown shows that, for both packages of measures, for Archetype 1 the greatest savings are delivered from the change in fuel type, followed by fabric improvements.

The measures modelled for Archetype 1 were more restricted than many other archetypes in the study, resulting in comparatively lower savings from fabric improvements. It was the only archetype modelled with a biomass boiler which, based on 2020 carbon factors, had comparatively lower boiler efficiency than the heat pumps modelled, although it had a lower carbon intensity.

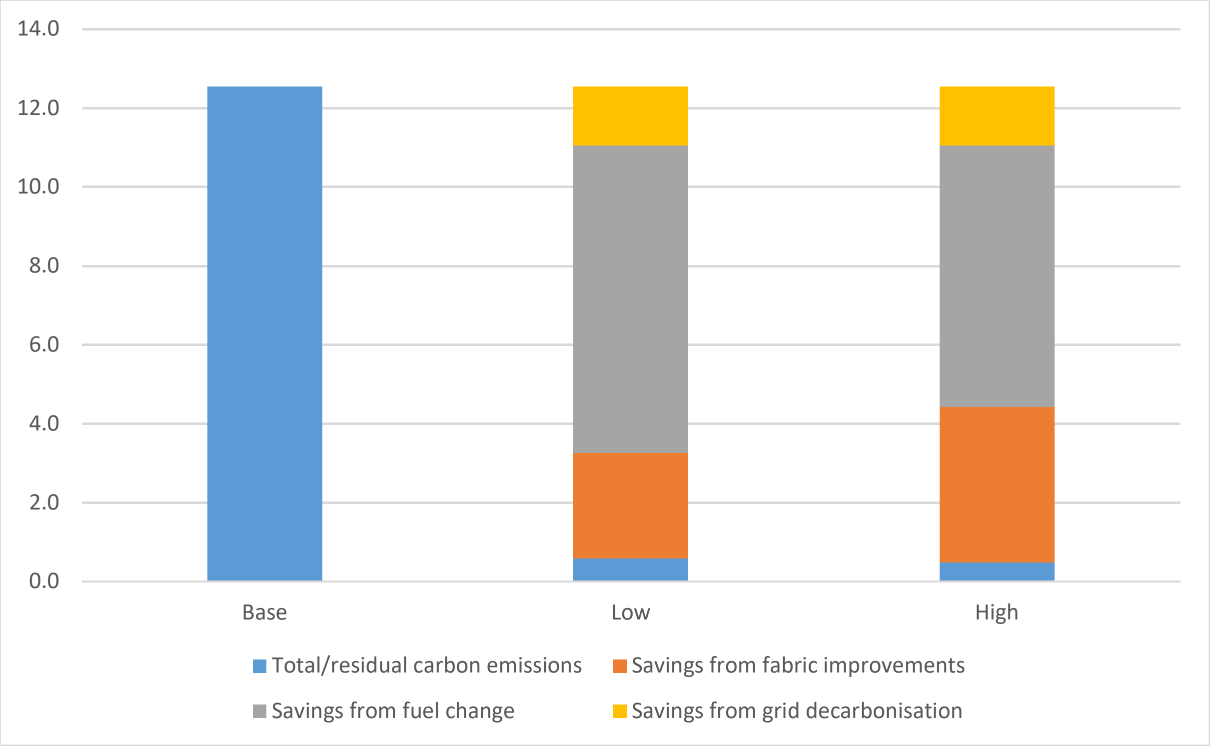

Figure 20: Archetype 1 breakdown of carbon savings for low and high packages

4.4 Archetype 2: Pre-1850 terrace

Archetype 2 represents one of two of the oldest buildings modelled based and is based on a Georgian townhouse. The three storey building model has a floor area of 180m^2, the largest floor area of all five archetypes. It is heated by a gas boiler and radiators and, as with Archetype 1, Archetype 2 has been modelled with a rear extension. When scaling up for this archetype, it has been assumed that 80% of dwellings would be retrofitted to the lower package and the remaining 20% to the higher package of measures, as outlined in **Appendix 4** (**Table A4.7)**.

The base case for this property had the second highest fuel consumption (35,746 KWh/year) when modelled in SAP 2012, and the second highest domestic hot water energy consumption (3,465 KWh/year). It also has the second highest carbon emissions of the five archetypes modelled (12,140 kgCO$_2$/year). In relation to space heating intensity, the base case was calculated to require 157 KWh/m^2 annually. Carbon emission intensity is 67 kgCO$_2$/m^2 annually and the base case achieved a SAP rating of D(57).

Following intervention with the low package of measures, the fuel consumption reduced to 7,109 KWh/year, and domestic hot water energy consumption reduced to 1,472 KWh/year. Electricity used for fuel increases between the base case (7,072 WKh/annum) and the low and high packages of measures to reflect the introduction of an ASHP as the main heating system. For the low package of measures, the electricity for fuel increased to 16,186 WKh/annum.

Carbon emissions reduced to 8,401 kgCO_2/year. Space heating intensity and carbon emission intensity both reduced (69 KWh/m^2/year and 47 kgCO_2/m^2/year, respectively). The improved SAP rating is D(64), which is similar to that achieved for Archetype 4. The cost of the low level measures package is estimated to be around £323/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £235/tCO_2.

Installing a higher package of measures, fuel consumption reduced to 4,579 KWh/year and domestic hot water energy consumption reduced to 1,472 KWh/year. For the high package of measures, the electricity for fuel increased to 9,726 WKh/annum, less than the lower package of measures to reflect the lower demand for space heating due to increased insulation levels.

Carbon emissions reduced to 5,048 kgCO_2/year. Space heating intensity and carbon emission intensity both reduced (45 KWh/m^2/year and 29 kgCO_2/m^2/year, respectively). The inclusion of a solar photovoltaic system in this property for the high level package of measures is estimated to produce 3930 KWh annually. This higher package of measures for Archetype 2 was 23 points higher than the low package of measures (B87), and 30 points higher than the base case. The cost of the higher level measures package is estimated to be around £446/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £378/tCO_2.

The running costs for Archetype 2 increase for electricity costs in the low package of measures (**Figure 21**), reflecting the lower thermal performance achieved by the intervention in parallel with switching to an ASHP (electricity) from a gas boiler. However, for this high level package, the electricity running costs reduce compared with the base case, partially supplemented by the electricity generated from the solar photovoltaic system.

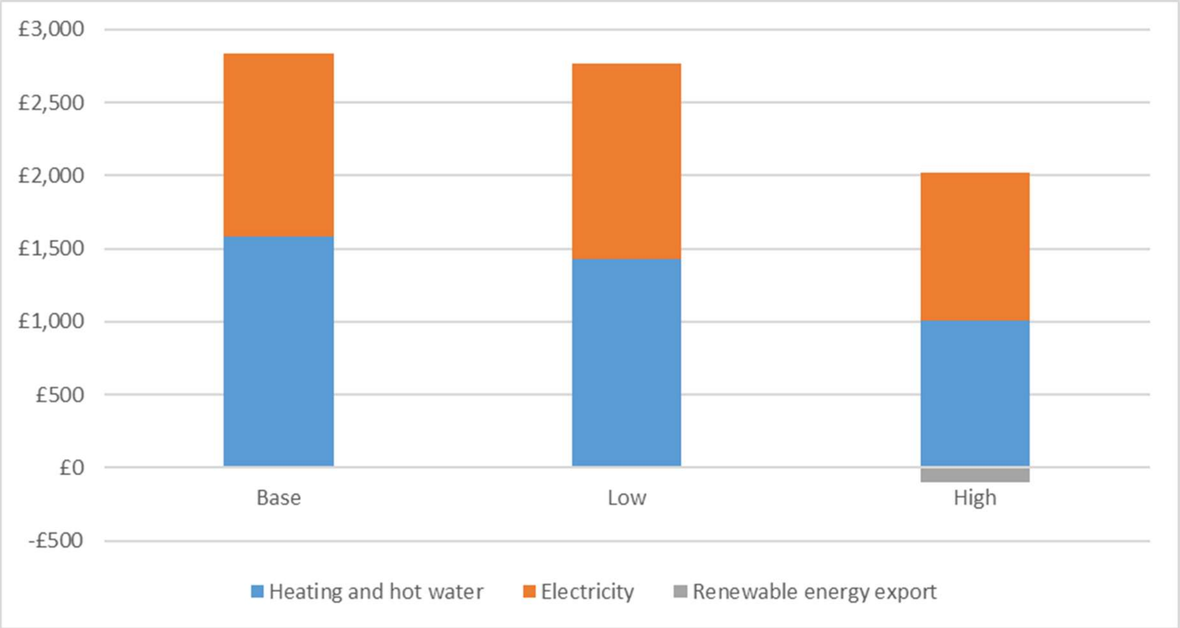

Figure 21: Archetype 2 running costs

Figure 22 shows the carbon savings for Archetype 2 relating to fabric improvements, fuel switching and from grid decarbonisation. For Archetype 2, the greatest savings were delivered by fabric improvements for both the low and high packages of measures, followed by the savings realised from grid decarbonisation.

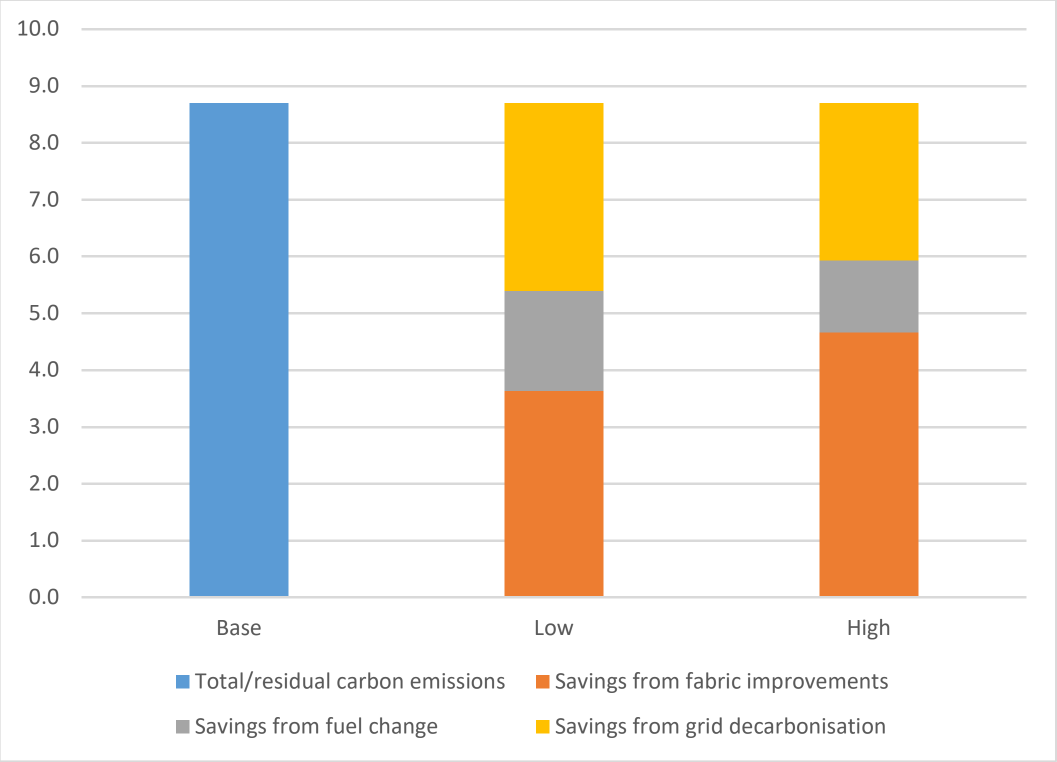

Figure 22: Archetype 2 breakdown of carbon savings for low and high packages

4.5 Archetype 3: Victorian/Edwardian medium terrace

Archetype 3 represents one of three Victorian/Edwardian archetypes modelled and, alongside Archetype 5 (Victorian/Edwardian small terrace) it represents one of the most common dwelling types of the pre-1919 stock. The two storey building model has a floor area of 104m^2 has been assumed to have aesthetic features to the front elevation. The base case has been modelled to have heat supplied by a gas boiler and radiators and includes a rear extension. When scaling up for this archetype, it has been assumed that 40% of dwellings would be retrofitted to the lower package and the remaining 60% to the higher package of measures, as outlined in **Appendix 4** (**Table A4.8)**.

