UNDERSTANDING CARBON IN THE HISTORIC ENVIRONMENT

Scoping Study

Final Report

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Executive Summary

The UK is committed to becoming carbon neutral by 2050, necessitating fundamental changes in energy sources and end uses over the next three decades. As climate change mitigation policy continues to grow in importance, securing and communicating opportunities to improve the energy efficiency of the English historic building stock through low carbon refurbishment is critical to its long-term survival. To date, regulations and policymakers measure the carbon emissions of buildings based on operational energy use only, ignoring the embodied carbon benefits of reusing the existing structure.

Very few studies have considered the whole life carbon of historic buildings. This study improves our understanding through the use of life cycle assessment and offers a more complete measurement method of all carbon emissions, both embodied and operational. The objective was to identify suitable methods and tools for the assessment of the life cycle carbon emissions of different concept-stage energy efficient refurbishment designs for historic buildings, and to assess the life cycle carbon emissions of two refurbishment case studies. This sample size is small and cannot be used to paint an overall picture of the potential carbon savings of refurbishing existing buildings for improved energy efficiency, however it demonstrates the need for more empirical data to be gathered and analysed. Heritage bodies, the development sector and building owners could contribute to this process, but it will also need to be driven by a revision of existing policies and regulations.

Based on a review of current research and industry best practice in the field, a detailed methodology was developed for this study to assess the life cycle impacts of different concept-stage designs for historic buildings including refurbishment and demolish-and-replace. This methodology was applied to two completed energy refurbishment projects: a one-off conversion of a chapel for residential use; and the refurbishment of an end-of-terrace Victorian house similar to many buildings in England. These case studies analysed the life cycle emissions of the actual refurbishment works that were carried out at each dwelling and their projected the long-term operational emissions. It was not the intention of this study to verify the suitability of these works as much guidance on heritage and moisture-related concerns has already been published by Historic England and other reputable sources.

The findings highlight that the energy efficient refurbishment of historic buildings is necessary to achieve performances similar to buildings. It was also found that existing regulations, which consider operational emissions only, are misrepresentative of the total carbon emissions of demolition and new construction. In the case of the New-build, the omission of embodied carbon emissions would underestimate the total emissions by nearly 30%. The prioritisation of refurbishment over demolition is inherently sustainable, as the waste of many materials with carbon already embedded in them would be avoided.

With a view to the 2030 and 2050 policy targets, the refurbishment of the Victorian terrace was found to achieve the best carbon reductions of all options considered. The life cycle carbon emissions of the Victorian Terrace Refurbishment are less than those of the New-build until approximately 60 years from now, at which point they remain competitive though slightly higher. As it would not be feasible or preferable to demolish and rebuild the entire existing building stock, this emphasises the comparable energy performance that can be achieved with historic buildings if they are refurbished with improved energy performance in mind. Historic building refurbishment was also found to achieve the best economic performances in terms of marginal abatement costs and savings-to-investment ratios.

Ideally, life cycle assessment will be done at the concept-design stage to guide the decision-making process, rather than after the fact. This research, however, did not identify a single one-stop-shop tool suitable for the calculation of life cycle analysis of refurbishments at the concept-design stage, but tools have been recommended which could be adapted, combined and/or extended to develop a suitable tool for refurbishment projects, which would make the process of LCA faster. A number of recommendations are made based on this study, which include: developing associated decision support tools such as computer applications; developing an ongoing data collection and analysis programme; developing practitioner guidance which addresses the special needs of historic buildings; and a number of specific considerations for further research.

Key Findings

This study compared the embodied and operational carbon emissions of two completed historic building refurbishments (a Victorian Terrace Refurbishment and a Chapel Conversion) to a standard New-build of a footprint adapted to match that of the case studies'. The key findings are:

- The Victorian Terrace Refurbishment and the Chapel Conversion together saved 266 tonnes of carbon compared to the Base-case.
- Embodied carbon accounted for 27.9-31.3% of the New-build life cycle emissions, but only accounted for 2.1% of the Victorian Terrace Refurbishment emissions. Embodied emissions for the Chapel Conversion accounted for 10.32% of its total life cycle emissions.
- The demolition of the Victorian Terrace Refurbishment and the Chapel Conversion account for 4.1% and 6.27% of the respective New-build's total carbon emissions.
- The case studies indicate that the energy efficiency of existing historic buildings must be improved if they are to compete with new buildings on life cycle emissions savings.
- By considering operational emissions only (which the building regulations currently do), the results underestimate the New-build emissions by approximately 30% over 60 years, giving this option a false advantage and making refurbishment appear to be a less attractive option for emissions savings.
- The life cycle carbon emissions for the Victorian Terrace Refurbishment were lower than the New-build up to 60 years from now and remained competitive thereafter due to the high embodied carbon emissions associated with the demolition and construction of the New-build.
- The Chapel Conversion emissions were higher than the New-build at 60 years due to the high quantity of materials required for conversions.
- After 60 years, the Victorian Terrace Refurbishment remained more competitive with the New-build than the Chapel Conversion due to a greater focus on improved energy efficiency and a lower initial embodied carbon investment.
- The Victorian Terrace Refurbishment performs considerably better than New-build both in terms of marginal abatement cost and savings-to-investment ratios. This indicates that refurbishment would be more cost effective and attractive as a policy option than demolition and new-build.
- The length of time before the New-build becomes less carbon intensive than the refurbished buildings is dependent on a number of factors, including the depth of energy efficient retrofit, indoor operational temperature, emission rates for demolition and the carbon intensity of refurbishment materials and systems.
- The temperature at which the buildings are operated at has a noticeable effect on their operational emissions. For example, if it is assumed the Victorian Terrace Refurbishment will be operated at 18°C while the New-build will be operated at 21°C, this extends the number of years it will take for the New-build to outperform the refurbished building from 63 to 74 years, a 17% increase.
- There is no 'one-stop-shop' LCA tool which practitioners can use for estimating the concept-design stage emissions for the refurbishment of historic buildings, but there is an opportunity to combine, adapt and/or extend existing tools, given the right guidance and considerations.

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1 Introduction

1.1 Context

The Intergovernmental Panel on Climate Change (IPCC) urged in its 2018 Special Report that global temperatures be kept to 1.5°C above pre-industrial levels if we are to avoid many of the substantial and irreversible damaging impacts to the earth's inhabitants and ecosystems (IPCC, 2018). Despite this, the UK Committee on Climate Change (CCC) has found that current commitments from countries across the world are inadequate and estimate that global warming will be in the order of 3°C by 2100.

Based on the recommendations from the CCC report *Net Zero: The UK's Contribution to Stopping Global Warming* (Stark and Thompson, 2019a), on 26 June 2019 the UK Parliament signed into law an amendment to the *Climate Change Act 2008* (S.I. 2019/1056), which amends the UK's carbon emission target for 2050 from at least 80% below 1990 levels to at least 100% below 1990 levels (*The Climate Change Act 2008 (2050 Target Amendment) Order 2019*, 2019). The UK is the first of the G7 nations to make a legally binding commitment to becoming carbon neutral by 2050. However, the UK is off track to achieve the associated 51% reduction in emissions by 2025 and 57% reduction by 2030 (*Carbon Budgets: How We Monitor Emissions Targets*, 2019; Stark and Thompson, 2019b).

According to the Green Construction Board, the built environment sector is currently responsible for 35-40% of total greenhouse gas (GHG) emissions in the UK (Sturgis, 2017) and for over 30% of global GHG emissions (IPCC, 2014; Huovila *et al.*, 2009). These emissions arise from three stages of a building life cycle - construction, operation and end-of-life. While the UK Part L building regulations have been guiding the reduction of operational emissions, the full impact of embodied emissions is not currently being meaningfully addressed, which for new residential buildings can account for more than 50% of a building's total GHG emissions over its lifetime (Sturgis and Papakosta, 2017). In addition to quantifying the emissions associated with the construction and operational phases of a building, the end-of-life stage is of equal importance as there are GHG emissions associated with the transportation, recycling and disposal of building materials.

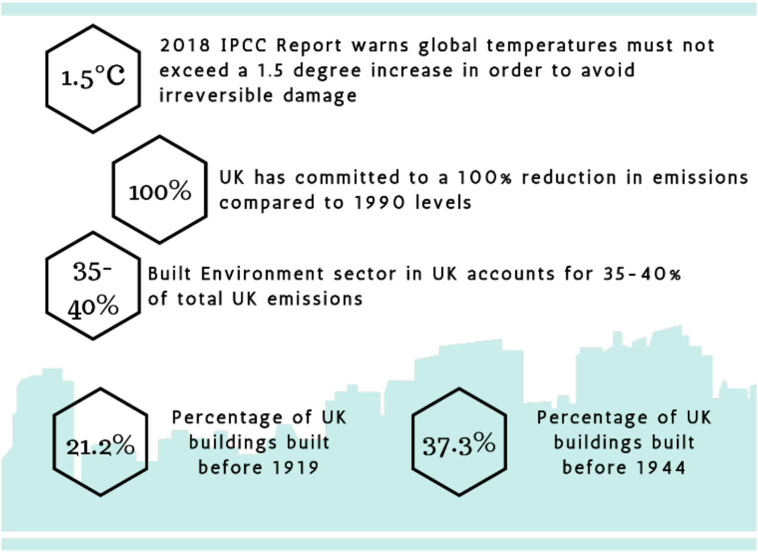

Figure 1. Key statistics relevant to the built environment and climate change mitigation

In an attempt to reduce emissions from the building sector, proposals have been made to demolish millions of inefficient dwellings and to replace them with new and more efficient buildings (Boardman *et al.*, 2005). This strategy is based on the operational emissions of buildings only and does not take into account the full environmental costs including: higher capital costs (both carbon and financial), greater production of waste and pollution, increased GHG emissions from the mining, production and transport of new materials, or the social costs of disruption, relocation, urban sprawl and potential loss of community and sense of place (Power, 2008). It also does not account for the heritage and cultural value of existing buildings and the historic built environment, which may be of local, national or international importance (Drury and McPherson, 2008; *National Planning Policy Framework (NPPF)*, 2019).

The refurbishment of existing buildings should be a considerable part of government policy to reduce carbon emissions from the built environment and construction industry. The reuse of materials is often advocated for in other sectors and this should be a focus for the building sector as well. There is currently little data available to policymakers on the total potential energy and carbon savings from the energy efficient refurbishment of existing buildings. More data and research are therefore required to assess the extent to which the refurbishment of historic or traditional buildings can reduce embodied carbon and operational emissions over a certain length of time when compared to other options for carbon mitigation in the building stock. Life Cycle Assessments (LCA) of refurbishment projects may be one way to produce the necessary supporting data, which this study demonstrates.

> ***Life Cycle Assessment:*** *an assessment of the environmental performance of materials, from the raw extraction and manufacturing to the disposal and recycling. It is the 'cradle-to-grave' approach of environmental assessment of buildings.*

There is a strong case for the establishment of a standard LCA methodology for refurbishment. LCA includes embodied impacts (associated with the materials) and operational impacts (associated with the use of the building after construction). Numerous embodied carbon assessment studies have shown that a standard methodology or database for the calculation of embodied carbon does not yet exist for refurbishment, leading to difficulties in the comparison of different design options (Pomponi and Moncaster, 2018; Pomponi, Moncaster and De Wolf, 2018; Pomponi and Moncaster, 2016; Birgisdottir *et al.*, 2017). One such study reviewed 102 peer-reviewed journal articles and identified 17 embodied carbon mitigation strategies (MS) for the built environment, which identified the need for tools, methods and methodologies and policy and regulation reform as the 4th and 5th most often cited mitigation strategies (see Table 1). There is also evidence to suggest that even when assessors start with the same type and quantity of information for a building, the results vary due to the subjective choices that an assessor may make particularly when they are not provided with enough information (Pomponi and Moncaster, 2018) (see Section 2.2 Data Sources).

Table 1. Selection of embodied carbon mitigation strategies (MS) for the built environment (listed according to occurrence – greatest to least) (Pomponi and Moncaster, 2016)

	Mitigation Strategies
1	Practical guidelines for a wider use of low-EC materials
2	Better design
3	Reduction, re-use and recovery of EE/EC intensive construction materials
4	Tools, methods and methodologies
5	Policy and regulations (governments)
6	Refurbishment of existing buildings instead of new built
7	Decarbonisation of energy supply/grid
8	Inclusion of waste, by-product and used materials into building materials
9	Increased us of local materials
10	Policy and regulations (construction sector)
11	People-driven change (key role of all BE stakeholders)
12	More efficient construction processes/techniques

13	Carbon mitigation offsets, emissions trading and carbon tax
14	Carbon sequestration
15	Extending the building's life
16	Increased use of prefabrication elements/off-site manufacturing
17	Demolition and rebuild

Prior to this study, only a few studies have considered both embodied and operational carbon of the refurbishment of historic buildings. A 2008 UK study compared the embodied and operational carbon of three refurbished properties with three newly built houses over a period of 50 years (Power, 2008). This study however is quite limited as it only considers the three life cycle stages of materials (raw material supply, transport and manufacturing) and does not take into account demolition emissions. A 2011 study in the US compared the carbon emissions of seven refurbished buildings to the base case scenario and a new building using LCA, however the traditional building stock and climate in the US would be quite different from the UK and therefore would not be directly comparable (Frey *et al.*, 2011). A 2016 Norwegian study undertook a life cycle assessment of a refurbished house built in 1936 and compared it to two alternative scenarios: 1) general maintenance of the house as-is and 2) demolition and rebuild (Berg and Fuglseth, 2018; Fuglseth *et al.*, 2018). The study showed that the refurbishment of existing buildings for improved energy efficiency may be a more preferable option from a climate change mitigation perspective and is a good example of the type of study necessary to better understand the carbon emissions of historic or traditional buildings.

While policies have been developed and enacted through building regulations to guide the improved energy efficiency of new and existing buildings, these regulations do not require the construction industry to take into account the embodied carbon of materials, their production, transportation, construction and demolition process. In order to significantly reduce GHG emissions in the short-term, policymakers will need to assess the impact of embodied carbon throughout the full construction industry supply chain, including refurbishment works to existing and historic buildings. The *RetroFirst* campaign led by the Architects' Journal champions the reuse and refurbishment of existing buildings as a means to reduce carbon emissions and waste from the building sector (Hurst, 2019). The campaign targets three means of reform: *tax* (reverse VAT rates so that renovation works are charged at 5% and new build is charged at 20%), *policy* (promote the reuse of buildings and materials through changes to planning and building regulations) and *procurement* (start by requiring all publicly-funded commissions to consider refurbishment before demolition and rebuild). The realignment of local authority and broader governmental policies and agendas to incentivise the retention and reuse of non-listed historic and existing buildings to reduce carbon emissions from the sector would also provide the non-listed historic built environment with a greater level of greater protection (Historic England, 2017).

1.2 Research Objective

This study has two main aims: 1) to identify suitable methods and tools for the assessment of the life cycle carbon emissions of different concept-stage energy efficient refurbishment designs for historic buildings (based on the current research and industry best practice); and 2) to begin the process of assessing the life cycle carbon emissions of completed historic refurbishment case studies to provide the evidence necessary for the decision-making process of designers, building owners, developers and policymakers. This latter aim involves identifying data requirements, choosing suitable key performance indicators for end-users, and developing a robust methodology to assess the life cycle carbon emissions of refurbishment.

This study uses life cycle assessment to calculate the embodied and operational carbon emissions associated with two completed refurbishment projects – one in northern England and one in London. The findings are based on actual data, and though this scoping study was only able to consider a small sample size, it has validated a need for a larger study covering varying levels of energy refurbishment (shallow to deep) applied to a much larger and varied typology of historic buildings typical to England and the UK. Hard data of the potential carbon savings provided by the reuse and refurbishment of existing buildings is a necessity to be able to drive policy reform that will incentivise lower carbon practices in the building sector.

1.3 Intended Users

Three main users of this research have been identified as historic building professionals (designers, specifiers and conservation consultants), policymakers and historic building owners. As agreed with Historic England, the output of this research is technical in nature and is therefore aimed primarily at the historic building professionals.

The three user groups will have different and specific life cycle and embodied carbon data requirements, which are outlined as follows:

> *Historic Building Professionals*: Designers, specifiers and heritage conservation consultants will need assessment methods, verifiable data and case studies upon which they can base their conservation and refurbishment decisions. Historic building professionals will need to understand Life Cycle Assessment methods and how to use less than perfect data and calculators to determine the lowest carbon energy refurbishment option. The historic building professional will also need to be aware of the material and moisture-related risks associated with energy refurbishment works in historic and traditional buildings.
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> *Policymakers*: Policymakers will require data that can inform both short- and long-term GHG emission reduction policies and targets for the built environment. While policies have been developed and enacted through building regulations to guide the improved energy efficiency of new and existing buildings, these regulations do not force the construction industry to take into account the embodied carbon of materials, their production, transportation, construction and demolition process. In order to significantly reduce GHG emissions in the short-term, policymakers will need to assess the impact of embodied carbon throughout the full construction industry supply chain, including refurbishment works to existing and historic buildings.
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> *Historic Building Owners*: Owners of historic buildings will be commissioning energy refurbishment works and will therefore require a basic understanding of why both embodied carbon and energy efficiency must be considered when making decisions about the future of their building. Building owners will need introductory information on what embodied carbon is, how it is calculated and why it needs to be assessed as part of any refurbishment project. Basic estimations of embodied carbon within different materials and construction processes will help building owners make informed decisions when working with their architect or conservation consultant.

1.4 Report Layout

Following on from the Introduction, this report is arranged as follows:

Chapter 2 introduces potential obstacles in gathering the required data for life cycle assessment, the limitations of existing LCA tools and data sources, and the impact of recycling and demolition emissions on life cycle assessments.

Chapter 3 begins with a description of the different phases and principles of life cycle assessment, life cycle inventory analysis, life cycle costing and marginal abatement costing. The impact of different sources of energy and factors that influence their carbon emission intensity is then discussed with reference to potential future emissions reductions and trade-offs. The chapter concludes with the detailed step-by-step methodology developed for this study and used to analyse the life cycle carbon emissions of the case studies.

Chapter 4 contains the case study analysis (using the methodology outlined in Chapter 4) and findings from the life cycle assessment of two dwellings: a refurbished Victorian terrace and a converted 19th century chapel.

Chapter 5 includes recommendations under five categories: decision support, data collection, data analysis, guidance and further research.

Finally, the study conclusions are summarised in **Chapter 6**.

2 LCA Data & Tools

2.1 Data Gathering Process

One of the greatest challenges of this study has been the acquisition of data. Architects may be unable to share data on their projects due to time constraints, an inability to access the data, insufficient data or reluctance by their clients to partake in the study. Architects may also be hesitant to share the data in case the findings do not reflect well on the energy refurbishment works they specified. Once appropriate case study buildings were identified, it also became apparent that many data providers were unable to source the type and breadth of data required for undertaking an LCA of the building, including a bill of quantities, design specifications, drawings, construction details, locational data, etc (see Table 18). This is one reason why only two buildings were assessed within the allotted timespan for this study.

In total, 16 potential case studies were considered for this report. Of these case studies, only two had suitable data that was received within enough time to allow for analysis (the Victorian Terrace Refurbishment and the Chapel Conversion). In addition, relevant data on a new domestic dwelling was obtained and used to create the New-build comparison for the two chosen case studies. The remainder of the potential case studies had to be discounted due to a lack of necessary data, including schedules of the refurbishment materials and details, quantities, costs, or restrictions on the use of data. One refurbishment case study was viable but could not be used due to the lack of a comparable new-build. Data were obtained for a low-carbon timber new-build, but were not used because the building would not be representative of embodied emissions for a typical new-build. For four of the case studies, permission to use the data by the property owners was not granted. Two contacts were willing to share data at later stage, but due to their own ongoing research, were unable to share data within the timeframe of this study. Six quantity surveyors involved in historic building refurbishment in the UK were contacted, however only one was granted permission to share data for three possible case studies during the last week of this study, which did not leave enough time to analyse the data. In total, data for five case studies were offered within the last few weeks of this study, but due to time constraints, LCA calculations could not be carried out.

2.2 Data Sources

2.2.1 Databases

Three databases were identified as being suitable for application to UK buildings to produce a building LCA: the Inventory of Carbon and Energy (ICE) database (Circular Ecology, 2019), the Green Guide (BRE Group, 2019) and the WRAP Embodied Carbon database (WRAP, 2019a; WRAP, 2019b) (see Table 16). These databases/tools were reviewed against the following criteria: source (where the data was extracted from), scope (how many materials are included), accessibility (price and ease of use), and update frequency (how often the data is updated to make sure it is accurate).

Out of the three databases, the Inventory of Carbon and Energy (ICE) database was deemed to be most suitable for this study for its ease of use, breadth of data and wide range of categories. The ICE database was updated in 2019 and it is available to download for free as a Microsoft excel file. The data were sourced from an extensive literature review carried out by the developers of ICE. The database includes 200 materials that are broken down into 30 main categories such as brick, cement, concrete, etc. The data on the global warming potential (GWP) of the products are expressed as kg CO_2e/m^2 or as kg CO_2e/kg. One limitation of the database is that it only provides the embodied emissions of building materials for LCA modules A1-A3 (raw material extraction, transport and manufacturing), i.e. Cradle-to-Gate. Additionally, it is a bit limited in the range of materials and systems included.

Global Warming Potential: *A measure of how much heat a greenhouse gas traps in the atmosphere, relative to carbon dioxide. Carbon dioxide has a GWP of 1, methane has a GWP of 25 and nitrous oxide has a GWP of 265. (See Section 3.2.1 for further details)*

2.2.2 Environmental Product Declarations

Given the limitations of the ICE database, it was necessary to use Environmental Product Declarations (EPDs) of building materials or products to supplement the ICE data with embodied emissions for the rest of the life cycle modules and for materials that were not included in the ICE database. Most EPDs were sourced through the National EPD System database, however not all product EPDs were available through this database and had to be sourced elsewhere. While EPDs provide data for many different environmental indicators such as resource depletion and health impacts, only data for GWP were extracted and used in this study.

There are, however, some problems with using EPDs for life cycle assessment as many of them also do not include all modules in their LCA calculations, which makes comparisons between products difficult. While the EPDs used are all in accordance with EN 15804:2012+A1:2013 (2014), which guides the development of EPDs for construction products and services, the standard allows for some aspects of the EPD to be up to the discretion of the EPD operator. This makes the comparison of products difficult. EPDs are based on Product Category Rules (PCR); each product type has its own PCR set by a PCR programme authority such as the British Research Establishment (BRE) Group. PCRs are based on ISO 14040 and ISO 14044, but as with EPDs, many aspects of the PCR are left up to the programme authority.

For a building professional to be able to make sustainable decisions during the concept-design phase, the products being considered must have EPDs based on the same PCR, include the same LCA stages, and they must be designed for the same functionality and use. For example, when comparing insulation systems, the comparison of GWP of both systems becomes difficult when they have different U-values. Comparison also becomes challenging when the functional unit of product EPDs differ. To carry out an LCA study on a building, the same functional unit must be used for each building element, for example per square meter or per kilogram. However, when EPDs have different functional units, this requires the user of the EPD to convert the data figures into the chosen functional unit for their study.

In addition, the GWP of different life cycle stages presented in the individual EPDs may not be accurate. In order to avoid double counting of carbon credits, an EPD operator must not assign a carbon credit to both module D (re-use stage) and again to the production stage of the product. For example, if the EPD reports -100 $kgCO_2e/m^2$ for the recycling stage, they must not then subtract these emissions from the raw material extraction and manufacturing stage of the product. EPDs certified by the BRE Group and The International EPD System avoid double counting by ensuring that every product LCA calculation assumes that the product is made from new raw material. However, for EPDs that have not been reviewed under these two programme authorities, it cannot be assured that this approach was followed. Additionally, many EPDs do not report data on all the modules. Modules A4-A5, B and D (see Figure 2) are often left out.

There may also be some issues with the reporting of recycled content of product. For example, some companies may report their product is 100% recyclable, but when describing their product, only a 10-15% recycled content in the product may be declared.

Due to the limited number of EPDs regulated by a single programme authority, it is not currently possible to ensure that all EPDs used in a study such as this have been regulated to the same extent. Most of the EPDs used for this study were certified by the BRE Group and The International EPD System, so for those EPDs a certain level of data quality can be assured. However, due to the lack of a central database for all EPDs, it was not possible to find all the required EPDs under the BRE Group or International EPD System PCR programmes. Since EPDs are not a legal requirement for all products in the UK, it makes it difficult to find the necessary information.

The EN 15804:2012+A1:2013 (2014) is currently under review and the revised standard, EN 15804-A2:2019, is due to be published in November 2019. It is expected to make the declaration of all LCA modules (A1-D) mandatory (except for specific cases) and to provide more complete guidance for the calculation of end-of-life recycling (Module D).

2.2.3 Data Ease-of-Use

Since the chosen functional unit to represent GWP in this study was m^2, a commonly used metric in LCA studies of buildings, the original data from the ICE database and the EPDs had to be converted into the chosen functional unit using data on product density, area or thickness. This was a time-consuming and laborious process since the necessary data were frequently not readily available and had to be converted to a format which was compatible with the specifications and drawings provided. For example, glass and timber data were combined in a way which could be applied to windows. A primary cause of this problem is the lack of an integrated LCA tool which can be used for historic building refurbishment. For this reason, it is recommended that a suitable LCA tool be used to carry out the necessary conversions to save time and simplify the LCA process (see Sections 2.3 and 5.1).

2.3 Existing LCA Tools

No single LCA tool was identified within this study that met the necessary criteria for LCA of refurbishment. However, there are some tools available which could be amended under the right guidance to be suitable for refurbishment projects. The capabilities and shortcomings of the MIT Design Advisor and One Click LCA are outlined below.

The MIT Design Advisor is a free online tool which simulates building energy use and operational emissions through a small number of inputs. It allows the user to compare the operational energy of different designs but does not provide information on embodied carbon. The tool is intuitive, relatively easy to use and requires little prior user expertise with LCA calculations. Building information can be input in less than half an hour, and there is a facility for comparing up to three different design options. It is web-based and, as a result, it can take several minutes for results to be compiled and communicated to the user. There is no function to save input file/building design options, meaning that the user must re-input all data should they want to carry out further analysis at a later stage. The functionality is also currently limited and would require the following improvements for use in England for LCA of historic building refurbishments:

- Extend current region weather files to offer greater coverage in England/UK (currently only London is supported);
- Include different building typologies which are more representative of English historic buildings (e.g. terraced buildings);
- Include different building elements which are more representative of historic buildings and suitable refurbishment details (e.g. roof types, wall types, insulation upgrades; include floors - e.g. suspended timber);
- Update lighting model to take account of new technologies (e.g. lighting assumptions with advent of LEDs); and
- Extend outputs from providing annual operational energy estimates to operational emissions over the building lifespan (using fuel and projected electricity emissions factors).

This final step would require the inclusion of different heating/cooling technologies (e.g. gas boilers, heat pumps, etc. since these use different fuel sources).

One Click LCA contains a database of many materials and their EPDs. The tool allows users to alter the data to create specific product mixes (for concrete, lime, etc.) and to request the addition of EPDs to the database if they are not already available in the tool. LCA specialists within One Click LCA will then review the EPDs and will request verification from the producers if their data is suspect. EPDs within the large One Click LCA database are also continuously updated and replaced when they expire. The tool is relatively easy to use as the quantities of materials can simply be input (in m^2, m^3, kg or unit) and the tool then calculates the embodied carbon of the products in $kgCO_2e$/desired functional unit. The tool carries out any conversion calculations necessary. It also calculates operational energy based on a regional electricity grid and different fuel sources, however it does not estimate building energy demand so the user must estimate this themselves at the concept-design phase. It should be noted that the electricity emissions intensity provided by One Click LCA does not vary over time, so it will overestimate life cycle emissions as the electrical grid is decarbonised. The user can also compare design options and identify where carbon can be reduced. The tool is relatively user friendly, ideal for the concept-design stage and suitable for historic/traditional buildings. However, it is not free of charge so it may not be suitable for building practitioners who rarely do an LCA as part of their refurbishment projects. Additionally, the tool does not give the user the option of calculating the emissions associated with the demolition of an existing building. To avoid users needing to consult another tool in conjunction with One Click LCA, it would need to be amended in these respects;

- The tool must have the option to estimate building energy use based on a small amount of inputs
- Demolition emissions must be included within embodied carbon calculations
- The fees to use may need to be subsidised to increase accessibility.

If a separate LCA tool for refurbishment projects were to be developed, it should only use EPDs that have been verified by the BRE Group and databases which have reliable data such as ICE. A discussion with the BRE Group about verifying a larger number of EPDs for products suitable to historic and traditional buildings would be required. A refurbishment LCA tool must also be designed to be applicable to the concept-design stage of a project when the greatest carbon savings can be made. The tool should encompass what is included in the above tools in addition to our recommendations for improvement.

2.4 Recycling Rate and Demolition Emissions

The construction and demolition (C&D) sector in the UK accounts for 15% of the overall national carbon emissions and generates the greatest amount of waste per year (BioRegional Development Group, 2011). The Department for Environment, Food and Rural Affairs declared a 92.1% recycling rate based on 2016 data (DEFRA, 2019), however it is not known what the total weight of recycled waste is based on. Whether these data are based on the total construction waste that arrives at a recycling centre or on the total construction waste actually recycled by the recycling centre could make a significant difference to the recycling rate. Additionally, in the scenario where a historic or traditional building is being demolished there is no information on the recycling rate of the waste or emissions associated with this. The demolition emissions of buildings are sensitive to the data available on C&D waste recycling rates.

3 Methodology

3.1 Introduction

This section describes the approach employed in estimating the life cycle carbon emissions, life cycle costs and marginal abatement costs for the case studies described in Section 4.

As no single LCA tool was identified which could calculate both the embodied and operational emissions of a refurbishment, a separate methodology was developed. The MIT Design Advisor was used to estimate a single output (see Sections 3.3 - 3.5 for full methodology).

3.1.1 Life Cycle Phases

The environmental impacts of buildings can be assessed by dividing their life cycles into stages that share common characteristics, which are: construction, operation, maintenance/refurbishment, and demolition and/or reuse (or decommissioning) (see Figure 2). Given the overriding importance of reducing GHG emissions from buildings, the impacts of these stages on carbon emissions (as opposed to energy) is the focus of this document. However, buildings have a wide variety of other significant environmental impacts that are not considered here, including resource depletion, water pollution, land-take, erosion, health impacts and impacts due to land filling of construction and demolition waste. The stages apply to all building types no matter what actual their lifespan is.

> *Construction* necessitates the use of a variety of resources including design teams, building materials, transport, plant and equipment. All of these require the use of fossil fuels and the emission of GHGs: designers require offices and transport; materials must be extracted, processed, transported and assembled, often being moved between multiple manufacturing locations; products must be moved to site; and construction requires on-site fuel consumption and waste.. While maintenance and repair occur during the operation of a building (see Figure 2), the emissions associated with this stage are actually embodied emissions. Where possible these are included in embodied emissions calculations, however the data on the carbon emissions associated with these is not usually available from databases or EPDs. For refurbishment projects, only construction related to the refurbishment works are considered as the embodied carbon of the original fabric has already been spent and has no consequence on current and future emissions (Menzies, 2011)
>
> *Operation* involves the use of energy to provide services such as heating, cooling, ventilation, lighting and powering equipment. Fuels such as electricity, natural gas, heating oil and solid fuels are traditionally used for these purposes and all result in GHG emissions either directly on-site (natural gas, heating oil and heating oil) or indirectly due to the combustion of fossil fuels off-site (electricity). The energy used in buildings is affected by many factors such as climate, exposure and lifestyle. Historically, building regulations have focused largely on reducing energy use (as opposed to emissions) from the operational stage due to its traditional dominance of life cycle emissions. However, as buildings become more operationally energy efficient, the relative importance of this stage is decreasing. For example, research suggests that the operation of ‘conventional’ buildings accounts for 80-90% of life cycle energy needs, falling to 50% for very low (operational) energy buildings (Cabeza *et al.*, 2013).
>
> *Maintenance* relates to the ongoing upkeep and repair of the building to maintain its current level of performance, but typically excludes large projects such as extensions. Maintenance activities consume materials and require the use of energy and therefore create GHG emissions in the same

way as for the construction stage. *Refurbishment* requires more materials and intervention than general maintenance and therefore higher emissions would be associated with this.