The base case for this property was calculated to have a fuel consumption of 15,300 KWh/year when modelled in SAP 2012. Its energy consumption for domestic hot water was 2,798 KWh/year. Its carbon emissions were calculated to be 6,098 kgCO$_2$/year and a space heating intensity of 128 KWh/m^2 annually. Carbon emission intensity is 59 kgCO$_2$/m^2 annually and the base case achieved a SAP rating of D(66).

Following intervention with the low package of measures, fuel consumption (3,545 KWh/year), and domestic hot water energy consumption (1,427 KWh/year) both reduced. Electricity used for fuel increases between the base case (4,218 WKh/annum) and the low and high packages of measures to reflect the introduction of an ASHP as the main heating system. For the low package of measures, the electricity for fuel increased to 6,363 WKh/annum.

Carbon emissions reduced to (3,302 $kgCO_2$/year). Space heating intensity and carbon emission intensity both reduced (60 KWh/m^2/year and 32 $kgCO_2/m^2$/year, respectively). The SAP score achieved for Archetype 3 was the highest across the five archetypes for each package of measures. The improved SAP rating is B(84), the second highest SAP across the archetypes for the low package measures. The cost of the low level measures package is estimated to be around £698/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £549/tCO_2.

Installing a higher package of measures, the space heating demand reduced to 4,251 KWh/year and energy consumption to 2,428 KWh/year. Domestic hot water energy consumption remained the same between the low and high package interventions (1,427 KWh/year). For the high package of measures, the electricity for fuel increased from 4,218 KWh/annum in the base case to 5,255 WKh/annum, reflecting the change the fuel used for space heating from gas (boiler) to electricity (ASHP).

Carbon emissions reduced to 2,727 $kgCO_2$/year, a greater reduction than achieved in the low package of measures. Space heating intensity and carbon emission intensity both reduced (41 KWh/m^2/year and 28 $kgCO_2/m^2$/year, respectively). The inclusion of a solar photovoltaic system in this property for the high level package of measures is estimated to produce 3930 KWh annually. This higher package of measures for Archetype 3 achieved a SAP score of B(90), 6 points higher than the low package of measures, and 24 points higher than the base case. The cost of the higher level measures package is estimated to be around £743/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £616/tCO_2.

The running costs for Archetype 3 reduced for both low and high level packages in comparison with the base case (**Figure 23**), with only a small reduction between low and high level packages identified. The running costs in the context of both levels of intervention are slightly mitigated by the inclusion of the solar photovoltaic system.

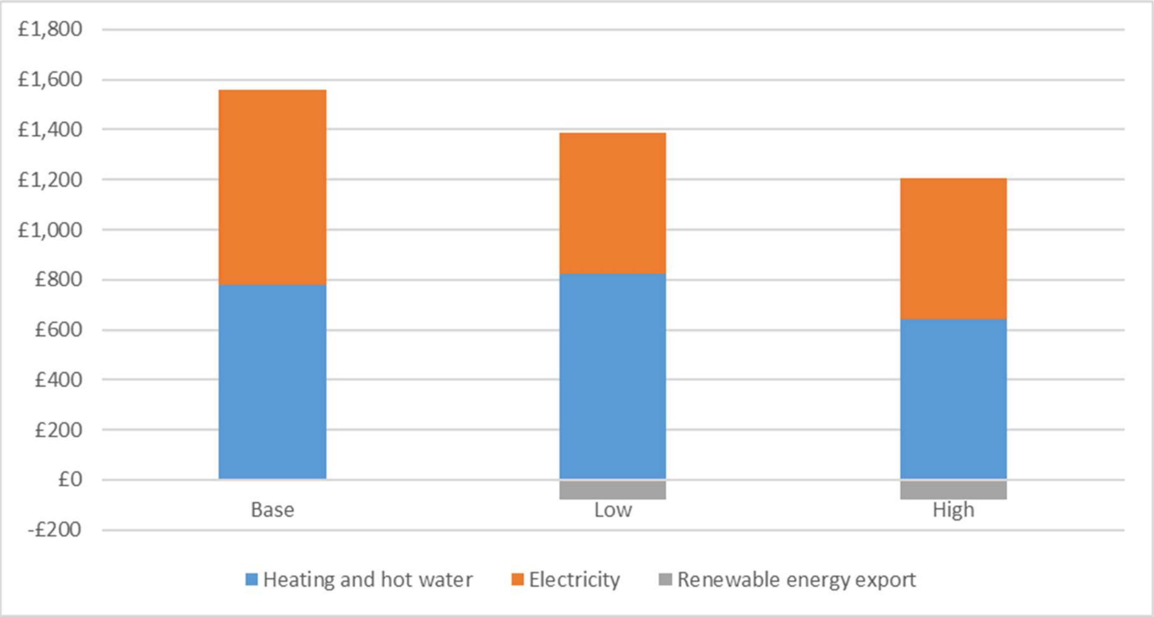

Figure 23: Archetype 3 running costs

Figure 24 shows the carbon savings for Archetype 3 relating to fabric improvements, fuel switching and from grid decarbonisation. For Archetype 3, the greatest savings were from grid decarbonisation for the low package of measures followed by fabric improvements. This is reversed for the high package of measures, which shows that the greatest saving is delivered by the fabric improvements.

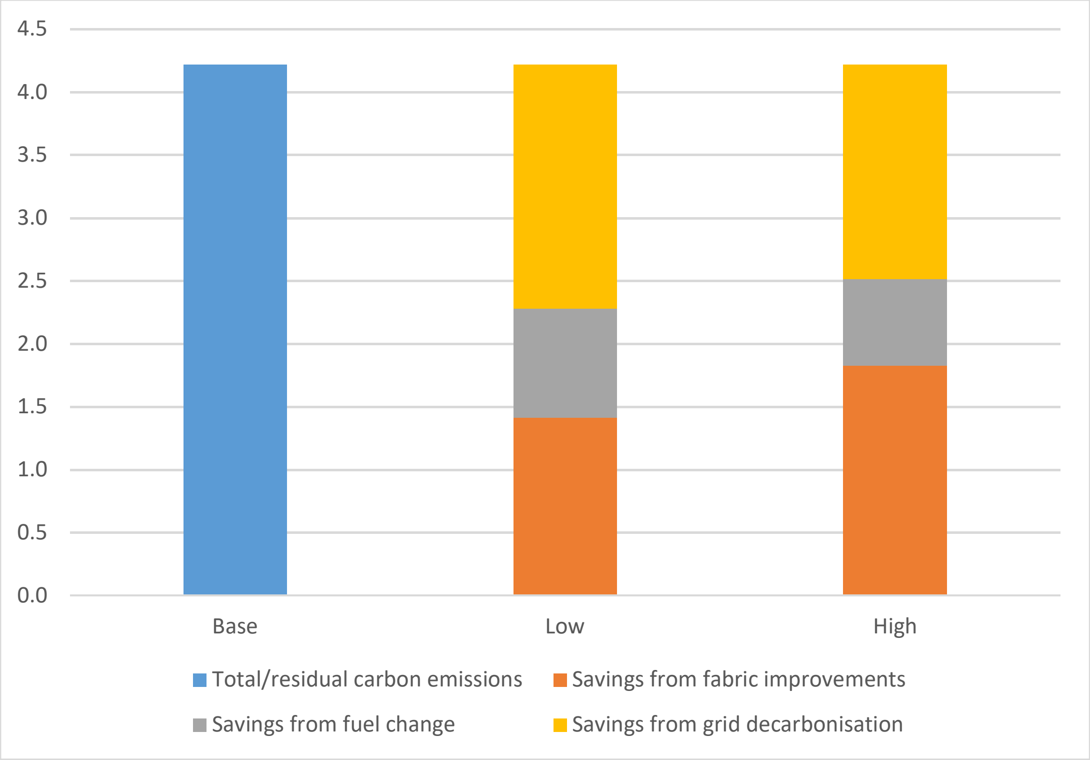

Figure 24: Archetype 3 breakdown of carbon savings for low and high packages

4.6 Archetype 4: Victorian/Edwardian semi-detached

Archetype 4 represents the second of three Victorian/Edwardian archetypes modelled. The three storey model has a floor area of $120m^2$, the largest of the Victorian/Edwardian properties modelled. It is assumed to have bay windows, ornate features to the front elevation and a rear extension. The base case has been modelled to have heat supplied by a gas boiler and radiators. The SAP rating is the second lowest across the archetypes, with Archetype 1 having the lowest SAP score. The SAP rating for the Archetype 4 (D56) base case is similar to Archetype 2 (D57). When scaling up for this archetype, it has been assumed that 30% of dwellings would be retrofitted to the lower package and the remaining 70% to the higher package of measures, as outlined in **Appendix 4** (**Table A4.9)**.

When modelled in SAP 2012, the base case for this property a fuel consumption of 25,549 KWh/year and an energy consumption for domestic hot water of 2,838 KWh/year was calculated. Its carbon emissions were calculated to be 8,636 $kgCO_2$/year and a space heating intensity of 185 KWh/m^2a. Carbon emission intensity is 72 $kgCO_2/m^2$ annually and the base case achieved a SAP rating of D(56). Total annual electricity fuel demand was calculated to be 4,826 KWh.

Following intervention with the low package of measures, fuel consumption reduced to 6,871 KWh/year, and domestic hot water energy consumption also reduced (1,447 KWh/year). Electricity used for fuel increased to 11,281 KWh/year reflecting the change a gas heating system (boiler) to an electrically-powered heating system (ASHP).

Carbon emissions reduced to 6,953 $kgCO_2$/year. Space heating intensity and carbon emission intensity both reduced (100 KWh/m^2/year and 58 $kgCO_2/m^2$/year, respectively). The improved SAP rating is D(65). The cost of the low level measures package is estimated to be around £582/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £428/tCO_2.

For the higher package of measures, for Archetype 4 fuel consumption to 4,040 KWh/year. Domestic hot water energy consumption remained the same between the low and high package interventions (1,447 KWh/year). For the high package of measures, the electricity for fuel increased from 4,826 KWh/annum in the base case to 8,461 WKh/annum.

Carbon emissions reduced to 4391 $kgCO_2$/year, a greater reduction than achieved in the low package of measures. Space heating intensity and carbon emission intensity both reduced (59 KWh/m^2/year and 36 $kgCO_2/m^2$/year, respectively).

For the high package of measures, the inclusion of a solar photovoltaic system is estimated to produce 2,116 KWh annually. This higher package of measures for Archetype 4 achieved a SAP score of C(79), 14 points higher than the low package of measures, and 23 points higher than the base case. The cost of the higher level measures package is estimated to be around

£640/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £519/tCO_2.

The running costs for Archetype 4 reduced for both low and high level packages in comparison with the base case (**Figure 25**), with only a small reduction between low and high level packages identified. The running costs in the context of both levels of intervention are slightly mitigated by the inclusion of the solar photovoltaic system.

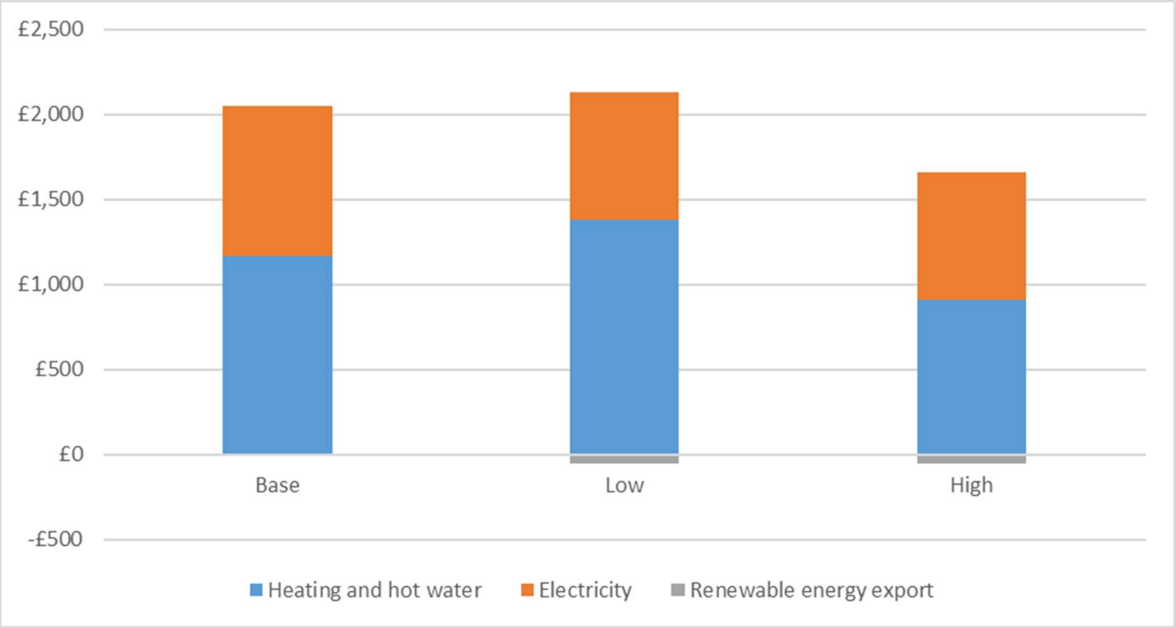

Figure 25: Archetype 4 running costs

Figure 26 shows the carbon savings for Archetype 4 relating to fabric improvements, fuel switching and from grid decarbonisation. For Archetype 4, the greatest savings were from grid decarbonisation for the low package of measures followed by fabric improvements. This is reversed for the high package of measures, which shows that the greatest saving is delivered by the fabric improvements.

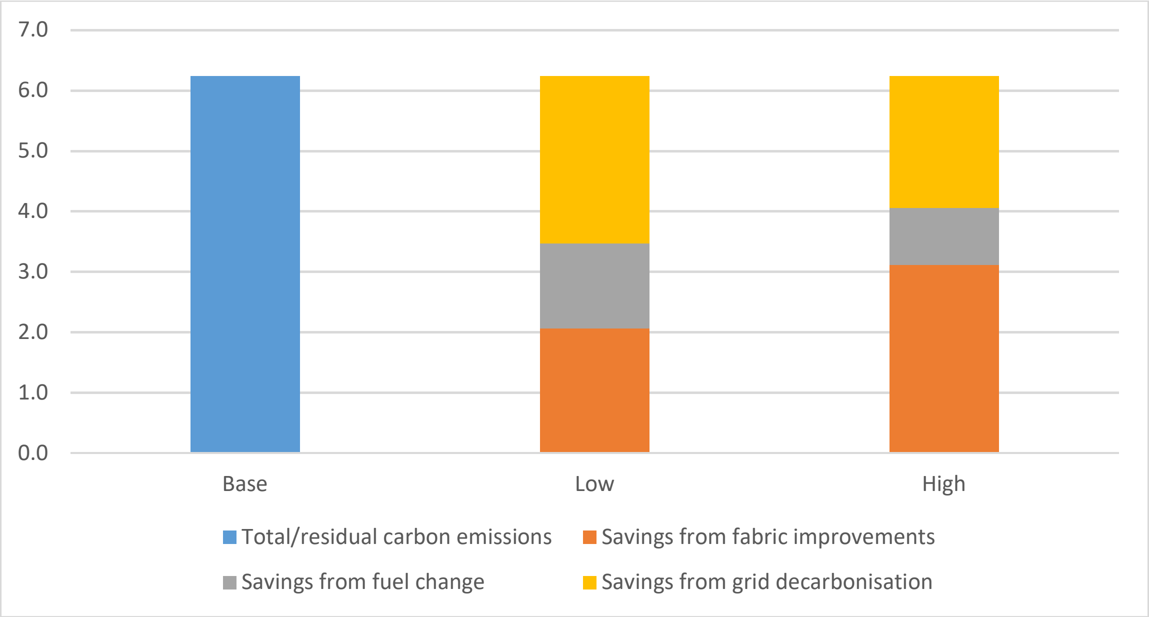

Figure 26: Archetype 4 breakdown of carbon savings for low and high packages

4.7 Archetype 5: Victorian/Edwardian small terrace

Archetype 5 is the Victorian/Edwardian small terrace and represents the final Victorian/Edwardian archetype. In addition to Archetype 3 (Victorian/Edwardian medium terrace), Archetype 5 represents one of the most common dwelling types in the pre-1919 housing stock (i.e. terraced dwellings). This two storey building is the smallest of all five archetypes at $57m^2$, and is assumed to have no visually important features or bay windows. As with three of the other archetypes (all except Archetype 1), the base case used a gas boiler to provide heating and hot water.

For scaling purposes, it is assumed that 20% of properties for this archetype will be retrofitted to the low level package, and the remaining 80% retrofitted to the higher package of measures. The measures of each package are outlined in **Appendix 4** (**Table A4.10)**.

Based on SAP 2012, the base case for this property a fuel consumption was calculated at 9,114 KWh/year. Energy consumption for domestic hot water was 2,254 KWh/year. The carbon emissions were calculated to be 3,693 $kgCO_2$/year and a space heating intensity of 139 KWh/m^2 annually. Carbon emission intensity is 65 $kgCO_2/m^2$ annually and the base case achieved a SAP rating of D(66), the same as Archetype 3 (Victorian/Edwardian medium terrace).

Following intervention with the low package of measures, the fuel consumption (1,483 KWh/year) and domestic hot water energy consumption (1,288 KWh/year) both reduced compared with the base case. Electricity used for fuel increased to 3,356 WKh/annum (from 2,385 WKh/annum in the base case) due to the change in fuel used for heating (i.e. electricity instead of gas). Electricity generated from the solar photovoltaic system was estimated at 1,814 KWh/year.

Carbon emissions reduced to (1,742 $kgCO_2$/year). Space heating intensity and carbon emission intensity both reduced (46 KWh/m^2/year and 31 $kgCO_2/m^2$/year, respectively). The SAP score achieved for Archetype 5 was the highest across the five archetypes for each package of measures. The improved SAP rating is B(88), the highest SAP across the archetypes for the low package measures. The cost of the low level measures package is estimated to be around £722/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £593/tCO_2.

Installing a higher package of measures, the space heating demand reduced to 2,003 KWh/year and space heating energy consumption to 1,144 KWh/year. Domestic hot water energy consumption remained the same between the low and high package interventions (1,288 KWh/year). For the high package of measures, the electricity for fuel increased from 2,385 KWh/annum in the base case to 3,017 WKh/annum, lower than the electricity fuel demand in the low measures package. This reflects the change the fuel used for space heating from gas (boiler) to electricity (ASHP), but also the higher thermal performance of the building resulting from the higher level package.

Carbon emissions reduced to 1,566 $kgCO_2$/year, a greater reduction than achieved in the low package of measures. Space heating intensity and carbon emission intensity both reduced (35 KWh/m^2/year and 28 $kgCO_2/m^2$/year, respectively). The solar photovoltaic system is the same size between both the low and high level packages and therefore the amount of electricity generated is the same between both packages (1,814 KWh/year). This higher package of measures for Archetype 5 achieved a SAP score of B(91) the highest across all archetypes modelled. This is 3 points higher than the SAP score achieved by the low package of measures, and 25 points higher than the base case. The cost of the higher level measures package is estimated to be around £752/tCO_2 based on 2020 carbon factors. Based on a 30-year average carbon factor, the cost per tonne of carbon saved is estimated at £633/tCO_2.

The running costs for Archetype 5 reduced for both low and high level packages in comparison with the base case (**Figure 27**), with only a small difference between running costs for low and high level packages identified. The running costs in the context of both levels of intervention are slightly mitigated by the inclusion of the solar photovoltaic system.

Figure 28 shows the carbon savings for Archetype 5 relating to fabric improvements, fuel switching and from grid decarbonisation. For Archetype 5, the greatest savings were from grid decarbonisation for the low package of measures followed by fabric improvements. As with Archetypes 3 and 4, this is reversed for the high package of measures, which shows that the greatest saving is delivered by the fabric improvements.