Demolition and reuse occur at the end of a building's life. It involves the use of energy for on-site demolition and transport of materials off-site. Demolition typically involves energy use and emissions, whereas the recycling and reuse of materials results in avoided emissions associated with the production of new materials from virgin materials. Where materials can be reused, the related avoided emissions can be credited to the building's life cycle. However, the emissions benefits of such materials can be accounted for either at the beginning or end of a building's life, but not both, since this would constitute the double counting of emissions benefits. This is particularly important for metals which typically have high energy production requirements but also high recycled contents (Hammond and Jones, 2011).

The sum of the GHGs from the construction, maintenance/refurbishment, and demolition and reuse phases is termed 'embodied' emissions. Operational emissions refer to the energy-related GHG emissions associated with the day-to-day use of a building as a result of the services such as space heating and cooling, lighting and powering of the building. Embodied and operational emissions together comprise the life cycle emissions of a building.

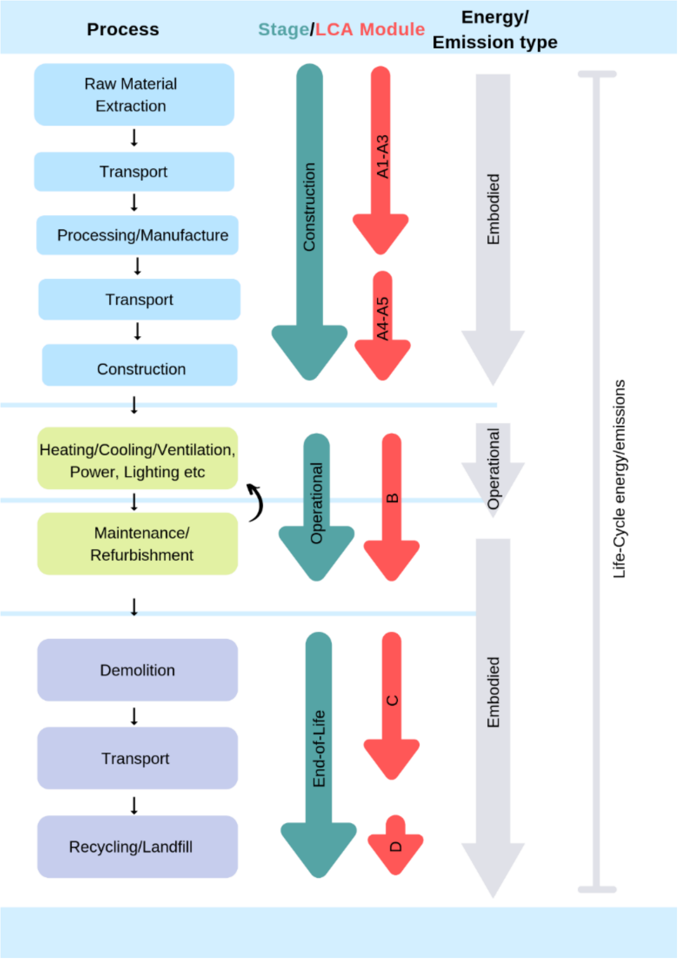


Figure 2. The stages of a whole life cycle of a building and the respective processes. Included are the LCA modules which are used in EPDs. Different energy and emissions types (embodied or operational) are associated with the processes.

An important consideration in estimating the environmental impacts of buildings is the choice of building lifespan (Rauf and Crawford, 2015; Hermans, 1999). Though many Georgian (c. 1714 – 1830) and Victorian (c.

1837 – 1901) buildings are still in use and can be expected to last many more years, no conclusive data on historic building lifespan were found for the UK. A Swiss study has found that the average age of buildings in Zurich when demolished has fallen from over 200 years to less than 70 years old (Aksözen, Hassler and Kohler, 2017). Systematic data collection is needed to understand the rate of demolition in the UK, how long buildings are typically in use and the factors that influence demolition.

Service Life: *period of time in which a building or component is designed to perform to its specifications.*

Lifespan: *period of time that a building or component actually performs to its specifications or fulfil its requirements.*

Reference Study Period (RSP): *time periods that are broadly representative of the service life of different buildings types. The fixed RSP for domestic buildings is 60 years, which allows comparison across different LCA studies* (Sturgis and Papakosta, 2017)

Buildings, however, are made up of many constituent parts, each of which has a different service life, so the concept of a single building lifespan is somewhat misleading. For this reason, the UK National Annex for EN 1990 classifies buildings as Category 4 structures and are given a design working life of 50 years before significant investment is needed. To allow the comparison of life cycle carbon emissions across all types and ages of buildings, the Royal Institute of Chartered Surveyors recommends the use of a 60-year reference study period (RSP), which is industry standard (Sturgis and Papakosta, 2017). This period is not chosen to represent the actual lifespan of a building but to represent the time berfore which a major intervention such as refurbishment may be required.

3.1.2 Principles of Life Cycle Assessment

LCA involves the estimation of the environmental impacts of products and services. The assessment process is well established and is formalized in the ISO 14040 and 14044 standards, which describe the main steps that should be undertaken in any life cycle study. These steps are summarized below:

> *Goal and Scope Definition* defines the purpose, motivation and objectives of the study, and describes the methodology to be used. As well as highlighting the study's motivation and intended audience, this step must clearly define and bound the system being studied, how impacts are allocated (e.g. whether impacts are allocated to by-products), the relevant impact categories (e.g. GWP) as well as data requirements and assumptions. The 'functional unit' must also be defined so that meaningful results can be compared with other studies providing the same function. The exact methodology used is chosen by the LCA practitioner but must be stated and follow the ISO guidelines (ISO 14044, 2006).
>
> *Life Cycle Inventory* (LCI) analysis involves the collection of data and selection of calculation procedures to estimate the flow of fuels, materials and emissions into and out of the building over its life cycle. This must be completed both for all embodied and operational stages and involves data collection, analysis and validation.

Life Cycle Impact Assessment (LCIA) involves estimating the environmental impacts of the system based on the inventory data compiled and calculated above. It includes the collection of results for the different impact categories chosen in the Goal and Scope Definition stage.

Interpretation, the last stage, involves the interpretation of results and considers significant environmental issues. It includes an evaluation of the study's completeness, sensitivity and consistency, as well as the formulation of conclusions, limitations, and recommendations.

3.2 Considerations for Operational Energy Use

3.2.1 Sources of Energy and their Associated Carbon Impacts

Global warming is caused by the emission of GHGs. The most common of these is carbon dioxide (CO_2, typically abbreviated as simply 'carbon'), but there are many other gases that contribute to global warming, two of which include methane (CH_4) and nitrous oxide (N_2O). Each GHG has a different warming effect on the earth's atmosphere. In order to sum the total effect of all gases, each is converted into its equivalent CO_2 warming effect and all CO_2-equivalents (CO_2e) are then summed. For example, CH_4 has an equivalent warming effect 25 times greater than CO_2, so CH_4 emissions (in kg) are multiplied by 25 and added to any carbon dioxide emissions. Similarly, N_2O (298 times greater than CO_2) and other GHGs are converted to their CO_2e and summed to give a total GWP for a mixture of GHG emissions.

Most of the energy used in buildings is derived from the burning of fossil fuels which release carbon dioxide and other GHGs into the atmosphere that ultimately results in global warming. Typical fuels used directly in buildings include heating oil, natural gas and coal. Emissions from these fuels depends on their chemical composition and the efficiency at which they are used in buildings. For example, heating oil releases 0.27kg of CO_2 when burned compared to 0.18kg for natural gas (see Table 2).

Table 2. Typical fuel emissions factors in the UK (Hill et al., 2018).

Fuel	Emissions (kg CO2e)	Litres petrol equivalent	Comment
Natural gas	0.18	0.08	Standard natural gas received through the gas mains grid network in the UK.
Burning oil	0.25	0.11	Main purpose is for heating/lighting on a domestic scale (also known as kerosene).
Gas oil	0.28	0.13	Medium oil used in diesel engines and heating systems (also known as red diesel).
Petrol (average biofuel blend)	0.23	0.11	Standard petrol bought from any local filling station (across the board forecourt fuel typically contains biofuel content).
Coal (domestic)	0.34	0.16	Coal used domestically.
Electricity (2018)	0.28	0.13	Emissions associated with the generation of electricity at a power station. Electricity generation factors do not include transmission and distribution.

Source *Department for Business, Energy & Industrial Strategy, Greenhouse gas reporting: conversion factors 2018*

Depending on whether these fuels are burned in a condensing (typically in the order of 88% efficient) or non-condensing (78% efficient) boiler, each unit of heat they deliver will result in different emissions. Figure 3 shows the emissions resulting from the delivery of one unit of heat to a building using different fuels and boiler efficiencies. The highest (non-condensing heating oil) is 69% higher than the lowest (condensing gas boiler). So, the same energy requirement in a building can result in significantly different emissions. To mitigate carbon emissions from the built environment, the CCC recommends the replacement of all fossil fuel-based heating systems with low carbon or carbon neutral systems alongside improving the thermal performance of existing buildings with additional insulation and draughtproofing.

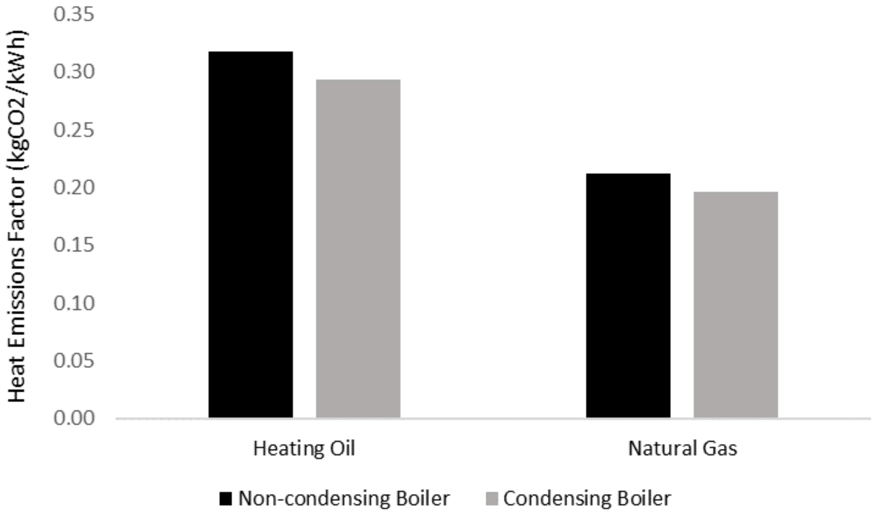


Figure 3. CO_2 emissions resulting from the delivery of one unit of heat in a building using different fuels and boiler types (BRE Group, 2008).

3.2.2 Decarbonisation of the Electricity Grid

Electricity usage also contributes to the carbon footprint of a dwelling. Traditionally, electricity was generated using power stations, each burning a particular fossil fuel at a different efficiency. The aggregate effect was the production of a unit of electricity with an average carbon intensity which did not vary greatly from year to year. However, around the beginning of the 1990s, renewable energy generation in the form of wind and, to a lesser extent, photovoltaics began to displace fossil fuelled electricity generation. As a result, the emissions intensity of electricity generation began to fall - a trend which continues today. Stark, Gault and Joffe (2018) show that the annual average emissions intensity of electricity generation has fallen from nearly 800gCO_2e/kWh in 1990 to less than 300gCO_2e/kWh today and is projected to fall to 41gCO_2e/kWh by 2035 (Department for Business Energy and Industrial Strategy, 2019).

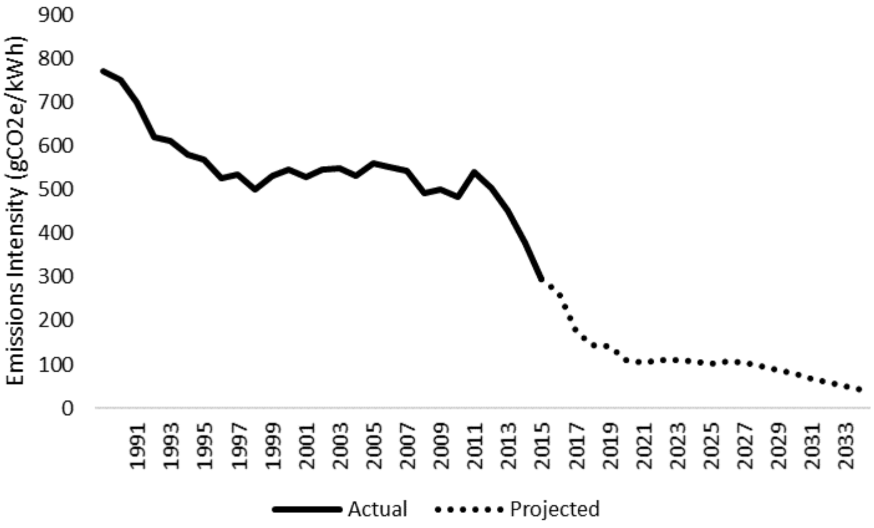


Figure 4. Actual and projected UK CO_2e emissions intensity of electricity generation (Stark, Gault and Joffe, 2018; BEIS, 2019a; BEIS, 2019b)

It should be noted that, while electricity emissions intensities are falling as a result of investment in renewable energy generation capacity and are likely to fall further in the future, the emissions intensities of fossil fuels which are traditionally used for space heating in buidlings (e.g. gas, oil, coal) are fixed and will not fall in the future.

Electricity demand is expected to rise for the UK residential sector until 2035 (at least), which is predicted to result in a 10% increase in emissions over 2016 levels (Department for Business Energy and Industrial Strategy, 2019), however household GHG emissions could be further reduced by the ongoing decarbonisation of the electricity grid.

It should be noted that the ongoing decarbonisation of the electricity grid was not calculated as part of this study due to time constraints and the difficulty in modelling this change.

3.2.3 Trade-offs between Energy Efficiency and Life Cycle Emissions

A key aspect in the life cycle environmental design of buildings is the trade-off between embodied and operational emissions. In simple terms, very low emission buildings can be achieved by significantly reducing energy consumption. This requires a greater investment in materials (e.g. insulation) and systems (e.g. ventilation heat recovery) than for an 'average' design. While this results in higher embodied carbon in the building, it should reduce operational emissions. The question is whether this initial investment in embodied energy is repaid by savings in operational energy over the lifespan of the building.

Figure 5 illustrates this point, in which three options are shown for an existing building:

> *Base-case*: the building continues to operate as normal and cumulative operational GHG emissions increase steadily over time;
>
> *New-build*: demolition and replacement of the existing building requiring a significant initial embodied energy investment but followed by low cumulative carbon emissions growth due to low operational energy requirements; and
>
> *Refurbishment*: the reuse and upgrading of the existing building (rather than demolishing and rebuilding) for improved energy efficiency, which result in an initial increase in embodied emissions but immediately lead to decreased operational emissions compared to the Base-case.

The relative life cycle performances of these scenarios depend on a variety of factors including the RSP of the building in question (see Figure 5). The cumulative life cycle emissions of the Base-case exceed those for the Refurbishment at point A, so if the building's RSP is greater than T_A then it would make sense from an emissions perspective to undertake energy efficiency upgrades. Similarly, if the RSP of the refurbished building is greater than T_B then it would make sense to opt for the New-build design.