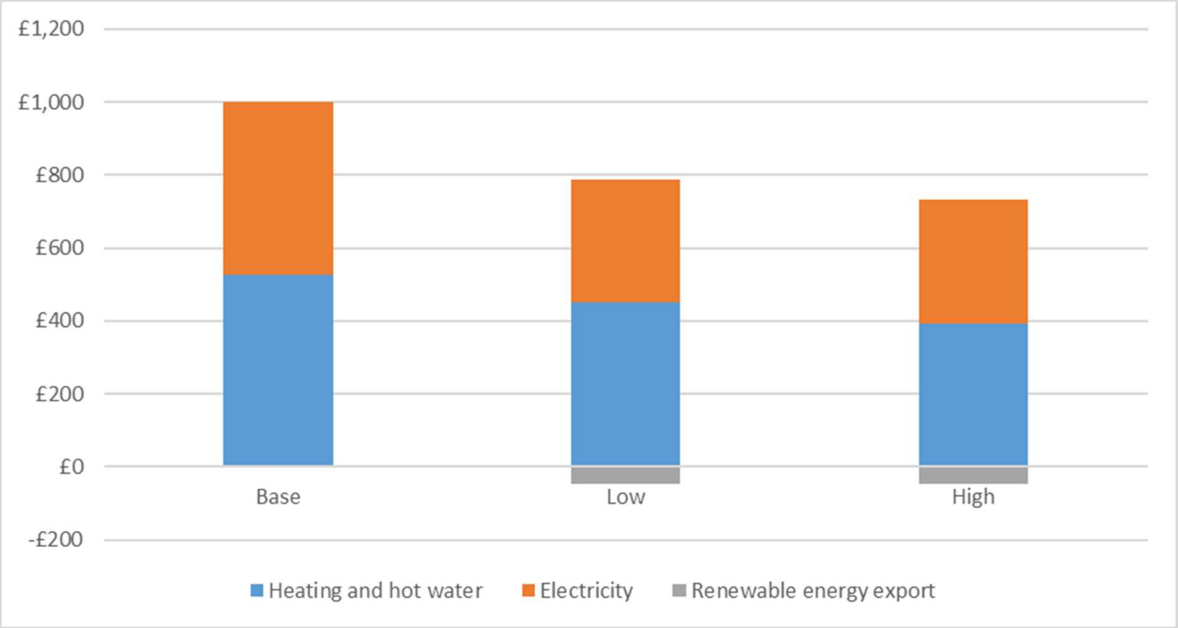

Figure 27: Archetype 5 running costs

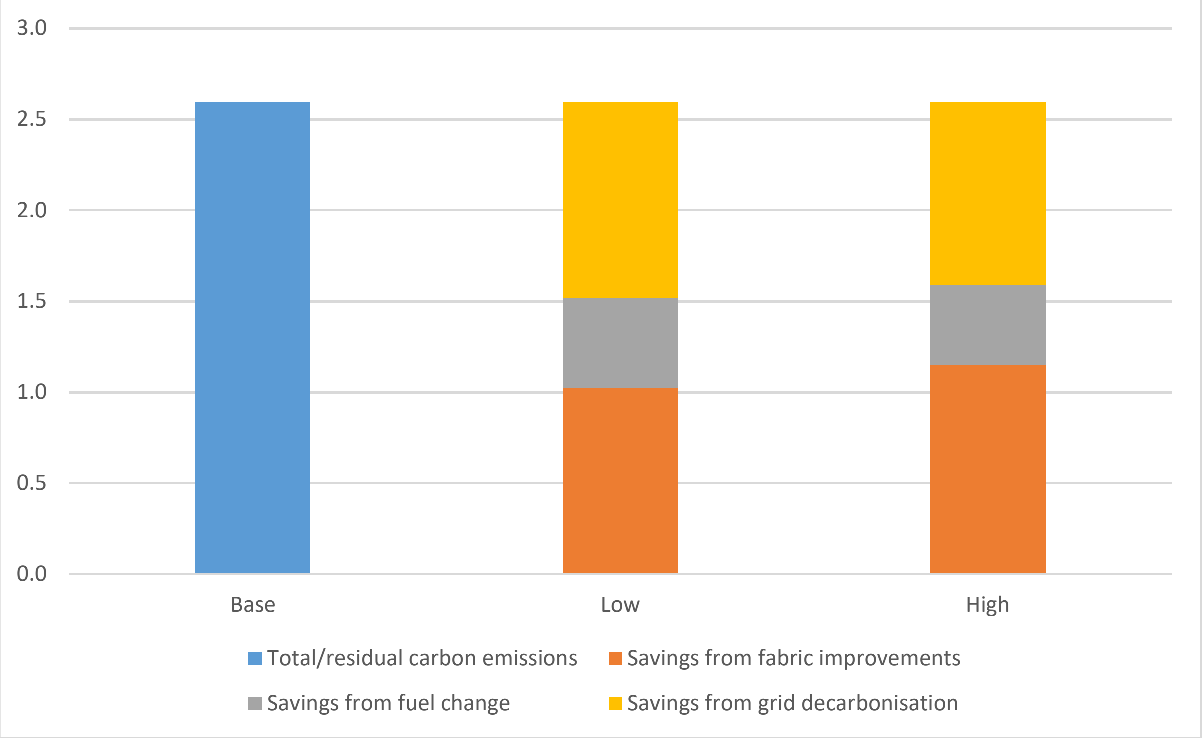

Figure 28: Archetype 2 breakdown of carbon savings for low and high packages

4.8 Additional observations

There were additional observations made based on the archetype models. Primarily these relate to the thermal performance of the extension floors and the performance of glazing.

Where an archetype was modelled with an extension, the extension floor (solid slab) was identified as typically having worse U-values than the suspended timber floor in the main house. This was partly due to higher conduction losses and the heat losses at the perimeter of the floor, in conjunction with the difficulty in retrofitting insulation to solid slabs, resulting in a lower thickness insulation being specified.

Secondary double glazing delivered better energy and carbon savings than completely replacing existing single glazing with double glazing. There is likely to be a greater level of convection heat losses between the single and secondary glazing due to a larger cavity than triple glazing. Actual performance of the glazing is likely to be impacted by occupant behaviours as well as good detailing during design and installation. Adequate ventilation to remove condensation between the single and secondary glazing needs to be considered, as does the impact of the secondary double glazing on general ventilation of the internal space and impact on daylight entering the building.

Greater savings for the air source heat pump are likely to be realised where a higher coefficient of performance (for example, a COP 2.5) is achieved and the heat pump utilises decarbonised electricity, emphasising the need to ensure an appropriately specified system which is correctly installed and operated.

4.9 Effects of orientation

The effects of orientation have been modelled for Archetype 5. There was a minor impact on the orientation in relation to space heating, but a more noticeable effect in relation to the output of the solar photovoltaic system. For example, in the base case, the orientation could change the space heating fuel demand by up to 1% (**Table 13**) and up to 2% in the high level package scenario (**Table 14**). This is more sensitive for properties with lower heating demand, and if the glazing is optimized for solar gain. In contrast, property orientation had a large effect on electricity generated from the solar photovoltaic system, with a reduction of a third when the property has a north orientation (**Table 15**). In reality, consideration could be given to the positioning of the photovoltaic panel on a particular roof (including outbuildings or other structures) and the orientation of the roof slope to reduce this effect.

Table 13: Impact of orientation changes to the Archetype 5 space heating fuel demand (*base case*).

Direction of front door	Space heating fuel	%
South	9,114	0%
East	9,192	+0.9%
North	9,154	+0.4%
West	9,192	+0.9%

Table 14: Impact of orientation changes to Archetype 5 space heating fuel demand (*high level package*)

Direction of front door	Space heating fuel	% change
South	1,144	0%
East	1,166	+1.9%
North	1,144	0%
West	1,166	+1.9%
South East	1,159	+1.3%

Table 15: Impact of orientation changes to Archetype 5 on electricity generation from solar photovoltaic system (*high level package*)

	PV yield	% change
South	1,814	0%
East	1,525	-15.9%
North	1,209	-33.4%
West	1,525	-15.9%
South East	1,293	-28.5%

4.10 Carbon reduction to 2050

Based on the archetypes modelled, between 2020 and 2050 it is anticipated that the total carbon emissions from the pre-1919 housing stock can be significantly reduced (**Figure 29**). This is through a combination of decarbonizing fuel sources and the large-scale deployment of low and high packages for improving the thermal and energy efficiency of pre-1919 dwellings and their building services. This combination is reflected in **Figure 30**, showing the current projected carbon factors of fuel sources and the reducing annual carbon emissions from the pre-1919 housing stock based on the five archetypes modelled in this study. There is a clear strategy for the decarbonisation of the main electricity network resulting in a projected fall in its carbon factor, and therefore electricity has been adopted as the main source of heating for the archetypes presented. However, the carbon factors of other sources, particularly gas and oil remain high, and therefore a move away from these sources has been suggested. There may, however, be opportunities to identify alternative fuel sources and/or develop a strategy to decarbonize the main gas network, which would increase the range of options for future modelling. For the purpose of this research, which was to identify the energy and carbon reduction potential, electricity appears to be a primary option for space and hot water heating. It is also worth noting that, whilst biomass has a low carbon factor, there will be additional considerations about its deployment including space requirements, sourcing of fuel, and its impact on air quality and the environment.

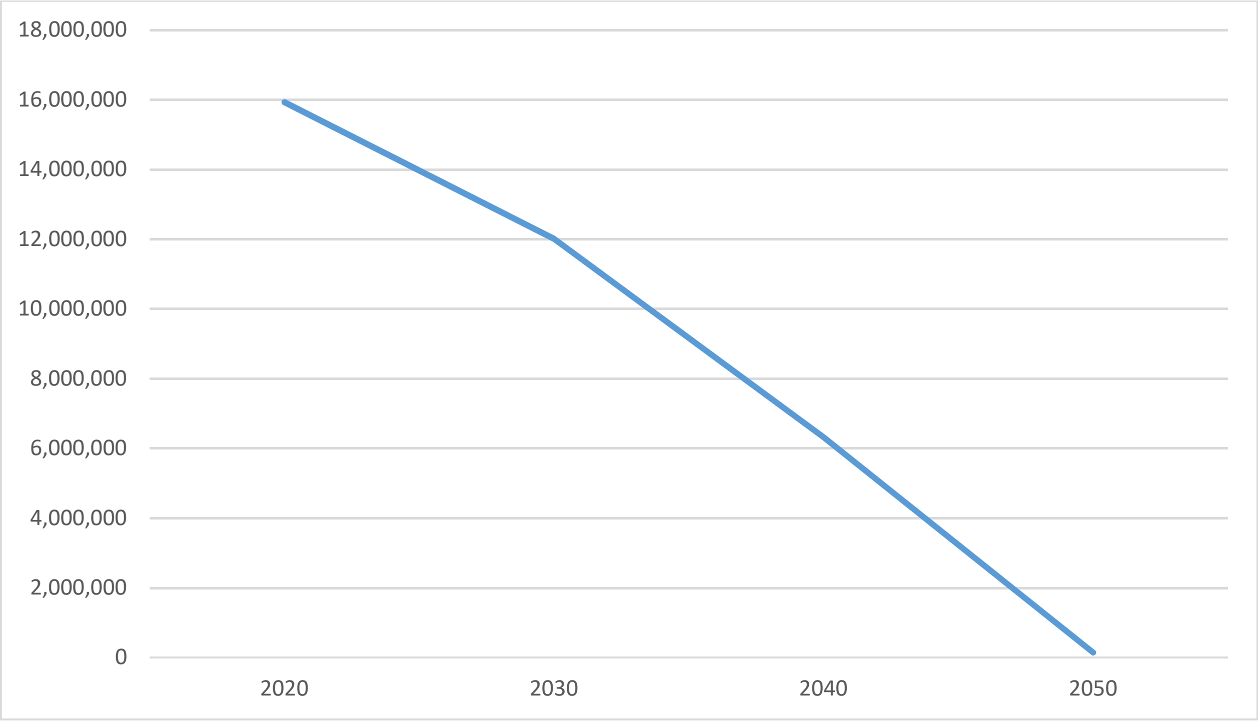

Figure 29: Total annual carbon emissions (CO_2/tonnes) from the pre-1919 housing stock (*based on the five archetypes modelled*)

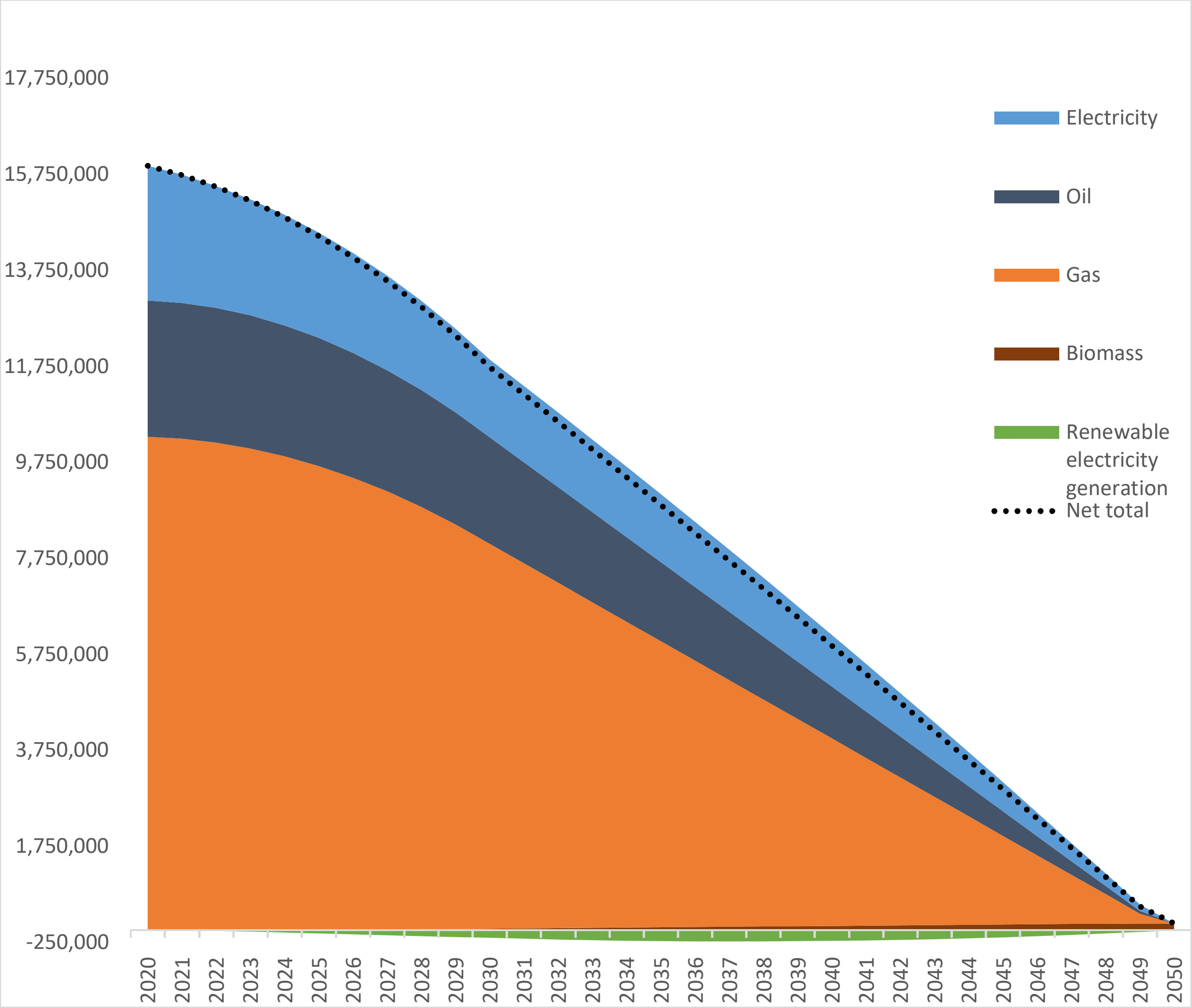

Figure 30: Total carbon emissions (CO_2/tonnes) by fuel type for pre-1919 housing stock (*based on projected carbon factors and annual carbon emissions resulting from retrofitting of packages*)