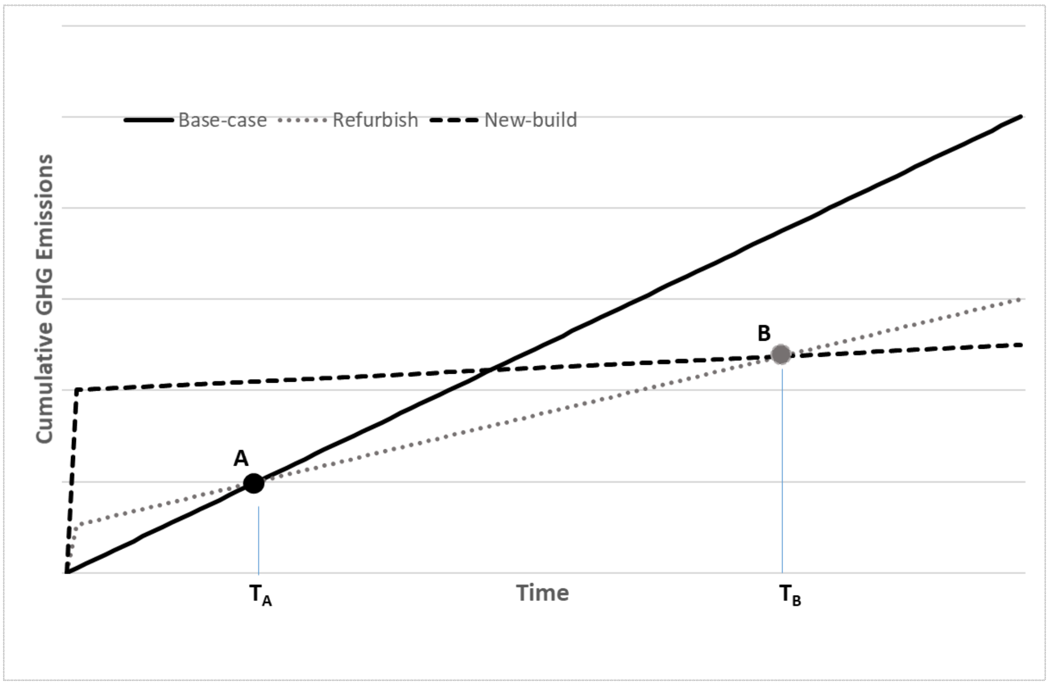


Figure 5. Indicative cumulative construction and operational emissions for three different building refurbishment scenarios.

These scenarios are indicative only and serve to illustrate the trade-offs between the main life cycle stages and how these are affected by building lifespan. See Sections 4.3 and 4.4 for life cycle assessments of actual refurbishment projects that quantify the emissions intensities of the repair, maintenance, demolition and reuse stages.

3.3 Life Cycle Assessment Methodology

This section is split into five steps: 1) establishing the scope of the study; 2) estimating embodied emissions (demolition, new-build, refurbishment and maintenance); 3) estimating demolition emissions; 4) estimating operational energy use and calculating the associated operational emissions; and 5) bringing these results together to estimate life cycle emissions.

3.3.1 Step 1. Establish the Scope

Both case studies involve the refurbishment of existing dwellings or their replacement on a like-for-like basis, so the functional unit of one building allows for the comparative analysis of each design option.

Three impact categories are used in this study. CO_2e is the primary impact category used since this is the standard international measure of GWP. Quantities are expressed as kilogrammes or tonnes of CO_2e. The main impacts are also expressed in litres of petrol, carbon sequestered by a South England oak forest and miles driven by an average UK car to provide more tangible approximate measures, since it is difficult to conceptualise tonnes of carbon dioxide equivalent.

The building cases within this study include: the 'Base-case', i.e. making no changes to the building and continuing to operate it as-is; 'Refurbishment' and 'Conversion' (depending on the case study), both of which improve the energy efficiency of the building; and the 'New-build', which entails the demolition, removal and replacement of the existing building with a new building complying with, but not exceeding, current building standards. These are based on actual projects therefore no assumptions are made on the materials/systems used.

The sensitivity of the results to RSPs was estimated for a lifespan of up to 120 years. The value of forecasting over a long period diminishes given the very large uncertainties it introduces for key input values; therefore 120 years was chosen as the maximum period of forecasting. In addition to estimating life cycle carbon emissions for different RSPs, cumulative emissions were estimated in both 2030 and 2050 since these represent important target years for policymakers.

3.3.2 Step 2. Estimate Embodied Emissions

Approximately 40 material emissions factors from the ICE database and EPDs were used to estimate embodied emissions relating to demolition, refurbishment, construction and maintenance. The GWP data in ICE was represented in CO_2e/kg, while the data from EPDs were presented in many different functional units (per m^2, per m^3, per kg or per unit) and so many of the data had to be converted to m^2 using product density, area or thickness.

- The following key input data were obtained for each case study building case:
    a. basic building information: gross floor areas (m^2); overall dimensions (m);
    b. building location: geographic location (postcode or region and urban/rural classification);
    c. building element areas: wall, window, door, roof (m^2);
    d. building materials: type (category); quantity (kg, m^3, m^2, number); densities (kg/m^3);
    e. demolition quantities: type (category); quantity (kg, m^3, m^2, number).

- A number of key input parameters affecting the calculation of emissions were chosen:
    a. heating technology efficiency (80% and 90% for old and replacement boilers respectively);
    b. a maximum assessment period of 120 years was chosen.

- CO_2e emission intensities were obtained for all relevant building materials (CO_2e per unit: kg, m^3, m^2, number) from the ICE database. Where data from the ICE database were limited EPDs were used for additional materials. These accounted for all international carbon emissions. A construction and demolition waste factor of 23.72 $kgCO_2e$/tonne was used (DEFRA, 2019), see Section 3.3.3 for further details

- Maintenance requirements for each building case were estimated in terms of material types, quantities and intervals based on data collected by the Carbon Leadership Forum (2018). Scheduled replacement of windows was assumed every 30 years, roofing every 100 years and boilers every 20 years. The refurbishment of smaller items was ignored since these will have only a small impact on overall life cycle results (data on emissions associated with this is also not usually available). Larger structural items such as walls and roof trusses are assumed to survive for the maximum 120 years considered.

- Present and estimated future CO_2e emission intensities for all fuels and electricity were obtained for the maximum 120-year study period from the database 'Greenhouse gas reporting: conversion factors 2018' (Hill *et al.*, 2018).

- Embodied emissions were estimated using process analysis:

(1)

$$EE_{DO} = \sum_{i=1}^{N} EI(m)_i \times Q(m)_i \times WF_i$$

Where: EE_{DO} is the embodied energy of the building case;

$EI(m)_i$ is the CO_2e emissions intensity of material *i*;

$Q(m)_i$ is the quantity of material *i*;

WF_i is the waste factor for material *i*; and

N is the number of materials in the building.

Note that *EI* and *Q* relate to construction, maintenance and demolition where relevant. On-site emissions are omitted in this calculation since emissions data are difficult to obtain and since they constitute a small amount of life cycle emissions.

3.3.3 Step 3. Estimate Demolition Emissions

Demolition emissions are estimated using a demolition emissions intensity which is based on a construction and demolition (C&D) recovery rate of 92% (DEFRA, 2019), a C&D waste emissions factor of 1kgCO_2e/tonne for recovered waste and 285kgCO2$_e$/tonne for landfilled waste (WRAP, 2019), giving a weighted average of 23.72 kgCO_2e/tonne (0.92 x 1 + 0.08 x 285) (see Equation 2). These emissions are added to the total embodied emissions of the New-build as it is assumed here that this New-build is constructed on the site of a historic building which had to be demolished for this purpose.

$$EI_{dem} = R_{C\&D} \times EI_{C\&D} + R_{LF} \times EI_{LF} \tag{2}$$

Where: EI_{dem} is the demolition emissions intensity;

$R_{C\&D}$ and R_{LF} are the C&D and land fill recovery rates respectively;

$EI_{C\&D}$ and EI_{LF} are the C&D and land fill emissions intensities respectively.

3.3.4 Step 4. Estimate Operational Emissions

The MIT Design Advisor was trialled as a simple-to-use and free online tool for estimating operational energy requirements using a small number of building input parameters (Urban, 2007). The tool was trialled for usability, however due to the issues identified with the tool (see Section 2.3), a separate methodology was developed for calculating operational emissions. The MIT Design Advisor tool was used for only one output as described below.

The following specifications were used in the calculation of operational emissions for the Base-case, Refurbishment, Conversion and New-build case studies:

- Operational emissions were estimated using an hourly energy balance model complying with BS EN ISO 52016-1:2017 *Energy Performance of Buildings* (British Standards Institution, 2017)

- Weather data from the nearest synoptic weather station to each building location was obtained. EnergyPlus representative meteorological year data were used for this purpose (*EnergyPlus*, 2019).
- Base-case lighting energy use was based on 5.9kWh/m^2.yr; it was assumed that this fell to 1.9kWh/m^2.yr in the Refurbishment/Conversion and New-build case with the adoption of high-efficacy lighting systems such as LEDs and fluorescents (Zimmermann *et al.*, 2012; Abergel, 2019).[1] Operational emissions were then estimated using the fuel emissions factors described above.
- The operational energy requirements for each building case were also estimated using the MIT Design Advisor tool. This was undertaken for the purposes of assessing the usability of the tool for possible use in concept building design assessment by non-experts. It estimates annual space heating, cooling and lighting loads based on the weather patterns for specific locations for a typical year. The case studies used the outputs from the model.
- The fuel consumption for each building case was then estimated based on the conversion efficiencies:

$$Q(f)_j = Q(e)_j / \eta_j \tag{3}$$

Where: $Q(f)_j$ is the quantity of fuel type *j* used;

$Q(e)_j$ is the quantity of end-use energy delivered by fuel *j* (an output from the MIT Design Advisor); and

η_j is the conversion efficiency of for the device using fuel *j*.

- Estimating the operational emissions for each building case involved using process analysis:

$$OE_{DO} = \sum_{k=1}^{P} \sum_{j=1}^{M} EI(f)_{j,k} \times Q(f)_j \tag{4}$$

Where: OE_{DO} is the life cycle operational emissions for the building case;

$EI(f)_{j,k}$ is the CO_2e emissions intensity of fuel *j* in year *k*;

$Q(f)_j$ is the estimated annual quantity of fuel used by the building case;

M is the number of fuels used; and

P is the RSP.

3.3.5 Step 5. Estimate Life Cycle Emissions

The life cycle carbon emissions for each building case were taken as the sum of the embodied emissions (demolition, construction and maintenance) and the operational emissions:

(5)

---

[1] A UK survey found that 10kWh/m_2.yr was the average 2011 consumption (Zimmermann *et al.*, 2012), However a 41% reduction in lighting energy consumption was reported between 2011-18, giving and average usage of 5.9kW/m^2.yr (BEIS, 2019c). The use of LEDs and fluorescent lights results in an average usage of only 1.9kWh/m_2.yr, not taking account of rebound. Lighting efficacy data was based on IEA data (Abergel, 2019).

$$LCE_{DO} = EE_{DO} + OE_{DO}$$

3.4 Life Cycle Cost Methodology

Life cycle costing is concerned with estimating the total costs of a project from cradle to grave. It considers all costs associated with the life cycle of the building (e.g. design, construction, operation, maintenance and demolition/recycling). Because of the time value of money (where costs incurred in the future are not as valuable as those incurred today), all future costs are discounted to a base year using a discount rate. The sum of all future discounted costs is the life cycle cost (LCC). The discount rate depends on a wide variety of factors but is typically in the range of 5-10% in real terms.

To estimate the life cycle cost of each building case, the following steps were followed:

- An appropriate range of private investor discount rates were chosen. There is much debate on this issue. A recent discussion paper by Steinbach and Staniaszek (2015) propose a rate of between 3 and 6% while Warner and Pleeter (2001) provide estimates ranging from 0% to 30%. We use a range of 0-10% which covers the most common range of estimates.

- For each building case, construction costs (CC_{DO}) were obtained from bills of quantities (BOQs), outline specifications and preliminary cost reports. In this study, the refurbishment and conversion case study costs were provided by the relevant design teams, whereas the New-build capital costs were obtained for the reference domestic design and adjusted to reflect the relevant regional construction cost.

- Maintenance unit costs were estimated for the replacement of elements such as windows, roofs and boilers. These were used with relevant maintenance material types, quantities and intervals (see Step 7) to estimate life cycle maintenance costs:

$$MC_{DO} = \sum_{k=1}^{P} \sum_{i=1}^{N} UC(m)_{i,k} \times Q(m)_i \times 1/(1+r)^k \qquad (6)$$

Where: MC_{DO} is the life cycle discounted maintenance costs for the building case;

$UC(m)_{i,k}$ is the unit cost of maintenance material/process i in year k;

$Q(m)_i$ is the annual quantity of maintenance material/process used by the building case;

r is the discount rate;

N is the number of materials used; and

P is the lifespan.

- Unit fuel prices and standing charges were obtained from BEIS (BEIS, 2019a; BEIS, 2019b). These were used in combination with the estimated fuel consumption for each building case to estimate annual operating costs:

(7)

$$OC_{DO} = \sum_{k=1}^{P}\sum_{j=1}^{M} UC(f)_{j,k} \times Q(f)_j \times 1/(1+r)^k$$

Where: OE_{DO} is the life cycle discounted operating cost of the building case;

$UC(f)_{j,k}$ is the unit cost of fuel j in year k;

$Q(f)_j$ is the annual quantity of fuel used by the building case;

r is the discount rate;

M is the number of fuels used; and

P is the lifespan.

- The life cycle cost of the building case is the sum of the construction, maintenance and operating costs:

$$LCC_{DO} = CC_{DO} + MC_{DO} + OC_{DO} \tag{8}$$

3.5 Marginal Abatement Cost Methodology

The Marginal Abatement Cost (MAC) is the cost of reducing carbon emissions by one unit using an alternative technology, design or system. For example, where a building energy refurbishment costs money to implement but results in GHG emissions savings, then the cost per unit saving is the emissions savings divided by the cost of implementation. More precisely, the marginal abatement cost is the savings in life cycle emissions divided by the additional life cycle costs of a project. MAC can be used by policymakers to rank the most cost-effective emissions reduction interventions.

The MAC was obtained by dividing the difference in life cycle costs between the Refurbishment / Conversion / New-build and the Base-case. This difference was then divided by the relevant difference in costs. The marginal abatement cost represents the life cycle cost of reducing emissions by one unit of carbon dioxide equivalent through the implementation of an energy efficient design option (e.g. energy efficient building refurbishment) and is calculated using the following equation:

$$Marginal\ abatement\ cost = \frac{Life\ cycle\ cost\ of\ new\ design\ option\ -\ Life\ cycle\ cost\ of\ Base\_case}{Life\ cycle\ carbon\ cost\ of\ Base\_case - Life\ cycle\ carbon\ cost\ of\ new\ design\ option}$$

or,

$$MAC_{DO,a} = \frac{LCC_{DO,a} - LCC_{BC}}{LCE_{BC} - LCE_{DO,a}} \tag{9}$$

Where: $MAC_{DO,a}$ is the marginal abatement cost of building case a;

$LCC_{DO,a}$ is the life cycle cost of a building case;

MAC_{BC} is the base case life cycle cost;

$LCE_{DO,a}$ are the life cycle emissions of building case a; and

LCE_{Bc} are the base case life cycle emissions.

3.6 Sensitivity Analysis

- The life cycle emissions, life cycle cost and marginal abatement cost models were interrogated to investigate the effects of variations in important inputs. These are outlined below.
- *Internal temperatures* varied from 21°C to 18°C in one-degree increments.
- *RSP* varied from 60 to 120 years in 60-year increments.
- Two scenarios for *electricity emissions* factors are used: the first ('Electricity_BEIS') is based on the Department for Business, Energy and Industrial Strategy (BEIS) projections up to 2035 with emissions assumed to fall linearly to zero by 2050 and remain at zero thereafter (BEIS, 2019c); the second ('Electricity_2019') assumes emissions remain at their 2019 average rate (see Figure 6).
- *Discount rates* are varied between 0 and 10% (real) in 2.5% increments.