4.11 Cost of carbon reduction actions

Based on the literature, implementing the improvements in the low and high package of measures to the existing pre-1919 dwellings to improve energy efficiency range from £10,000 to over £50,000. Additionally it is unclear what building works are included in the estimates in much of the literature. Based on the cost estimates generated as outlined in **Section 2.2**, an average weighted cost of improvements was estimated as £550/tCO_2 based on 2020 carbon factors, slightly higher than the costs estimated by Element Energy and UCL (2019) (i.e. £418/tCO_2 +12%). However, these new estimates do not take account of possible savings through economies of scale and maturing of the market.

Indicative costs for the low measures package range between £125/tCO_2 to £722/tCO_2 based on 2020 carbon factors or £115/tCO_2 to £593/tCO_2 based on a 30-year average carbon factor (**Table 16**). For the high measures package, cost per tonne of CO_2 saved range from

£202/tCO_2 to £633/tCO_2 based on 2020 carbon factors, and £212/tCO_2 to £752/tCO_2 based on a 30-year average carbon factor.

Table 16: Cost of carbon reduction per £/tCO_2 saved

Archetype	**Low package (base, 2020 carbon factors) (£/tCO_2)**	**Low package (base, 30-year average carbon factors) (£/tCO_2)**	**High package (base, 2020 carbon factors) (£/tCO_2)**	**High package (base, 30-year average carbon factors) (£/tCO_2)**
1	£125/tCO_2	£115/tCO_2	£212/tCO_2	£202/tCO_2
2	£323/tCO_2	£235/tCO_2	£446/tCO_2	£378/tCO_2
3	£698/tCO_2	£549/tCO_2	£743/tCO_2	£616/tCO_2
4	£582/tCO_2	£428/tCO_2	£640/tCO_2	£519/tCO_2
5	£722/tCO_2	£593/tCO_2	£752/tCO_2	£633/tCO_2

Based on the cost estimates per archetype, for the proportion of dwellings (terraces, semi-detached and detached dwellings only) retrofitted to the low and high level packages of measures outlined in **Appendix 2 Tables A2.1 and A2.2**, it is estimated that this would have a total cost of approximately £193 billion, or a mean average of £6.4 billion annually. Given that the cost of boiler replacements in the UK is estimated to be in the region of £2.5-3 billion annually for all buildings (BEIS, 2017b), some of the cost of a retrofit programme could be supported by reassigning investment. It is recognised that the estimate for new boilers installed annually is not confined to the pre-1919 building stock, nor to domestic properties alone. However, this indicates potential opportunities for the identification of different finance mechanisms to support the energy performance upgrade of the pre-1919 building stock. Further, the recent announcement from the Government about the Green Homes Grant providing up to £5,000 (or up to £10,000 for designated poorer households) to support home energy efficiency improvements (HM Treasury, 2020). Where improvements are undertaken, it is unlikely further improvements will be made in the near future (Organ, 2015) and therefore grants supporting £5,000 - £10,000 investment in energy efficiency could represent a missed opportunity to make more extensive improvements across pre-1919 housing.

4.12 Sensitivity analysis

To ascertain how changes in the assumptions affect the outputs, sensitivity analyses were undertaken for two primary assumptions. The first was performed to test the impact of deployment rate on carbon emission reduction. Altering the scaling up of the deployment of low and high packages from 10 years to 5 years, results in an estimated additional saving of 200 million tonnes of carbon, reflecting carbon savings across a longer period of time (**Figure 31**).

The second assumption relates to costing. Based on weighted averages for each of the modelled archetypes and the proportion assumed to be retrofitted with low and high packages of measures, Table **16** and **Figure 32** shows the change in the cost per tonne of carbon saved where project costs are adjusted. Removing costs associated with professional fees and contingency to reflect the 'add on' nature of the improvements to existing planned works, reduces the cost per tonne from £550 to £420/tCO_2. When removing VAT from the works, this falls further still to £362/tCO_2.

Table 16: Cost per tonne CO_2 for central scenario and changes to cost assumptions

	Low package	**High package**	**Weighted average**
Central scenario including electricity grid decarbonisation	£410	£663	£550
Central scenario excluding electricity grid decarbonisation	£410	£663	£550
Cost of measures, enabling works and 20% VAT	£313	£506	£420
Cost of measures, enabling works (no VAT)	£270	£436	£362

Based on weighted averages for each archetype and package of measures, the cumulative emissions and annual cost of the modelled carbon reduction measures modelled are shown in **Figure 33**. Where the cost of the works includes the measures and enabling works, the average annual cost of works to the pre-1919 stock modelled (i.e. 74% of the pre-1919 housing stock) reduces from £6.4 million (central scenario) to £4.9 billion (inclusive of 20% VAT) and £4.2 billion (exclusive of VAT).

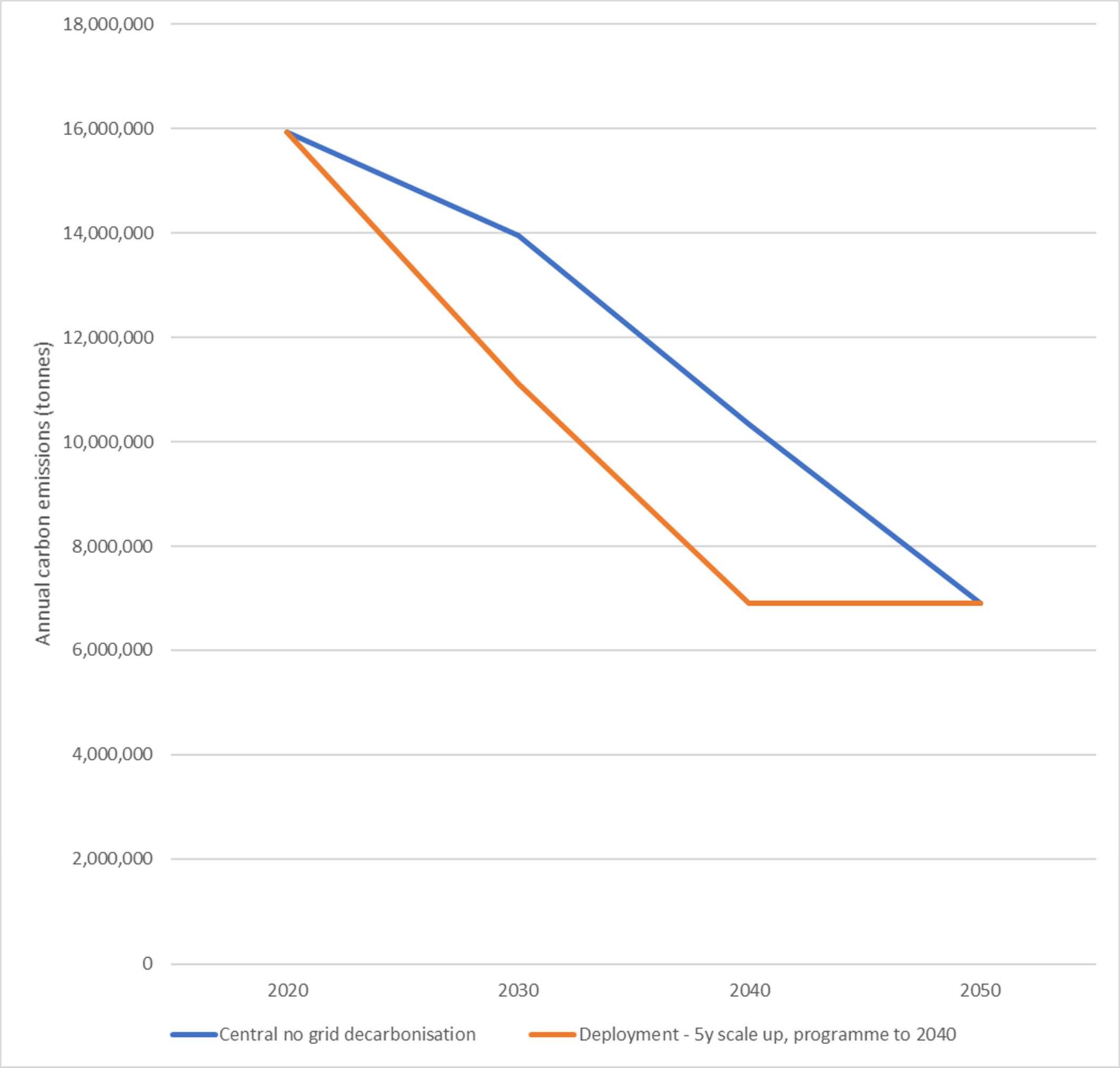

Figure 31: Sensitivity analysis for reduction in total annual emissions (tonnes CO_2)

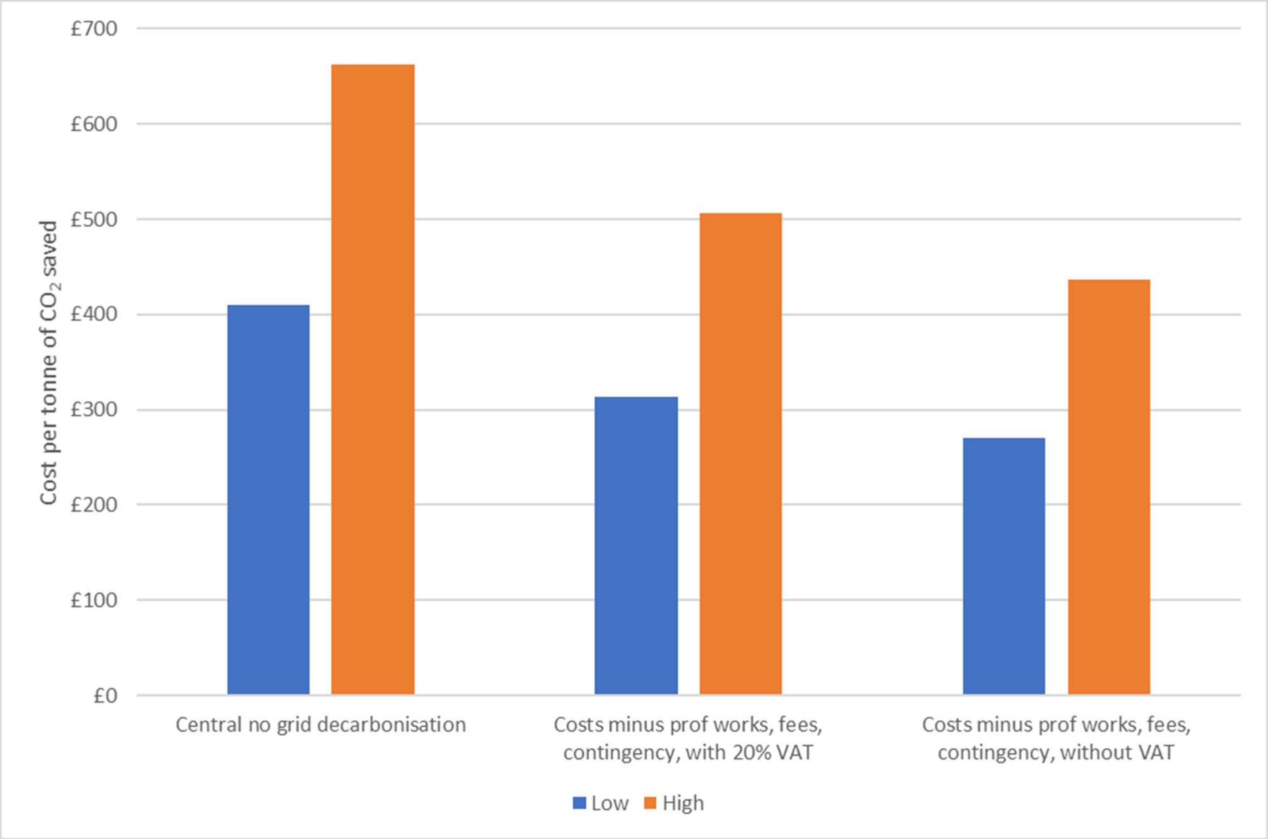

Figure 32: Sensitivity analysis for cost per tonne CO_2 for low and high packages

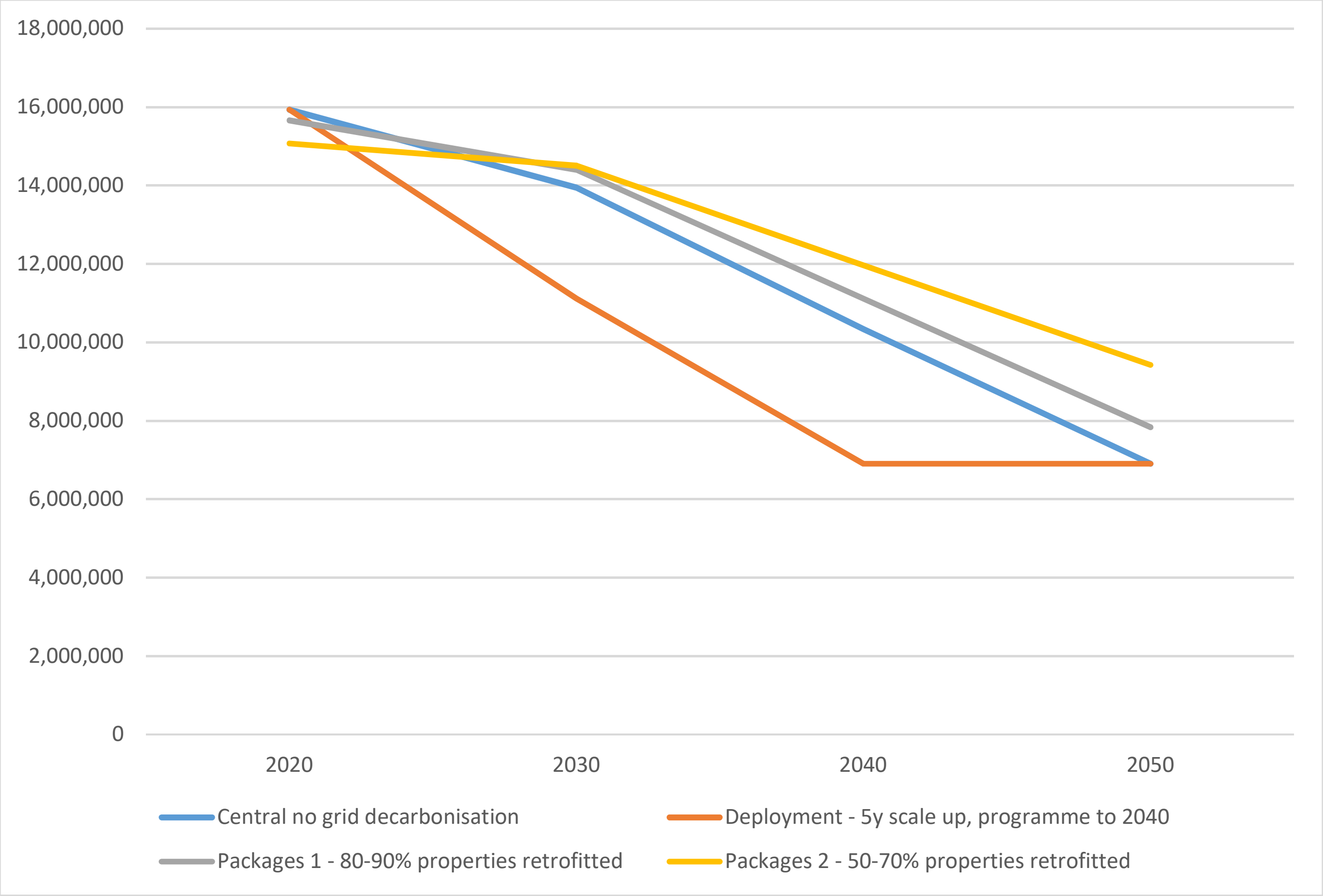

Figure 33: Sensitivity analysis for cumulative annual emissions (tCO_2) and annual average cost of improvements

5. Key findings

The pre-1919 building stock represents important heritage value, regardless of designation (i.e. listed) and conservation area status. It also has significant energy and carbon saving potential, particularly when considered beyond the designated and conservation area subset of pre-1919 buildings. However, caution is needed in relation to the specification and detailing of interventions; this should be done with as complete understanding as possible about how the individual building performs and occupant behavioural preferences to not only reduce the likelihood of an energy performance gap, but also to avoid potential maladaptations and negative unintended consequences. Decisions about measures should, where possible, consider the current and future weather projections for the region to avoid future damage to the building or impacting negatively on occupant health. Adequate ventilation is crucial for indoor air quality and to mitigate summer overheating, and any ventilation strategy should consider how to reduce occupants inadvertently reducing this ventilation.

Based on an analysis of the individual elements, mechanical ventilation in the five archetypes modelled had negative savings in relation to energy and carbon because such technology is energy using, and due to the airtightness levels did not result in observable savings in energy or carbon. However, for the purposes of contributing to a healthy internal environment, mechanical ventilation may form part of the wider ventilation strategy to avoid the accumulation of condensation and indoor pollutants.

Across the archetypes, it was noticed that single glazed windows with the addition of double glazed secondary glazing perform almost as well in the model as triple glazing, highlighting a potentially important consideration in the way pre-1919 glazing is upgraded. Care should be taken to detail such systems to limit or avoid instigating thermal bridging and other issues, as outlined in research by Weeks et al. (2013) and Historic Environment Scotland (2010). Although loft insulation has been traditionally perceived as a relatively 'easy win' measure to improve, due to the likelihood of insulation already being present as highlighted by BRE (2008) (**Section 3.5**), increasing this insulation was shown in the archetype modelling to have a more minor saving than other fabric interventions.

Orientation of a building is important, but mostly for informing where to position technology such as solar photovoltaic panels, as there appears to be little effect on space heating demand. However, the literature indicates that regional conditions, particularly relating to the wetting and drying of external walls should be considered when specifying thermal improvement measures, alongside additional considerations (e.g. occupant behaviours and preferences, risk of overheating, aesthetic value).

The cost of implementing a package of energy efficiency improvements across the pre-1919 housing stock has been estimated at £410/tCO_2 to £663/tCO_2 for low and high packages (respectively) under the central scenario, or £550/tCO_2 as a weighted average, although these costs are dependent on a large range of variables. The cost per tonne of operational carbon saved reduces to £420/tCO_2 when considering only the cost of the measures and enabling works, excluding professional fees and preambles. Excluding 20% VAT also has an impact, reducing the cost to £362/tCO_2 (weighted average).

Based on these costs and the proportion of the pre-1919 housing stock retrofitted to low and high level packages, it has been estimated that the annual cost of retrofitting three-quarters of pre-1919 housing would be in the region of £6.4 billion up to 2050. This reduces to £4.9 billion per year when considering only the cost of the measures and enabling works (inclusive of 20% VAT) and to £4.2 billion per year when removing VAT. Additional investments are likely to be required in heating networks and the decarbonisation of the main gas network, alongside the existing decarbonisation strategy for the main electricity network.

6. Study limitations

This report is based on a five-week research project. Although the analysis is based on full SAP 2012 to avoid limitations found in RdSAP, greater energy and carbon saving potentials and greater overall analysis may be possible if more complex modelling were to be undertaken.

The quantitative analysis has not considered climate change projections, which is estimated in the existing literature as likely to contribuite to lower space heating demand across the UK overall (Wood et al., 2015). However, energy demand for comfort cooling may become more common, particularly during summer months (Wood et al., 2015). The impact of climate projections on building energy demands represents an opportunity for future research.

The available data about the number of buildings in conservation areas, and rigorous data on the exact number of listed pre-1919 buildings varied. These are potential areas for future research.

Only five archetypes were modelled, representing around three quarters of the housing stock. However, further analysis could be done to consider the remaining housing stock as well as potentially disaggregate the information; further disaggregation could be done for regional variation, consideration of tenure, household structures, and so on. Due to time constraints, only one archetype was modelled for different orientations.

7. Future research areas

During the research project, a number of areas for future research were identified. These are outlined below (**Table 17**).

Table 17: Suggested areas of further research

Energy and carbon reduction	Interventions for other forms of pre-1919 buildings, particularly converted flats which represent a growing proportion of the pre-1919 housing stock.
	The potential energy and carbon reduction in non-domestic and quasi-domestic pre-1919 buildings
	Differences of occupancy patterns, household structure and tenure in relation to amount of energy use and potential energy saving
	The impact of climate projections on building energy demand particularly in relation to heating and cooling.
Pre-1919 building stock generally	Identification of rigorous numbers of pre-1919 buildings in relation to listed and non-listed, and those inside and outside of conservation areas
Technology	The application of different technologies and measures in the pre-1919 building stock, and their effects on the building and occupants. Technologies to include: • Ventilation strategies (e.g. dMEV) • Insulation (walls, loft, floors)
	Heat networks and their suitability in the pre-1919 stock, and how to implement without negatively impacting on heritage significance
	The impact of low-carbon refrigerants for heat pumps on further carbon reductions
Overheating	Strategies for reducing future effects of overheating in pre-1919 buildings
Costs	In-depth investigation of the real cost of interventions to improve the thermal and energy efficiency of pre-1919 buildings.