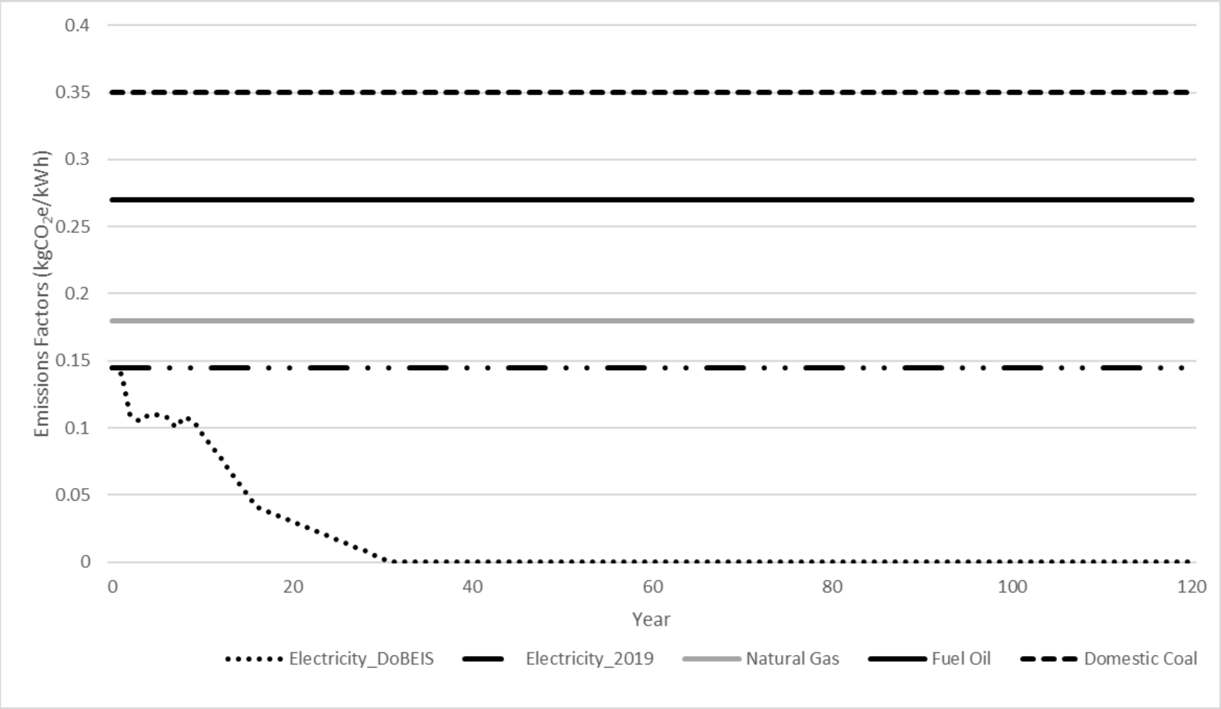


Figure 6. Emissions factors used, showing two scenarios for electricity.

4 Case Studies

4.1 Scope

For the purpose of this study, data for two completed energy refurbishment projects were obtained for analysis. The first case study involved the energy efficient refurbishment of a Victorian-era red brick end-of-terrace dwelling in the East Midlands, which was retained as a single-family dwelling. The second case study involved the conservation, energy efficient upgrade and conversion of a small 19th century chapel in London into a single-family dwelling. It should be noted that the former is likely to be representative of a great number of English terraced dwellings and involved energy efficient interventions only. The latter is less representative both in terms of the nature of the chapel building itself and the extent of the works necessary to convert it for residential use.

The two case studies were analysed according to the methodology outlined in Section 3 and the findings are provided in Sections 4.3, 4.4 and 4.6. These sections provide results on the life cycle carbon emissions, savings-to-investment ratios and marginal abatement costs for different reference study periods, internal building temperatures and explore the relative carbon, economic and policy performances of the different building refurbishment options.

The intention of these case studies was to analyse the life cycle emissions of the actual refurbishment works that were carried out at each dwelling, not to verify the suitability of these works or to provide guidance on the energy refurbishment of traditional and historic buildings.

As only two case studies were analysed within this scope of this study, the findings can only be taken as indicative of carbon emissions from the refurbishment scenarios represented. A larger pool of data will need to be assessed in order to identify patterns and inform policy.

4.2 Base-case and New-build

The life cycle carbon emissions of the following two case studies were assessed against the Base-case and New-build.

The *Base-case* represents the case study building before any energy efficiency upgrades or material changes were made. As no material changes are being made to the Base-case, the embodied emissions at this point are zero. The operation of the building therefore continues as normal, and by modelling the current energy use and sources, we can see how much carbon the building can be expected to emit over a specified period of time if no improvements are made to the building fabric.

The *New-build* is based on an actual residential building that is currently under construction and has been designed to meet to current building regulations and standards. The dwelling is representative of new residential construction in the UK, with concrete block cavity walls and high levels of insulation in the walls, roof and ground floor slab. As the modelling of life cycle carbon emissions for the New-build start with the construction of the building, the life cycle emissions include the embodied emissions of the new structure, the embodied emissions of any structure that was demolished on that site (if applicable) and the operational emissions going forward for a specified period of time.

4.3 Victorian Terrace Refurbishment, East Midlands

4.3.1 Background

In 2011, the relevant local district council approved the implementation of measures to improve the thermal efficiency of a vacant end-of-terrace house. Based on the as-built solutions, refurbishment works included the installation of five different insulations types:

- Type A: 65mm polyisocyanurate (PIR) insulation with aluminium foil facings on both sides, finished with plasterboard
- Type B: 55mm PIR insulation with aluminium foil facings on both sides fixed with battens to provide a 25mm gap for a service zone to avoid puncturing the integrated vapour control layer, finished with plasterboard
- Type C: 9-25mm lime plaster applied to brick, followed by 100mm wood fibreboard insulation and a thin finishing coat of lime plaster
- Type D: 300mm of mineral wool insulation to the depth of the joists and 100mm of wood fibre on the loft hatch
- Type E: 100mm or 300mm wood fibreboard insulation between the floor joists with an air tightness membrane over the joists.

Different sections of the ground floor walls were insulated internally with Type A and Type B, while the first floor walls were insulated internally with Type C. The suspended timber floor on the ground floor was insulated with 100mm of Type E, the first floor joists were insulated with 300mm of Type E, and the loft was insulated with Type D.

4.3.2 Building Option Inputs

Key inputs to the life cycle carbon emissions model are summarised in Table 3 for each of the building case: Base-case, Refurbishment and New-build.

Table 3. Key inputs to the life cycle carbon emissions model for the Victorian Terrace Refurbishment

Victorian Terrace Refurbishment

Building option	**Base-case**	**Refurbished**	**New-build**
Assumed climate	Finnigley	Finnigley	Finnigley
Year built	1891	1891, refurbished 2019	2019
Building height	2-storey	2-storey	2-storey
Floor area (m2)	83.1	83.1	83.1
Summary of works	None	Energy efficient retrofit of the existing dwelling including insulation (wall, attic, floor), secondary glazing, draught proofing	Complete demolition of the existing dwelling and its replacement with typical new domestic building using cavity blockwork, PIR insulation, timber floors, triple glazing, pitched roof.
Structure	Load-bearing masonry	Load-bearing masonry	Load-bearing masonry
Envelope	Solid brick; single glazed sash windows	Internally-insulated solid brick; single glazed sash windows with secondary glazing	Insulate cavity wall; triple glazing
Glazing (%)	18	18	18
Heating system (efficency)	Gas-fired (80%)	Gas-fired (80%)	Gas-fired (90%)
Wall R-value (m2-K/W)	0.6	3.23	6.25
Roof R-value (m2-K/W)	2.94	6.25	9.09
Air Change Rate (l/s.person)	7.5	5	5

Life cycle costs comprise both building, operational and maintenance costs. Building costs included the capital costs of construction and, where necessary, site clearance (i.e. for New-build). Operational costs include all energy-related space heating and lighting costs. Maintenance costs include scheduled replacements of windows (30 year), roofing (100 year) and boilers (20 year). Building costs were based on reported refurbishment costs (£23,182) and estimated new-build costs (£119,679), the latter based on an estimate by a quantity surveyor. These costs were adjusted for inflation where relevant to bring them to the base (2018) year of analysis. Operational (energy) costs were based on the simulated energy use and average 2018 domestic energy prices, which are summarised in Table 4 (BEIS, 2019a; BEIS, 2019b).

Table 4. Average 2018 domestic energy prices (BEIS, 2019a; BEIS, 2019b).

	Unit Cost (£/kWh)	**Fixed Cost** (£/year)
Gas	0.0365	84.60
Electricity	0.1490	82.55

4.3.3 Emissions Results

The construction-related embodied carbon emissions were estimated to be 1.2 tCO_2e (2.1% of total emissions) and 16.35 tCO_2e (27.9% of total emissions) for the Refurbishment and New-build (including demolition) respectively. The low value recorded for the Refurbishment is due to the use of wood fibre insulation board which stores carbon and is therefore treated as a carbon-negative material. The demolition emissions associated with the New-build made up 4.1% of its total emissions. There are no embodied emissions for the Base-case as the carbon embedded in the existing fabric has already been spent and has no consequence on current and future emissions. The operational emissions of the Refurbishment and New-build accounted for 97.9% and 72.1% of the total emissions respectively. Annual operational energy use was estimated to be 11,142kWh, 4,800kWh and 3,499kWh for the Base-case, Refurbishment and New-build respectively.

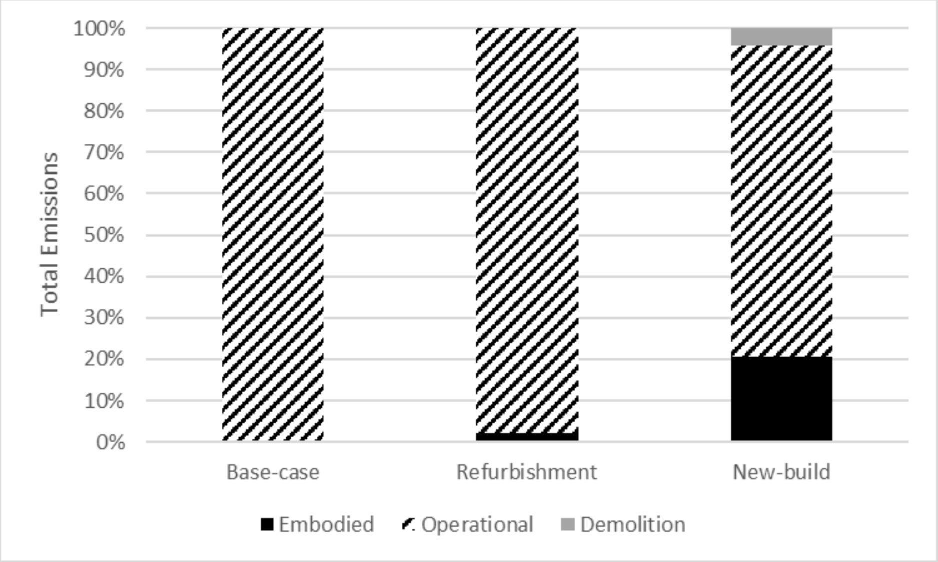


Figure 7. The percentage of embodied, operational and demolition emissions of total emissions associated with the Base-case, Refurbishment and New-build within the 60-year RSP. The embodied emissions of the New-build in the graph exclude the demolition emissions to show the percentage of demolition emissions separately.

Figure 8 shows the estimated life cycle carbon emissions for each building case for different reference study periods. Year 0 represents embodied construction emissions only (i.e., no operational emissions). In all cases, life cycle carbon emissions increase with the reference study period due to ongoing fuel consumption and maintenance. The Base-case results in the highest emissions for reference study periods 60-120 years due to the carbon impact associated with its high space-heating fuel use. New-build emissions increase at the lowest rate, but they start with higher construction emissions in Year 0. Life cycle carbon emissions are approximately equal for the Refurbishment and New-build after a reference study period of 60 years, after which Refurbishment exceeds New-build.

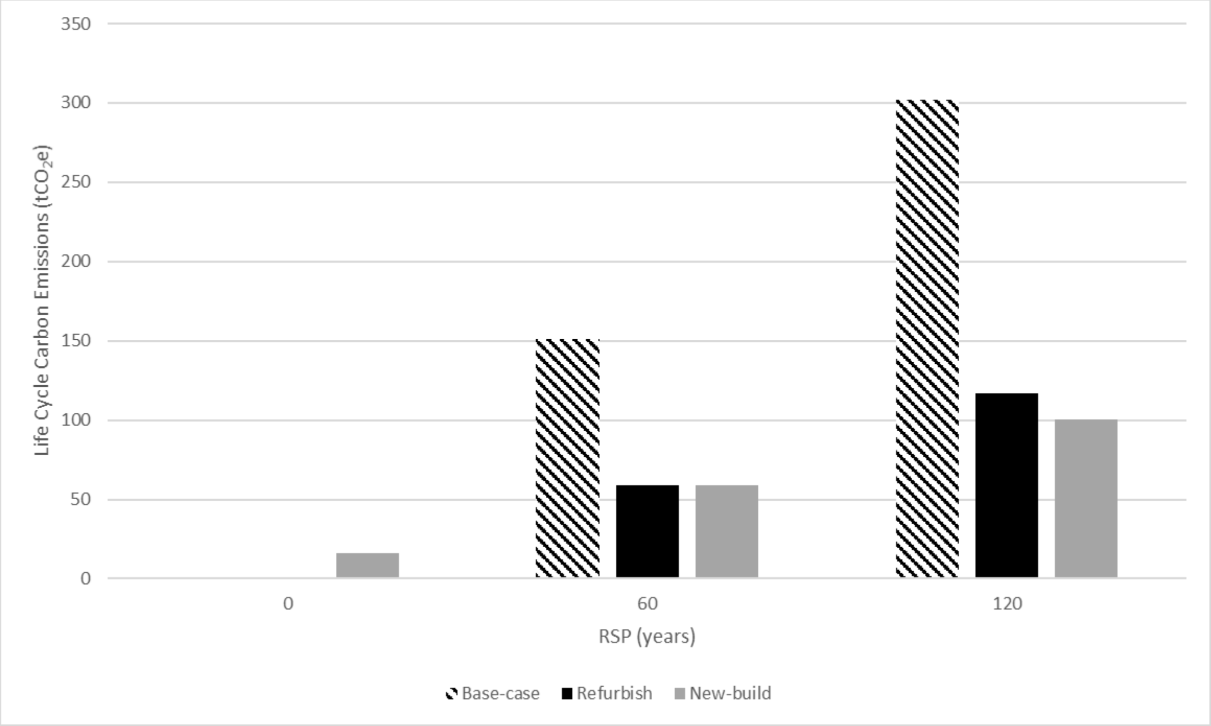


Figure 8. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 5 shows the emissions for the three building cases for a reference study period of 60 years and an internal temperature of 21°C expressed both in conventional tCO_2e and alternative measures: litres of petrol (Ecoscore, 2019), metres squared of carbon dioxide sequestered by British oak forest in one year (Morison *et al.*, 2012) and kilometres driven by an average 2018 British car (The Society of Motor Manufacturers and Traders, 2019).

Table 5. Alternative measures of life cycle carbon emissions for the Victorian Terrace Refurbishment assuming a 21°C internal temperature and a 60-year reference study period.

Design Option	**Carbon** (tCO_2e)	**Petrol** (litres)	**Oak Woodland** (m^2)	**Car Use** (miles)
Base-case	151	34,811	5,600	607,840
Refurbish	59	13,589	2,186	237,288
New-build	59	13,479	2,168	235,350

Given the fact that the government policy has set carbon reduction targets for 2030 and 2050 it is worth noting the emissions performances of the different building cases on these dates. In 2030, the life cycle carbon emissions for the Base-case, Refurbishment and New-build are 38, 16 and 27 tCO_2e respectively; the equivalent figures in 2050 are 89, 36 and 42 tCO_2e. Based on these figures, the Refurbishment would best help reach policy targets.