8. References

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Appendix 1 – Costs extracted from the literature

Table A1.1: Example from existing literature of costs of whole house energy improvements

Source	**Total cost**	**Range**	
		Minimum	**Maximum**
Historic Environment Scotland (2018)	£15,090		
Superhome Network (no date-a) (pre-1919 properties, carbon reduction assessed by Assessor)		£10,000	£60,000
Hartless and Staden (2013)		£15,000	£52,000
Existing Homes Alliance (2010)	£18,300 (low level package) £29,500 (medium level package) £54,100 (high level package)		

Table A1.2: Example from existing literature of costs of home insulation

Source	**Measure**	**Unit cost**	**Average total cost**
INTERNAL WALL INSULATION			
Energy Saving Trust (2020)	Internal wall insulation		£7,400 for average semi
BEIS (2017)	Internal wall insulation	£55 to £140/m^2 of wall	£5,000 to £10,400 for a small semi.
Neroutsou and Croxford (2016)	Internal wall insulation	£77.10/ m^2	
Sweett Group (2014)	Internal wall insulation	£123/m^2	
	Internal wall insulation (natural)	£368/m^2	
	Internal wall insulation (high-tech)	£359/m^2	
SuperHome Network (no date-b)	Internal wall insulation		£5,831 (2 or 3-bed end terrace); £4,171 (mid-terrace);

			£5,669.10 semi
EXTERNAL WALL INSULATION			
Energy Saving Trust (2020)	External wall insulation		£13,000 for average semi
BEIS (2017)	External wall insulation or insulating render	£55 to £180/m^2	£7,000 to £9,000 for a small semi
Neroutsou and Croxford (2016)	External wall insulation	£77.10/ m^2	
Sweett Group (2014)	External wall insulation	£161/ m^2	
	External wall insulation (natural)	£150/ m^2	
SuperHome Network (no date-b)	External wall insulation		£11,027.79 (2 or 3-bed end terrace); £8,075.04 (mid-terrace); £12,130.57 semi £12,523.96 detached
SuperHome Network (no date-b)			£9,400 (2 or 3-bed end terrace); £5,900 (mid-terrace); £10,340 semi
Energy Saving Trust (2020)	Loft insulation		£285 - £395
BEIS (2017)	Loft insulation	£10 - £20/ m^2	£180 - £610 for small semi
Neroutsou and Croxford (2016)	Loft insulation (wood fibre and mineral wool to 0.197W/m^{2}K)	£70.60/ m^2	
Neroutsou and Croxford (2016)	Loft insulation (mineral wool to 0.127W/m^{2}K)	£25.70/ m^2	
Historic Environment Scotland (2015)	Loft insulation	£22.54/ m^2	
Sweett Group (2014)	Roof Insulation (rigid)	£82/ m^2	
	Roof Insulation (natural)	£30/ m^2	

	Roof Insulation (loose-fill)	£14/ m^2	
BEIS (2017)	Suspended floor insulation	£1/m^2 for material plus £550 fixed installation cost, to £95/m^2	£750 for large semi-detached dwelling
Neroutsou and Croxford (2016)	Suspended floor insulation (wood fibre and mineral wool to 0.178 W/m^{2}K)	£36.70/ m^2	
Neroutsou and Croxford (2016)	Suspended floor insulation (wood fibre and mineral wool to 0.134 W/m^{2}K)	£77.70/ m^2	
Historic Environment Scotland (2015)	Suspended floor insulation (wood fibre)	£92/ m^2	
Sweett Group (2014)			

Appendix 2 – Packages of measures

Table A2.1: Measures adopted for low energy efficiency impact scenario by archetype

Archetype Number	**1**	**2**	**3**	**4**	**5**
Period	Pre-1850, detached	Pre-1850, terrace	Victorian/ Edwardian, medium/large terrace	Victorian/ Edwardian, semi-detached	Victorian/ Edwardian, small terrace
Solid wall insulation (External: 160mm wood fibre board. Internal: 60mm wood fibre board)	No	External wall, extension only	External wall – rear elevation only	External wall – rear elevation and extension	External wall – rear elevation only. Internal wall – front only
Loft insulation (320mm wood fibre batt)	Yes	Yes	Yes	Yes	Yes

Floor insulation (160mm wood fibre)	Extension only – assumed solid slab extension so 40mm insulation	Extension only – assumed solid slab extension so 40mm insulation	Yes	Yes	Yes
Secondary (double) glazing	Front only	Front only	No	No	No
Double glazing	Back and extension	Back and extension	Yes	Yes	Yes
Triple glazing	No	No	No	No	No
Low energy lighting	Yes	Yes	Yes	Yes	Yes
Air source heat pump (assumed Coefficient of Performance, COP)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)
Solar photovoltaic panel	No	No	Yes (3.5kWp)	Yes (2.4kWp)	Yes (2.1kWp)
Mechanical ventilation (dMEV) (assumed airtightness)	dMEV ($9m^3/m^2/hr$)	dMEV ($8m^3/m^2/hr$)	dMEV ($7m^3/m^2/hr$)	dMEV ($8m^3/m^2/hr$)	dMEV ($6m^3/m^2/hr$)

Table A2.2: Measures adopted for high energy efficiency impact scenario by archetype

Archetype Number	**1**	**2**	**3**	**4**	**5**
Period	Pre-1850, detached	Pre-1850, terrace	Victorian/ Edwardian, medium/large terrace	Victorian/ Edwardian, semi-detached	Victorian/ Edwardian, small terrace
Solid wall insulation (External: 160mm wood fibre board. Internal: 60mm wood fibre board)	External wall – rear elevation only.	External wall – rear elevation only. Internal wall – front elevation	External wall – rear elevation only. Internal wall – front elevation	External wall – rear elevation. Internal wall – front elevation	External wall – front and rear elevations

Loft insulation (320mm wood fibre batt)	Yes	Yes	Yes	Yes	Yes
Floor insulation (160mm wood fibre)	Yes	Yes	Yes	Yes	Yes
Secondary (double) glazing	No	Front only	No	No	No
Double glazing	Yes	Yes	No	No	No
Triple glazing	No	No	Yes	Yes	Yes
Low energy lighting	Yes	Yes	Yes	Yes	Yes
Air source heat pump (assumed Coefficient of Performance, COP)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)	Yes (COP 1.75)
Solar photovoltaic panel	Yes (2.5kWp)	Yes (4.55kWp)	Yes (3.5kWp)	Yes (2.45kWp)	Yes (2.1kWp)
Mechanical ventilation (dMEV) (assumed airtightness)	dMEV ($8m^3/m^2/hr$)	dMEV ($7m^3/m^2/hr$)	dMEV ($6m^3/m^2/hr$)	dMEV ($7m^3/m^2/hr$)	dMEV ($5m^3/m^2/hr$)

Appendix 3 – Overview of model assumptions

Table A3.1: Overview of model assumptions

Issue	Assumption	Rationale
Decarbonisation of national electricity grid	100 g/kWh carbon intensity by 2030 (a), zero by 2050 (b)	(a) Committee on Climate Change and National Grid modelling; (b) National net-zero carbon target by 2050
Decarbonisation of gas grid	No decarbonisation	(a) No national strategy for decarbonisation of the gas grid; (b) No contradiction with energy demand reduction strategy
Heating fuel for off-grid properties	Pre-retrofit – oil (a), post-retrofit – biomass (b)	(a) Predominant off-gas heating fuel;

		(b) Initially modelled as heat pump, but the heat demand was over 100 kWh/m^2 which was not felt to be cost-effective. Biomass felt to be best alternative low-carbon fuel
Heat networks	Not modelled	(a) Heat source not relevant to fabric/ventilation strategy; (b) With national net-zero carbon targets, heat networks will have to be zero carbon as well, so the main difference in the modelling would be the efficiency compared to heat pumps. Heat pump and/or waste heat driven heat networks likely to be more efficient at plant level but higher network losses; (c) Very difficult to reliably estimate number of properties suitable as heat networks highly site-specific.
Hydrogen/hybrid heat pumps	Not modelled	(a) Not established technologies, very difficult to estimate potential; (b) Very difficult to estimate consumer/install prices.
Unregulated electricity demand (appliances)	As assumed by SAP 2012	
Stable deployment level	Total number of properties divided by 25 years	(a) Maximum length of time possible to retrofit all stock by 2050 with a 10-year scale-up period
Scale-up period	10 years	(a) Current level of deep retrofits is close to zero; (b) 10 years considered reasonably ambitious scale-up period given the technical challenges and market development needs.
Install cost reductions with scale	No reductions assumed	(a) It is reasonable to expect install costs reductions with scale, but any % reduction assumed would be speculative as there is nothing to base an assumption on.

Appendix 4 – Measures and archetypes

Table A4.1: Measures for modelling packages

Insulation	Glazing	Lighting	Technology
External wall insulation - 160mm wood fibre board	Secondary glazing (double glazed)	Low energy lighting	Air source heat pump (ASHP)
Internal wall insulation (IWI) - 60mm wood fibre board	Double glazing		Photovoltaic panels
Loft insulation (LI) - 320mm wood fibre batt	Triple glazing		Mechanical ventilation heat recovery/ decentralized mechanical extract ventilation
Floor insulation - 160mm wood fibre			

Table A4.2: Overview of study archetypes

Archetype number	Period	Form	Average floor area* (m²)	Storeys	Features	Base case heating
1	Pre-1850	Detached, stone, rural	179	3	Rear extension	Oil boiler and radiators
2	Pre-1850	Georgian terrace	180	3	Rear extension	Gas boiler and radiators
3	Victorian/ Edwardian (1850 – 1918)	Medium/large terrace	104	2	Front elevation ornate features, rear extension	Gas boiler and radiators
4	Victorian/ Edwardian (1850 – 1918)	Semi-detached	120	3	Bay windows, ornate features, rear extension	Gas boiler and radiators
5	Victorian/ Edwardian (1850 – 1918)	Small terrace	57	2	None	Gas boiler and radiators

*Average floor areas only available for 1850-1919 domestic properties.

Table A4.3: Summary of base, low and high energy efficiency improvement scenario inputs and parameters - by archetype (based on SAP 2012 version 9.93)

Parameter	Archetype 1 - base	Archetype 1 - low	Archetype 1 - high	Archetype 2 - base	Archetype 2 - low	Archetype 2 - high
Building description	Pre-Victorian (pre-1850), detached, three storey, hip roof	Pre-Victorian (pre-1850), detached, three storey, hip roof	Pre-Victorian (pre-1850), detached, three storey, hip roof	Georgian (Pre 1850s), terrace, three storey, duo pitch roof	Georgian (Pre 1850s), terrace, three storey, duo pitch roof	Georgian (Pre 1850s), terrace, three storey, duo pitch roof
Floor type - main	Suspended timber, uninsulated	Suspended timber, uninsulated	Suspended timber, insulated	Suspended timber, uninsulated	Suspended timber, uninsulated	Suspended timber, uninsulated
Floor type - extension	Ground bearing concrete, uninsulated	Ground bearing concrete, insulated	Ground bearing concrete, insulated	Ground bearing concrete, uninsulated	Ground bearing concrete, insulated	Ground bearing concrete, insulated
Wall type - main	Stone, solid, uninsulated	Stone, solid, uninsulated	Stone, solid, partially insulated (EWI)	Stone, solid, uninsulated	Stone, solid, uninsulated	Stone, solid, insulated (EWI + IWI)
Wall type (extension)	Solid brick, uninsulated	Solid brick, insulated (EWI)	Solid brick, insulated (EWI)	Solid brick, uninsulated	Solid brick, insulated (EWI)	Solid brick, insulated (EWI)
Wall thickness - main (mm)	500	500	500	500	500	500
External wall u-value - main (W/m^{2}K)	2.00	2.00	2.00	2.00	2.00	0.23-0.49
External wall u-value - extension (W/m^{2}K)	0.70	0.19	0.19	1.50	0.19	0.19
Roof u-value - main (W/m2K)	1.50	0.15	0.15	2.30	0.15	0.15
Roof u-value - extension (W/m^{2}K)	0.40	0.15	0.15	2.30	0.15	0.15
Party wall u-value (W/m^{2}K)	0.00	0.00	0.00	0.00	0.00	0.00

Floor u-value - main (W/m^{2}K)	0.77	0.77	0.20	0.35	0.35	0.20
Floor u-value extension (W/m^{2}K)	1.02	0.45	0.45	1.07	0.46	0.46
Window u-value – Secondary glazing (W/m^{2}K)	4.80	4.80	N/a	4.80	N/a	N/a
Window u-value - Secondary Glazing (W/m^{2}K)	N/a	1.21	N/a	N/a	1.21	N/a
Window u-value – Double glazing (W/m^{2}K)	2.80	1.50	1.50	2.80	N/a	1.50
Window u-value – Triple glazing (W/m^{2}K)	N/a	N/a	N/a	N/a	N/a	N/a
Door u-value (W/m^{2}K)	2.90	1.90	1.90	2.90	1.90	1.90
Y - value	0.15	0.15	0.15	0.15	0.15	0.15
Airtightness (m^3/m^{2}hrs @50Pa)	12.00	9.00	8.00	12.00	8.00	7.00
Ventilation strategy	Natural ventilation with intermittent extract	Decentralised mechanical extract ventilation(dMEV)	Decentralised mechanical extract ventilation(dMEV)	Natural ventilation with intermittent extract	Decentralised mechanical extract ventilation(dMEV)	Decentralised mechanical extract ventilation(dMEV)
Main heat - source	Oil boiler	Biomass- pellet bulk	Biomass- pellet bulk	Gas condensing - system boiler	ASHP	ASHP
Main heat - efficiency (%)	83.50	70.00	70.00	79.00	175.10	175.10
Thermal store (litres)	160.00	160.00	160.00	160.00	160.00	160.00
Thermal store - insulation (mm)	38.00	80.00	80.00	38.00	80.00	80.00

Controls	Programmer and room thermostat	Full time and temperature zone control	Full time and temperature zone control	Programmer and room thermostat	Full time and temperature zone control	Full time and temperature zone control
PV (kWp)	0.00	0.00	3.50	0.00	0.00	4.55
Assumed occupancy (number)	2.98	2.98	2.98	2.98	2.98	2.98
Living area fraction (%)	0.18	0.18	0.18	0.18	0.18	0.18

Parameter	**Archetype 3 - base**	**Archetype 3 - low**	**Archetype 3 - high**	**Archetype 4 - base**	**Archetype 4 - low**	**Archetype 4 - high**	**Archetype 5 - base**	**Archetype 5 - low**	**Archetype 5 - high**
Building description	Victoria/Edwardian (1850-1899), medium - large terrace, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), medium - large terrace, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), medium - large terrace, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), semi, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), semi, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), semi, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), small terrace, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), small terrace, two storey, duo pitch roof	Victoria/Edwardian (1850-1899), small terrace, two storey, duo pitch roof
Floor type - main	Suspended timber, uninsulated	Suspended timber, insulated	Suspended timber, insulated	Suspended timber, uninsulated	Suspended timber, partly insulated	Suspended timber, insulated (EWI + IWI)	Suspended timber, uninsulated	Suspended timber, insulated	Suspended timber, insulated
Floor type - extension	Ground bearing concrete, uninsulated	Ground bearing concrete, insulated	Ground bearing concrete, insulated	Ground bearing concrete, uninsulated	Ground bearing concrete, insulated	Ground bearing concrete, insulated	Ground bearing concrete, uninsulated	Ground bearing concrete, insulated	Ground bearing concrete, insulated
Wall type - main	Brick, solid, uninsulated	Brick, solid, partially insulated (IWI)	Brick, solid, insulated (EWI+IWI)	Brick, solid, uninsulated	Brick, solid, insulated	Brick, solid, insulated	Brick, solid, insulated	Brick, solid, partly insulated (EWI)	Brick, solid, insulated (EWI)

Wall type (extension)	Cavity, insulated	Cavity, insulated (EWI)	Cavity, insulated (EWI)	Cavity, insulated	Cavity, insulated (EWI)	Cavity, insulated (EWI)	Cavity, insulated	Cavity, insulated (EWI)	Cavity, insulated (EWI)
Wall thickness - main (mm)	215	215	215	215	215	215	215	215	215
External wall u-value - main (W/m^{2}K)	1.70	0.23-1.7	0.23-0.49	1.70	0.23-1.7	0.23-0.49	1.70	0.23-1.7	0.23
External wall u-value - extension (W/m^{2}K)	0.70	0.19	0.19	0.70	0.19	0.19	0.70	0.19	0.19
Roof u-value - main (W/m2K)	0.30	0.15	0.15	0.30	0.15	0.15	0.30	0.15	0.15
Roof u-value - extension (W/m^{2}K)	0.40	0.15	0.15	0.40	0.15	0.15	0.40	0.15	0.15
Party wall u-value (W/m^{2}K)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Floor u-value - main (W/m^{2}K)	0.40	0.20	0.20	0.66	0.20	0.20	0.60	0.20	0.20
Floor u-value extension (W/m^{2}K)	1.07	0.46	0.46	1.09	0.47	0.46	N/a	N/a	N/a

Window u-value – Secondary glazing (W/m²K)	4.80	N/a	N/a	4.80	N/a	N/a	4.80	N/a	ASHP
Window u-value - Secondary Glazing (W/m²K)	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a
Window u-value – Double glazing (W/m²K)	2.80	1.50	N/a	2.80	1.50	N/a	2.8	1.5	N/a
Window u-value – Triple glazing (W/m²K)	N/a	N/a	0.80	N/a	N/a	0.80	N/a	N/a	0.8
Door u-value (W/m²K)	2.90	1.90	1.90	2.90	1.90	1.90	2.9	1.9	1.9
Y - value	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Airtightness (m^3/m^2hrs @50Pa)	12.00	7.00	6.00	12.00	8.00	7.00	12	6	5
Ventilation strategy	Natural ventilation with intermittent extract	Decentralised mechanical extract ventilation(dMEV)	Decentralised mechanical extract ventilation(dMEV)	Natural ventilation with intermittent extract	Decentralised mechanical extract ventilation(dMEV)	Decentralised mechanical extract ventilation(dMEV)	Natural ventilation with intermittent extract	Decentralised mechanical extract ventilation(dMEV)	Decentralised mechanical extract ventilation(dMEV)
Main heat - source	Gas condensin	ASHP	ASHP	Gas condensin	ASHP	ASHP	Gas condensin	ASHP	ASHP

	g - system boiler			g - system boiler			g - system boiler		
Main heat - efficiency (%)	84.02	175.10	175.10	84.02	175.1	175.1	84.02	175.1	175.1
Thermal store (litres)	160.00	160.00	160.00	160	160	160	160	160	160
Thermal store - insulation (mm)	38.00	80.00	80.00	38	80	80	38	80	80
Controls	Programmer and room thermostat	Full time and temperature zone control	Full time and temperature zone control	Programmer and room thermostat	Full time and temperature zone control	Full time and temperature zone control	Programmer and room thermostat	Full time and temperature zone control	Full time and temperature zone control
PV (kWp)	0.00	3.50	3.50	0	2.45	2.45	0	2.1	2.1
Assumed occupancy (number)	2.77	2.77	2.77	2.86	2.86	2.86	1.89	1.89	1.89
Living area fraction (%)	0.25	0.25	0.25	0.18	0.18	0.18	0.3	0.3	0.3

Table A4.4: Essential and desirable data for model construction (Source: BRE Group, 2019)

Essential	**Desirable**
Gross Internal Floor Area (m^2)	Primary heating and hot water system (type, seasonal efficiency)
Storeys (number)	U-values (W/m^2K)
Wall thickness	Dimensions (m)
Floor type (solid, suspended)	Window glazing type (single, double, triple)
Openings (type, m^2)	Number of habitable rooms (number)
Floor to ceiling height (m)	Airtightness (m^3/m^2hrs @50Pa)
Roof type (duo, hip, mono, flat)	Presence of a draught lobby
SAP rating (points)	Ventilation (natural, extract, MEV/MVHR)

Table A4.5: Proportion of properties assumed to be retrofitted to the low and high energy efficiency measures packages

Archetype number	**Assumed proportion of archetype**	
	Low level package	**High level package**
1 (pre-1850, detached)	80%	20%
2 (pre-1850, terrace)	80%	20%
3 (Victorian/ Edwardian medium terrace)	40%	60%
4 (Victorian/ Edwardian semi-detached)	30%	70%
5 (Victorian/ Edwardian small terrace)	20%	80%

Table A4.6: Archetype 1 measures by package type

Measure	**Low package**	**High package**
External wall insulation	160mm wood fibre board to extension only	160mm wood fibre board to rear elevation
Loft insulation	320mm wood fibre board	320mm wood fibre board
Floor insulation	40mm wood fibre to extension	160mm wood fibre throughout
Secondary glazing (double)	Front elevation only	None
Double glazing	Rear and extension	Throughout
Low energy lighting	Yes	Yes
Heating	Biomass (70% efficiency)	Biomass (70% efficiency)
Solar photovoltaic panel	None	3.5kWp
Mechanical ventilation (dMEV) (*airtightness*)	Yes (*$9m^3/m^2.hr$*)	Yes (*$8m^3/m^2.hr$*)

Table A4.7: Archetype 2 measures by package type

Measure	**Low package**	**High package**
External wall insulation	160mm wood fibre board to extension only	160mm wood fibre board to rear elevation
Internal wall insulation	None	60mm wood fibre board to the front elevation
Loft insulation	320mm wood fibre board	320mm wood fibre board
Floor insulation	40mm wood fibre to extension	160mm wood fibre throughout
Secondary glazing (double)	Front elevation only	None
Double glazing	Rear and extension	Throughout
Low energy lighting	Yes	Yes
Heating	ASHP (COP 1.75)	ASHP (COP 1.75)
Solar photovoltaic panel	None	4.55kWp
Mechanical ventilation (dMEV) (*airtightness*)	Yes (*8m^3/m^2.hr*)	Yes (7*m^3/m^2.hr*)

Table A4.8: Archetype 3 measures by package type

Measure	**Low package**	**High package**
External wall insulation	160mm wood fibre board to rear elevation	160mm wood fibre board to rear elevation
Internal wall insulation	None	60mm wood fibre board to the front elevation
Loft insulation	320mm wood fibre board	320mm wood fibre board
Floor insulation	160mm wood fibre	160mm wood fibre throughout
Double glazing	Throughout	None
Triple glazing	None	Throughout
Low energy lighting	Yes	Yes
Heating	ASHP (COP 1.75)	ASHP (COP 1.75)
Solar photovoltaic panel	3.5kWp	3.5kWp
Mechanical ventilation (dMEV) (*airtightness*)	Yes (*7m^3/m^2.hr*)	Yes (*6m^3/m^2.hr*)

Table A4.9: Archetype 4 measures by package type

Measure	**Low package**	**High package**
External wall insulation	160mm wood fibre board to rear elevation	160mm wood fibre board to front and rear elevations
Loft insulation	320mm wood fibre board	320mm wood fibre board
Floor insulation	160mm wood fibre	160mm wood fibre throughout
Double glazing	Throughout	None
Triple glazing	None	Throughout
Low energy lighting	Yes	Yes
Heating	ASHP (COP 1.75)	ASHP (COP 1.75)
Solar photovoltaic panel	2.45kWp	2.45kWp
Mechanical ventilation (dMEV) (*airtightness*)	Yes (*8m^3/m^2.hr*)	Yes (*7m^3/m^2.hr*)

Table A4.10: Archetype 5 measures by package type

Measure	**Low package**	**High package**
External wall insulation	160mm wood fibre board to rear elevation	160mm wood fibre board to rear and front elevations
Internal wall insulation	60mm wood fibre to front elevation	None
Loft insulation	320mm wood fibre board	320mm wood fibre board
Floor insulation	160mm wood fibre	160mm wood fibre throughout
Double glazing	Throughout	None
Triple glazing	None	Throughout
Low energy lighting	Yes	Yes
Heating	ASHP (COP 1.75)	ASHP (COP 1.75)
Solar photovoltaic panel	2.1kWp	2.1Wp
Mechanical ventilation (dMEV) (*airtightness*)	Yes (*6m^3/m^2.hr*)	Yes (*5m^3/m^2.hr*)