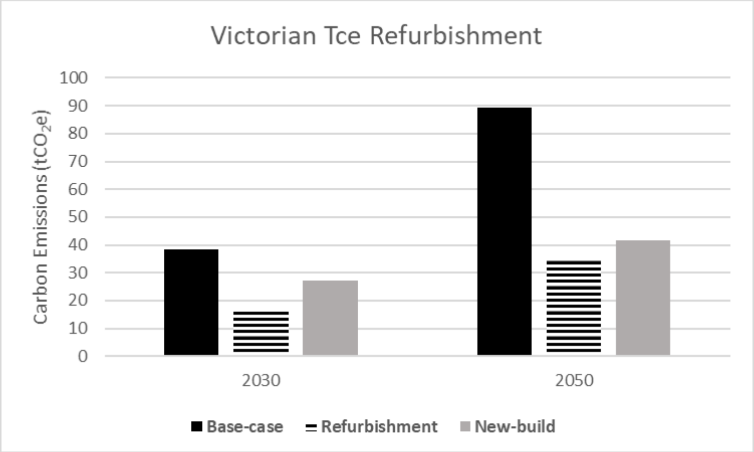
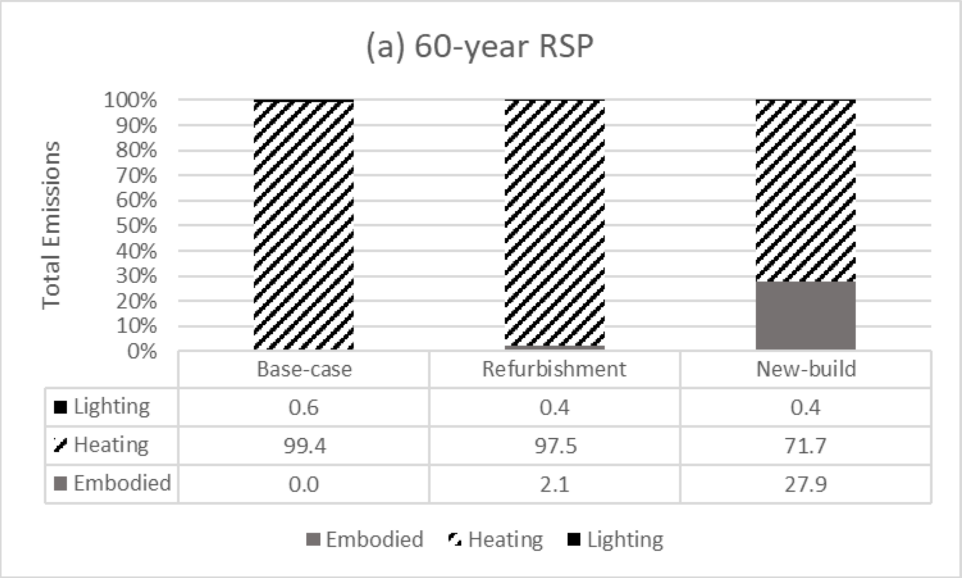


Figure 9. The estimated 2030 and 2050 emissions of the Base-case, Refurbishment and New-build.

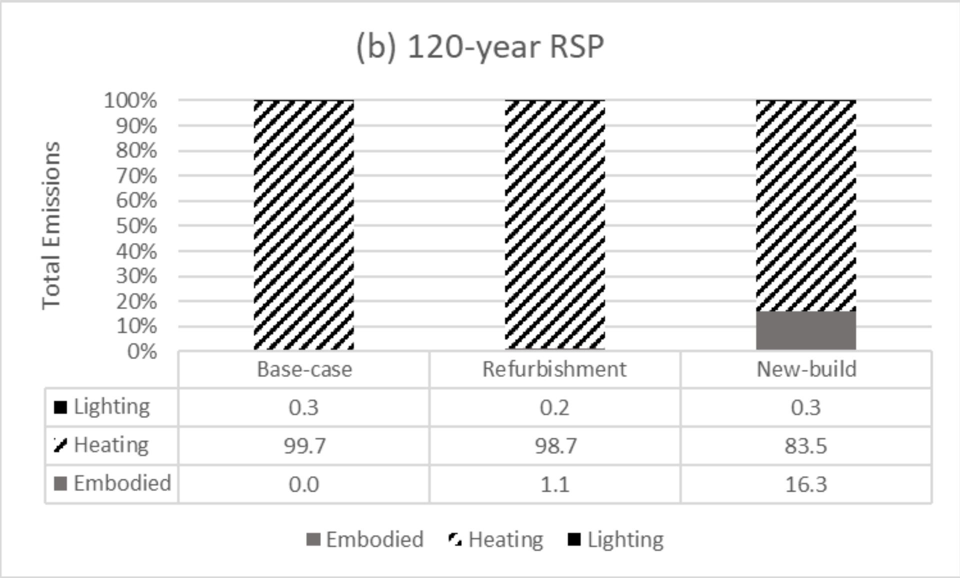
Figure 10 (a-d) shows the life cycle carbon emissions for each case for 60- and 120-year reference study periods broken down by embodied, heating and lighting emissions. This illustrates that embodied energy is an important life cycle carbon emissions component for the New-build only; for a 60-year reference study period it is a key component, accounting for 28% of emissions.

Figure 11 (a-d) shows the cumulative life cycle carbon emissions for the three building case over the first 100 years of operation (100 years is chosen as using the 60-year period would neglect the period at which the New-build takes over the Refurbishment in terms of emissions). Each figure represents a different internal temperature ranging from 21^{o}C down to 18^{o}C in 1^{o}C increments. The figures illustrate the time periods after which the New-build begins to outperform the Base-case and Refurbishment. It can be seen that the carbon emissions of the Base-case exceeds the New-build 10-12 years after construction depending on the internal temperature assumption; 63-74 years are required before the Refurbishment exceeds that of the New-build (see Table 6 for exact results).



	Base-case	Refurbishment	New-build
■ Lighting	0.6	0.4	0.4
▨ Heating	99.4	97.5	71.7
■ Embodied	0.0	2.1	27.9

Figure 10 (a-b). Life cycle carbon emissions for each case for 60- and 120-year reference study periods broken down by embodied, heating and lighting emissions (internal temperatures of 21°C). The percentage of each component for each building case are presented in the tables.



	Base-case	Refurbishment	New-build
■ Lighting	0.3	0.2	0.3
▨ Heating	99.7	98.7	83.5
■ Embodied	0.0	1.1	16.3

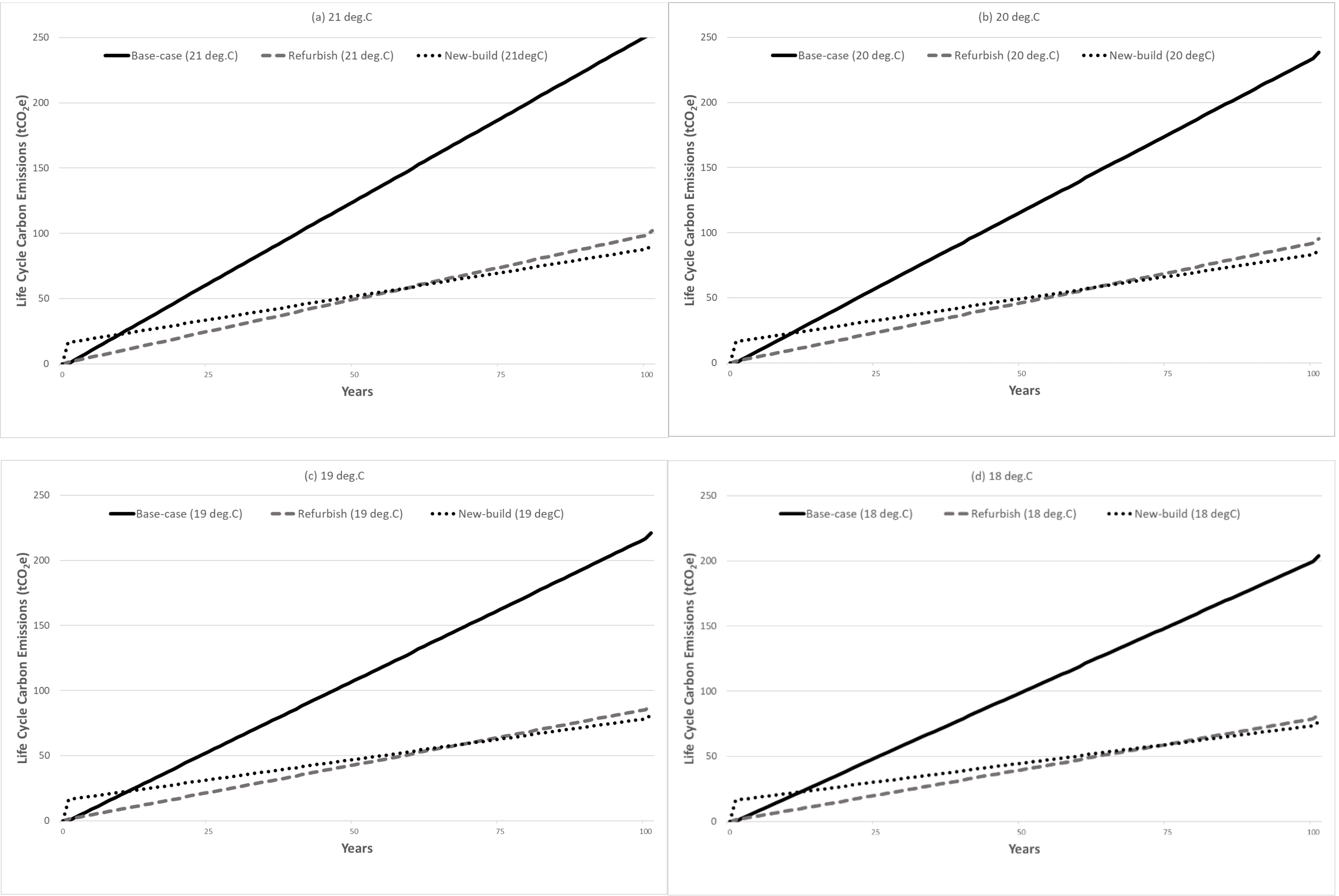


Figure 11 (a-d). Cumulative life cycle carbon emissions with different internal temperature assumptions.

Table 6. Time periods (years highlighted) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)			
	21	*20*	*19*	*18*
Base Case	10	10	11	12
Refurbish	63	63	68	74

Table 7 shows the differences in New-build and Refurbishment emissions under different operating temperatures. At temperatures 20°C, 19°C and 18°C for RSP 60, the Refurbishment emissions are lower than the New-build. After the 60 years, the New-build emissions are lower than the Refurbishment.

Table 7. Differences in New-build and Refurbishment life cycle carbon emissions (tCO_2e) using different reference study periods and internal temperature assumptions (negative indicates that Refurbishment is lower than New-build).

		Internal Temperature (degC)			
		21	**20**	**19**	**18**
RSP (yrs)	**60**	0	-1	-2	-3
	120	16	14	12	10

4.3.4 Financial Results

Table 8 shows the savings-to-investment-ratios (SIR) for the Refurbishment and New-build and summarises their sensitivities to different discount rates. Here the SIR is given by the life cycle energy savings divided by the total investment in refurbishment or a new building. A positive SIR exceeding a ratio of 1 indicates that a project is financially viable at the relevant discount rate, i.e. the total life cycle savings (through lower energy bills) are greater than the total costs. A negative SIR indicates that the cumulative discounted Refurbishment or New-build costs exceed the Base-case and the project is not viable. It can be seen that only the Refurbishment meets this criterion for the 120-year RSP at a discount rate of 0%. Given that discount rates of 5-10% are normally used in this type of analysis, these results indicate no building case is financially viable for a private investor and would require subvention to incentivise investment. The wide range of results shows that the SIR is very sensitive both to the discount rate chosen and the reference study period. In reality, however, economic decisions are made by individuals based on time frames lower than 60 years – typically of between 5 and 20 years. However, this analysis shows that SIRs always be less than one in this period, indicating that financial incentive are required for refurbishment for the case study.

Table 8. Savings-to-investment-ratios (SIR) for the Refurbishment and New-build for different discount rates. An SIR of greater than 1 indicates it is financially attractive.

Option	Discount Rate (%)	Reference Study Period (years)	
		60	120
Refurbish	**0**	-0.16	0.68
New-build	**0**	-0.80	-0.60
Refurbish	**2.5**	-0.57	-0.47
New-build	**2.5**	-0.90	-0.87
Refurbish	**5**	-0.74	-0.72
New-build	**5**	-0.94	-0.93
Refurbish	**7.5**	-0.82	-0.81
New-build	**7.5**	-0.96	-0.96
Refurbish	**10**	-0.86	-0.86
New-build	**10**	-0.97	-0.97

MAC indicates the total additional life cycle financial cost of an intervention per tonne of carbon saved and may be used by policymakers to identify where the best opportunities lie for carbon abatement in an economy. A positive MAC indicates that there is a cost in reducing carbon emissions, whereas a negative MAC indicates that financial savings would be achieved when investing in the new technology. It can be seen in Figure 12 that there are substantial abatement costs associated with the New-build. The Refurbishment, on the other hand, has much lower MACs which after Year 60 result in life cycle cost savings. Carbon prices are estimated to be in the range of 1,073 to 369 £/tCO_2e for New-build and 46 to -96 £/tCO_2e for Refurbishment. For the purposes of comparison, the *Report of the High-Level Commission on Carbon Prices* (2017) estimated carbon prices will need to be in the region of US$40–80 (32.8-65.6)/t$CO_2$e by 2020 and US$50–100 (41-82)/tCO_2e by 2030 to meet the goals of the Paris Agreement. Carbon costs below these may therefore be attractive to policymakers. MAC results therefore indicate that Refurbishment is more cost-effective in reducing life cycle emissions. Any reductions in refurbishment capital costs, for example through lower VAT rates, would improve MAC results.

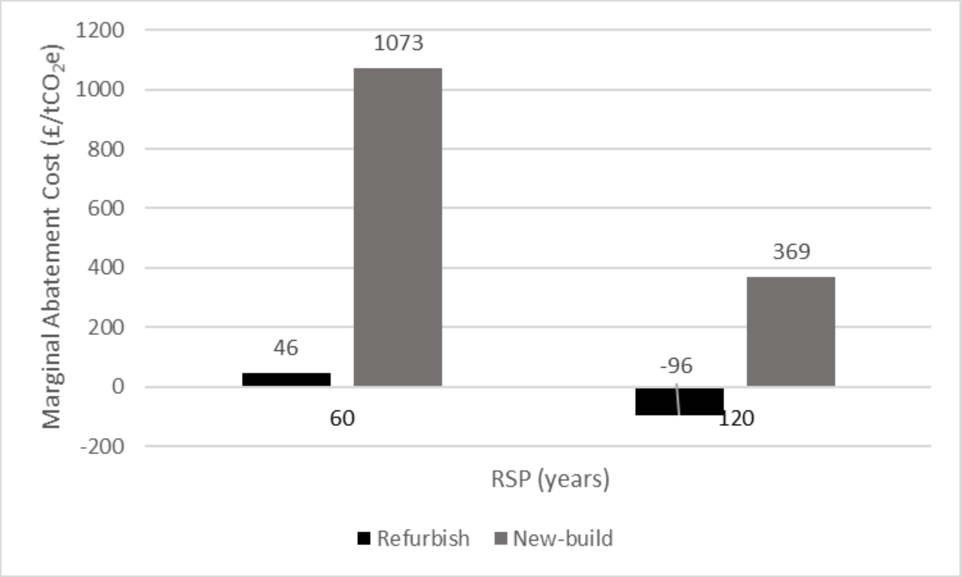


Figure 12. Marginal abatement costs (MAC) for the Refurbishment and New-build.

4.3.5 Internal Temperature Scenario

It is possible to investigate a number of scenarios which combine a variety of different variable inputs. One such scenario was developed to take account of the fact that poorly-insulated buildings (e.g. the Base-case scenario) tend to be operated at lower ambient temperatures and that highly-insulated buildings (e.g. refurbished or newly-built) may be operated at higher temperatures (often referred to as 'comfort taking' or 'the rebound effect') (BRE Group, 2013). For these reasons the following internal temperature scenario was investigated:

- Base-case: 18°C
- Refurbishment: 19°C
- New-build: 21°C

These temperatures are not meant to reflect perceived thermal comfort, merely the temperature at which refurbished buildings and new buildings might operate.

The carbon emissions for this scenario (referred to as 'Scenario_18-19-21) are presented in Figure 13 for the different reference study periods varying from 60 to 120 years. The Refurbishment marginally outperforms New-build in terms of emissions up to an RSP of 60 years, they are both even at 120 years. After this, the New-build emissions are lower than the Refurbishment. The figure can be compared to the results in Figure 8, which shows emissions for all building cases operating at an assumed 21°C internal temperature. Here it can be seen that the emissions for the Base-case fall slightly compared to the Refurbishment and New-build, and Refurbishment emissions fall relative to New-build. This results in longer time periods until the New-build outperforms both the Base-case and Refurbishment in terms of carbon emissions. Table 9 shows these time periods and it can be seen under Scenario_18-19-21, New-build outperforms Base-case and Refurbishment after 13 and 120 years respectively, as compared to 10-12 years and 63-74 years for scenarios with the same internal temperatures (see also Section 4.4.5 for the Chapel Conversion findings).

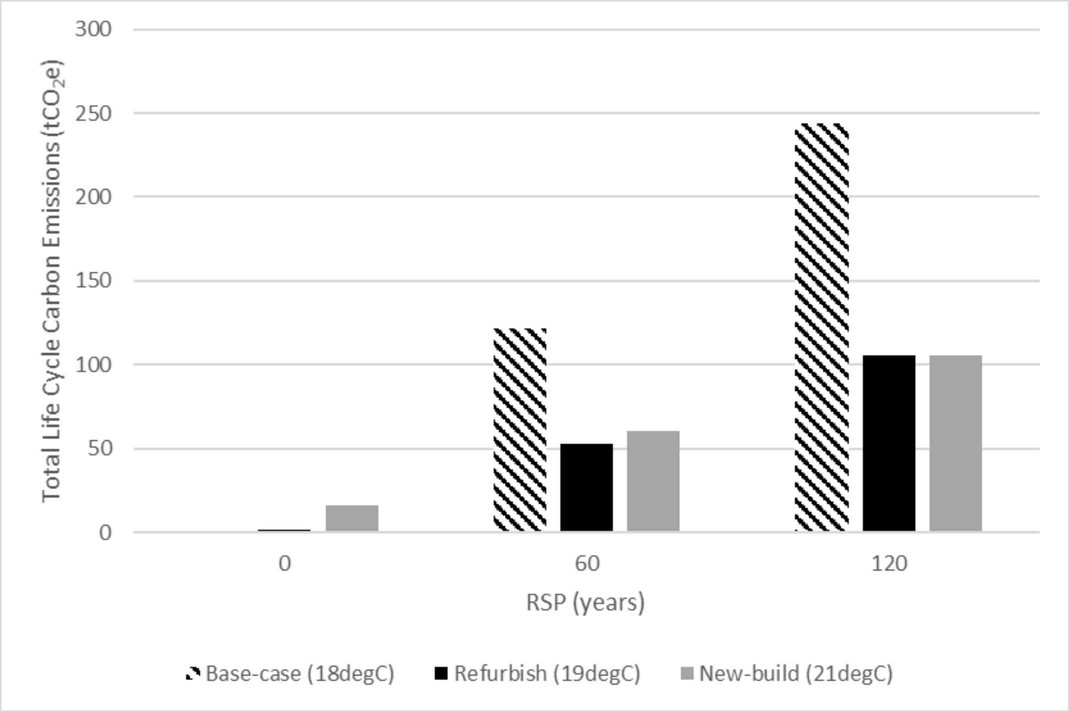


Figure 13. Estimated life cycle carbon emissions for each building case for different reference study periods assuming different internal temperatures, 18, 19 and 21 °C

Table 9. Time periods (years in yellow) after which the New-build outperforms the Base-case and Refurbishment for different internal temperatures.

	Internal Temperature (degC)				
	21	*20*	*19*	*18*	Scenario 18-19-21
Base Case	10	10	11	12	13
Refurbish	63	63	68	74	120

4.4 Chapel Conversion, London

4.4.1 Background

During 2015, a two-room derelict Gothic Revival chapel in London was converted into a one-bedroom single-family dwelling. A description of the refurbishment works is outlined below based on the construction drawings received from the architects.

Preparatory works included repairs to the internal and external stonework and brickwork, repointing of the facade, replacement of missing or broken roof slates, repair or replacement of rainwater goods, repair or replacement of stained glass windows, installation of supplemental side and roof windows, repairs to the internal timber cornices and rafters, removal of internal plaster, and the removal of the original floors.

To improve the energy efficiency and thermal performance of the building, the roof was drylined with a phenolic insulated plasterboard under the rafters and between the rafters with a 25mm cavity under the sarking board. The new floor was composed of an insulating limecrete with underfloor heating, with 40mm of insulation along the exterior wall and topped with an unspecified floor finish. New internal walls, composed of timber frames with rockwool insulation and plasterboard, were added to form the bathroom. The original stonework walls were finished internally with 20mm of insulating reed boards and 18mm of lime plaster.

The original windows were kept, and internal secondary double glazing was added to each existing window. Four new conservation rooflights were added above the East and West Chapel and four new openings with secondary double glazing were added to the east and west walls. The two original doors from the north entrance were relocated to the main south entrance and were placed in a new frame. The existing west entrance doors were fixed shut and covered with an insulating panel, and new glazed doors were installed within the existing frames of the north entrance. New internal doors were also added.

4.4.2 Building Option Inputs

The key inputs to the life cycle carbon emissions model are summarised for each of the building cases: Base Case, Conversion and New-Build in Table 10.

Table 10. Key inputs for the life cycle carbon emissions model for the Conversion

Chapel Conversion, London

Building option	Base-case	Conversion	New-build
Assumed climate	Gatwick	Gatwick	Gatwick
Year built	mid-19thC	mid-19thC - refurbished 2015	2019
Building height	1-storey	1-storey	1-storey
Floor area (m2)	56	56	56
Summary of works	None	Energy efficient retrofit and conversion of the existing chapel to a dwelling including: improved glazing; wall, roof and floor insulation; internal remodelling; conservation of internal and external materials.	Complete demolition of the existing dwelling and its replacement with typical new domestic building using cavity blockwork, PIR insulation, timber floors, triple glazing, pitched roof.
Structure	Load-bearing masonry	Load-bearing masonry	Load-bearing masonry
Envelope	Solid masonry, uninsulated solid floor, timber single glazed windows.	Insulated masonry, insulated solid floor, insulated roof, timber single glazed windows with secondary glazing.	Insulate cavity wall; triple glazing
Glazing (%)	15	15	15
Heating system (efficency)	Gas-fired (80%)	Gas-fired (80%)	Gas-fired (90%)
Wall R-value (m2-K/W)	0.43	0.91	6.25
Roof R-value (m2-K/W)	0.40	5.56	9.09
Air Change Rate (l/s.person)	7.5	5	5

Life cycle costs comprise both building, operational and maintenance costs. Building costs included the capital costs of construction and, where necessary, site clearance (i.e. for New-build). Operational costs include all energy-related space heating and lighting costs. Maintenance costs include scheduled replacements of windows (30 year), roofing (100 year) and boilers (20 year). Building costs were based on reported conversion costs (£422,150) and estimated New-build costs (£104,161), the latter based on an estimate by a quantity surveyor. These costs were adjusted for inflation where relevant. Operational (energy) costs were based on the simulated energy use and average 2018 domestic energy prices (BEIS, 2019c), which are summarised in Table 4.

4.4.3 Emissions Results

The construction-related embodied carbon emissions were estimated to be 9.9 tCO_2e (10.32% of total emissions) and 18.8 tCO_2e (31.13% of total emissions) for the Conversion and New-build (including demolition). There are no embodied emissions for the Base-case as the carbon embedded in the existing fabric has already been spent and has no consequence on current and future emissions. The demolition emissions associated with the new build accounted for 6.7% of its total emissions. The operation emissions for the Conversion and New-build accounted for 89.68% and 68.87% of total emissions respectively. Annual operational energy use was estimated to be 19,944kWh, 7,145 and 3,447Wh for the Base-case, Conversion and New-build.

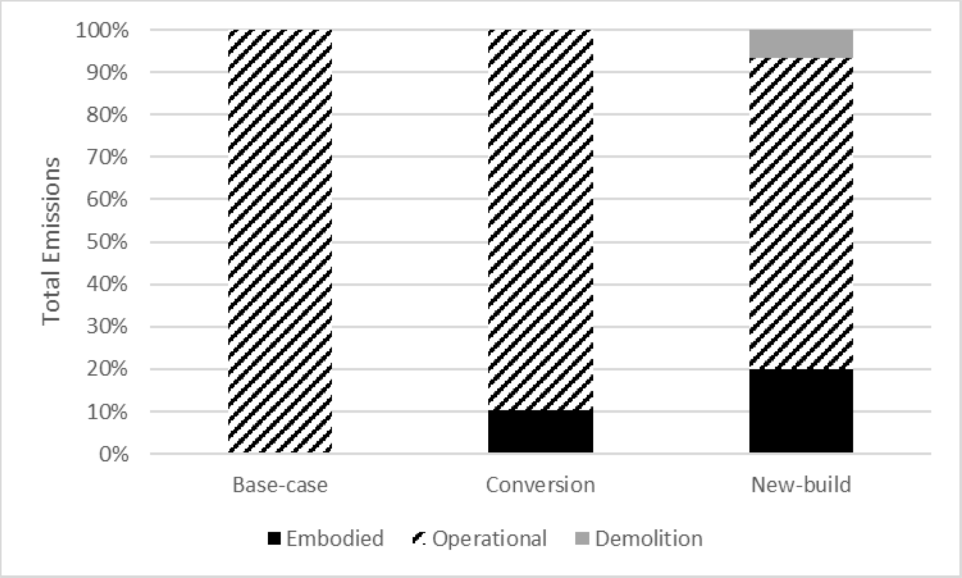


Figure 14. The percentage of embodied, operational and demolition emissions of total emissions associated with the Base-case, Conversion and New-build within the 60-year RSP. The embodied emissions of the New-build in the graph exclude the demolition emissions to show the percentage of demolition emissions separately.

Figure 15. Estimated life cycle carbon emissions for each building case for different reference study periods

shows the estimated life cycle carbon emissions for each building case for different reference study periods. Life cycle carbon emissions increase with the RSP due to emissions related to fuel consumption and maintenance. The Base-case results in the highest emissions for reference study periods 60-120 years which are dominated by emissions from fuel used in space heating. While New-build emissions are highest in Year 0, these increase at the lowest rate so that by Year 60 they are already lower than all other cases.

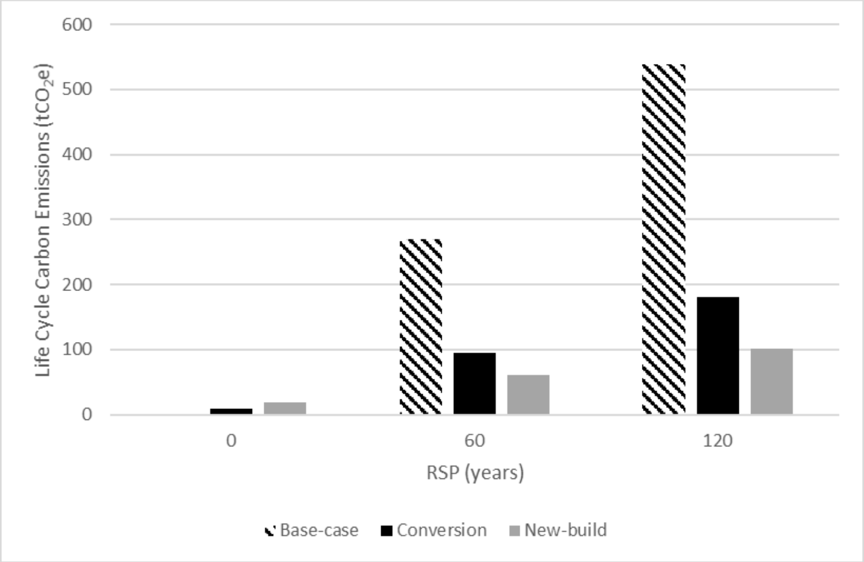


Figure 15. Estimated life cycle carbon emissions for each building case for different reference study periods

Table 11 shows the emissions for the three building cases for a reference study period of 60 years and an internal temperature of 21°C expressed as: carbon dioxide equivalent, litres of petrol (Ecoscore, 2019), metres squared of carbon dioxide sequestered by British oak forest in one year (Morison *et al.*, 2012) and kilometres driven by an average 2018 British car (The Society of Motor Manufacturers and Traders, 2019).

Table 11. Alternative measures of life cycle carbon emissions for the Chapel Conversion assuming a 21°C internal temperature and a 60-year reference study period.

Design Option	**Carbon** (tCO_2e)	**Petrol** (litres)	**Oak Woodland** (m^2)	**Car Use** (miles)
Base-case	270	62,069	9,985	1,083,803
Conversion	96	22,033	3,544	384,728
New-build	60	13,870	2,231	242,191

The 2030 life cycle carbon emissions for the Base-case, Refurbishment and New-build are 68, 31 and 29 tCO_2e respectively; the equivalent figures in 2050 are 159, 61 and 44 tCO_2e. Based on these figures, the New-build would best help reach policy targets for both years.

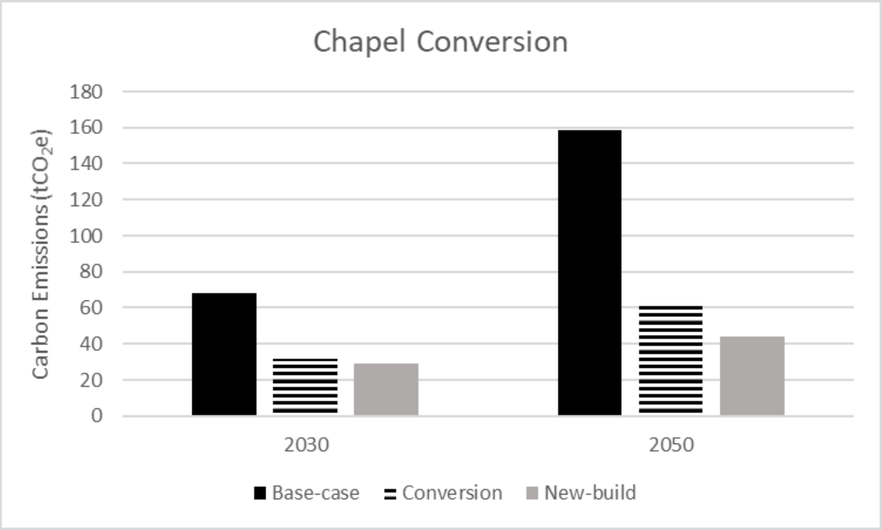
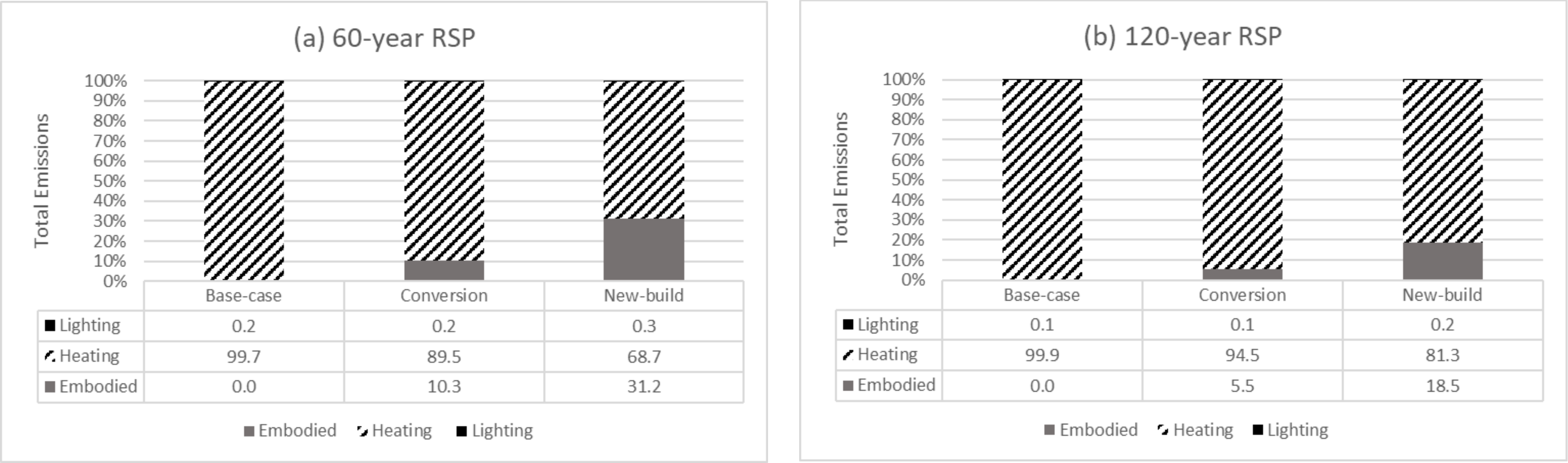


Figure 16. The estimated 2030 and 2050 emissions of the Base-case, Conversion and New-build.

Figure 17 (a-d) shows the life cycle carbon emissions for each case for the 60- and 120-year reference study periods broken down by embodied, heating and lighting emissions. This illustrates that operational emissions dominate, but that embodied emissions are most significant for the New-build over shorter life spans.

Figure 18 (a-d) shows the cumulative life cycle carbon emissions for the three building cases over 60 years. Each figure represents a different internal temperature ranging from 21ºC down to 18ºC. It can be seen that the carbon emissions of the Base-case exceeds the New-build 6-7 years after construction, depending on the internal temperature assumption; it is estimated to take 13-16 years before the Conversion exceeds that of the New-build (see Table 12 for exact results).



(a) 60-year RSP

	Base-case	Conversion	New-build
■ Lighting	0.2	0.2	0.3
▨ Heating	99.7	89.5	68.7
■ Embodied	0.0	10.3	31.2

(b) 120-year RSP

	Base-case	Conversion	New-build
■ Lighting	0.1	0.1	0.2
▨ Heating	99.9	94.5	81.3
■ Embodied	0.0	5.5	18.5

Figure 17 (a-b). Life cycle carbon emissions for each case for 60- and 120-year reference study periods broken down by embodied, heating and lighting emissions (internal temperature of 21°C). The percentage of each component for each building case are presented in the tables.

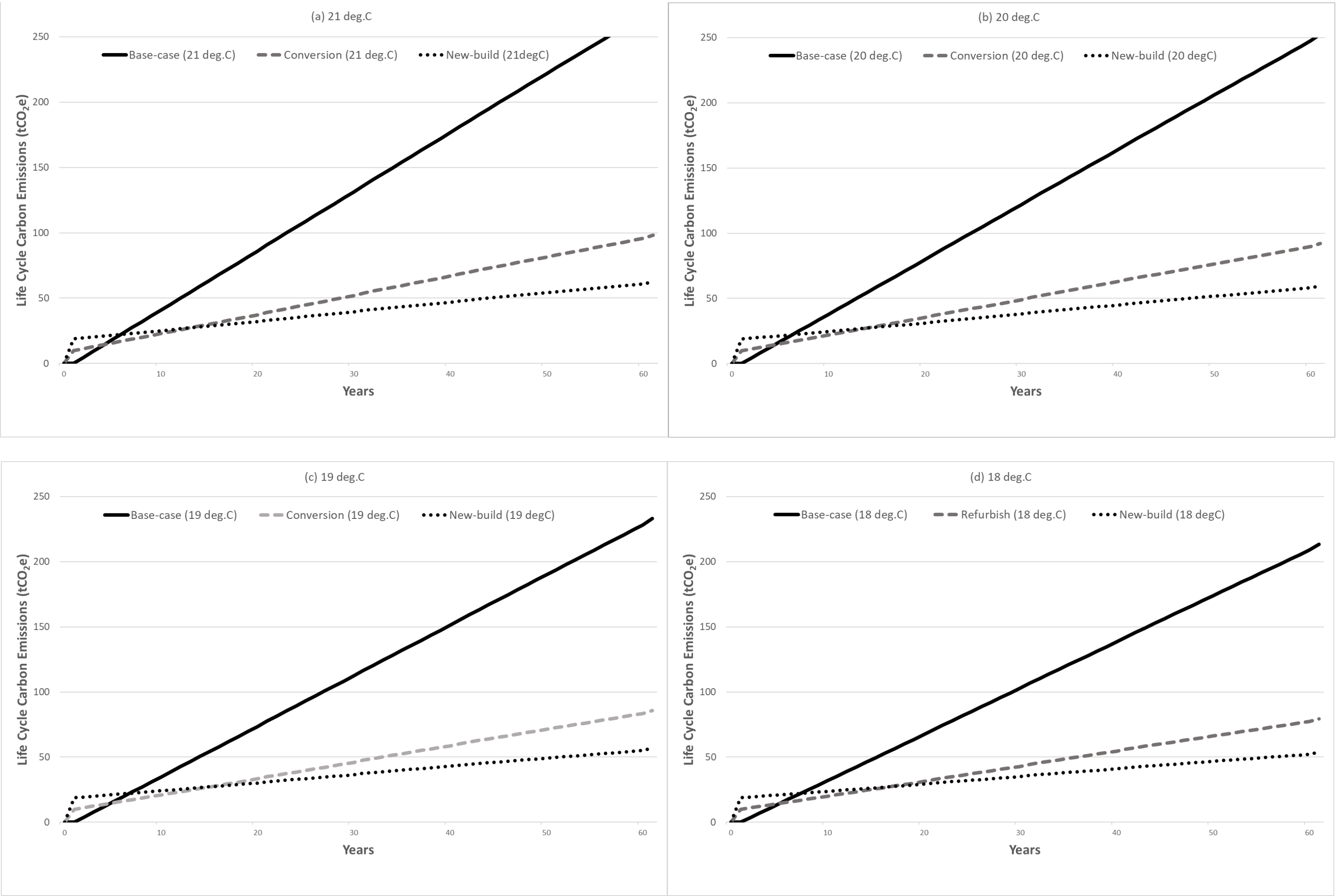


Figure 18 (a-d). Cumulative life cycle carbon emissions with different internal temperature assumptions.

Table 12. Time periods (years in yellow) after which the New-build outperforms the Base-case and Conversion for different internal temperatures.

	Internal Temperature (degC)			
	21	*20*	*19*	*18*
Base Case	6	6	6	7
Conversion	13	13	15	16

Table 13 below shows the differences in New-build and Conversion life cycle carbon emissions using different reference study periods and internal temperature assumptions. Variations in internal temperature assumptions result in variations of 20-27% in the results expressed as a percentage of New-build emissions, so these results are sensitive to internal temperature assumptions. The Conversion emissions are always higher than the New-build under each temperature scenario for all RSPs.

Table 13. Differences in New-build and Conversion life cycle carbon emissions (shades of red, in tCO_2e) using different reference study periods and internal temperature assumptions (negative indicates that Conversion is lower than New-build).

		Internal Temperature (degC)			
		21	**20**	**19**	**18**
RSP (yrs)	**60**	35	32	29	26
	120	80	73	67	60

4.4.4 Financial Results

Table 14 shows the savings-to-investment-ratios (SIR) for the Conversion and New-build for different discount rates. A positive SIR exceeding a ratio of 1 indicates that a project is financially viable. It can be seen that neither the New-build or the Conversion meets this criterion for the chosen RSPs.

Table 14. Savings-to-investment-ratios (SIR) for the Conversion and New-build for different discount rates. An SIR of greater than 1 indicates it is financially attractive.

Option	**Discount Rate (%)**	**Reference Study Period (years)**	
		60	**120**
Conversion	**0**	-0.91	-0.83
New-build	**0**	-0.54	-0.07
Conversion	**2.5**	-0.96	-0.95
New-build	**2.5**	-0.76	-0.71
Conversion	**5**	-0.97	-0.97
New-build	**5**	-0.85	-0.85
Conversion	**7.5**	-0.98	-0.98
New-build	**7.5**	-0.90	-0.90
Conversion	**10**	-0.99	-0.99
New-build	**10**	-0.92	-0.92

Marginal abatement costs are presented in Figure 19 where it can be seen that there are substantial abatement costs associated with the Conversion, particularly for lower reference study periods. The New-build has significantly lower MACs which fall significantly for an RSP of 120 years or more. Figure 19 shows carbon prices in the range of 2,432 to 1074 £/tCO_2e for the Conversion, and from 266 down to 17 £/tCO_2e for New-build. For the purposes of comparison, the *Report of the High-Level Commission on Carbon Prices* (2017) estimated carbon prices will need to be in the region of US$40–80/$tCO_2e$ by 2020 and US$50–100/$tCO_2e$ by

2030 to meet the goals of the Paris Agreement. The reason for the high Conservation MAC is the high cost of the work undertaken, rather than very low carbon savings. When the high cost is divided by the carbon savings, it results in a high cost per unit carbon saved.

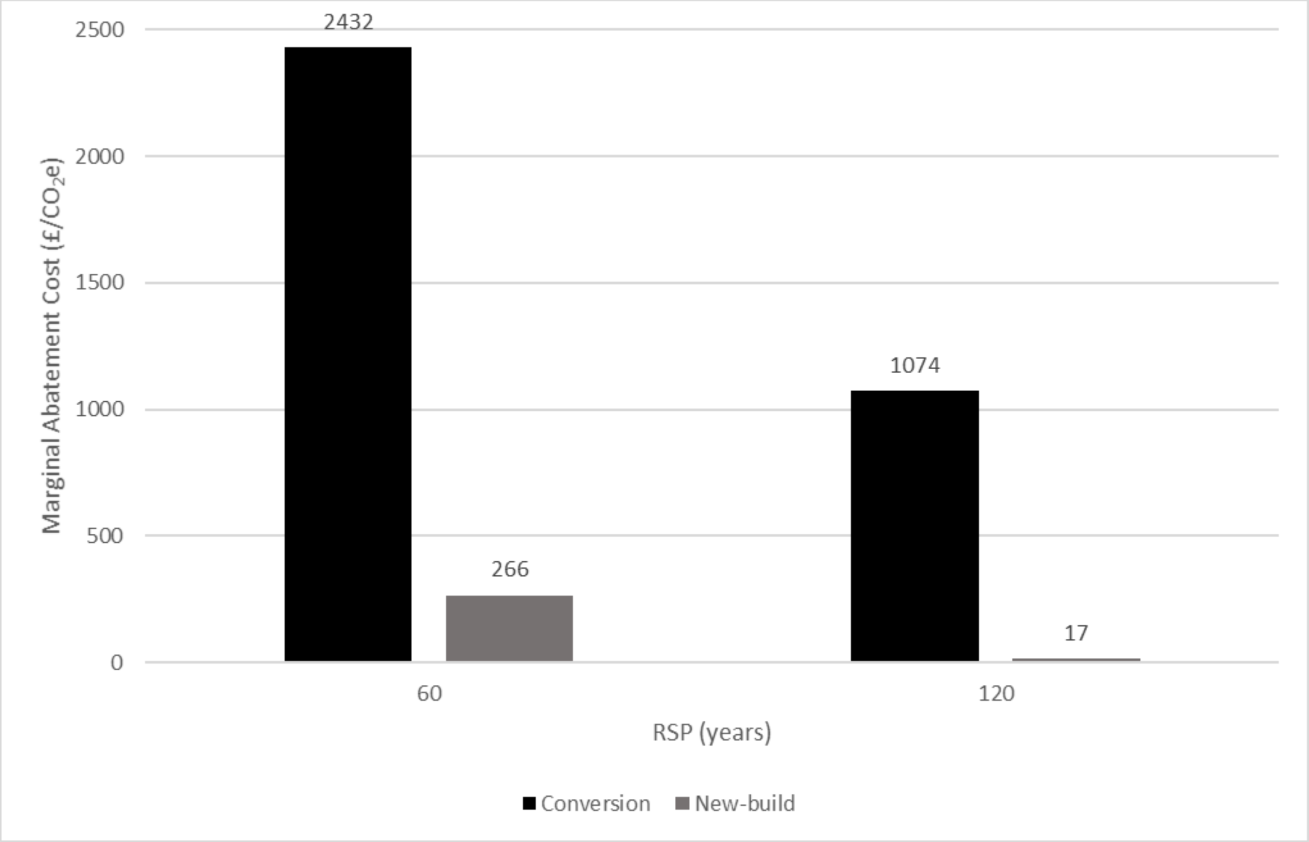


Figure 19. Marginal abatement costs (MAC) for the Conversion and New-build.

4.4.5 Internal Temperature Scenario

The carbon emissions for the Scenario_18-19-21 are presented in Figure 20 for the different reference study periods varying from 60 to 120 years. Under these assumptions, the New-build is still the best performer in terms of life cycle carbon emissions for all RSPs studied (see also Section 4.3.5 for the Victorian Terrace Refurbishment findings).

Figure 20 can be compared to

Figure 15. Estimated life cycle carbon emissions for each building case for different reference study periods

, where it can be seen that the emissions for the Base-case fall slightly compared to the Conversion and New-build, and Conversion emissions fall relative to New-build. This results in longer time periods until the New-build outperforms the Base-case and Conversion in terms of carbon emissions. Table 15 shows these time periods and it can be seen under Scenario_18-19-21, New-build outperforms Base-case and Conversion after 7 and 17 years respectively, as compared to 6-7 years and 13-16 years for scenarios with the same internal temperatures.

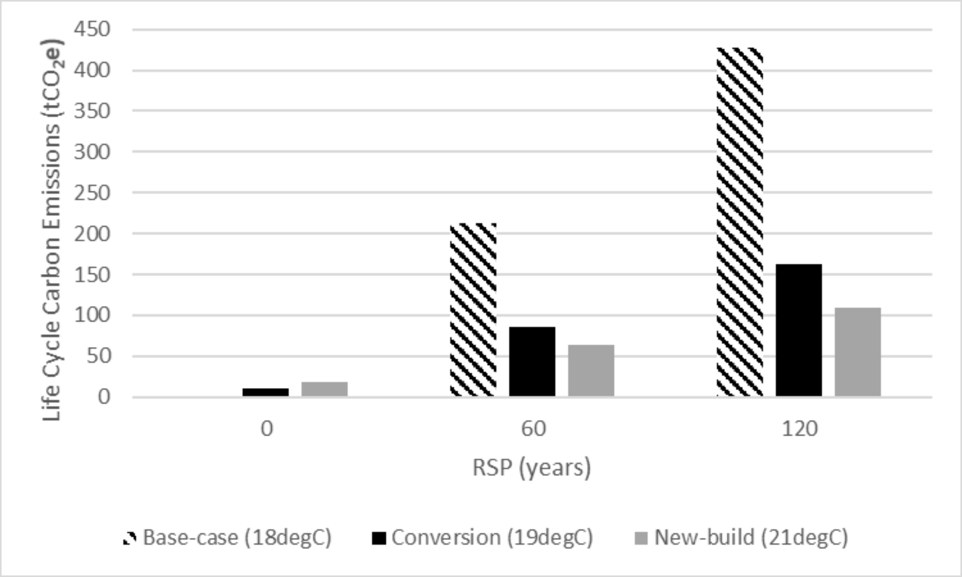


Figure 20. Estimated life cycle carbon emissions for each building case for different reference study periods (internal temperature of 21°C)

Table 15. Time periods (years in yellow) after which the New-build outperforms the Base-case and Conversion for different internal temperatures.

	Internal Temperature (degC)				
	21	*20*	*19*	*18*	Scenario 18-19-21
Base Case	6	6	6	7	7
Conversion	13	13	15	16	17

4.5 Limitations

Certain limitations apply to all life cycle assessments. The assessments are based on data, however the nature of making future projections will always have some degree of uncertainty as no one can be certain how long current conditions will remain the same. The following limitations identified in this study should be viewed not as faults, but as areas where further research should be undertaken (see also Section 5).

- The case study results relate to the specific projects analysed and given the small sample size, cannot be generalised to represent other projects with different characteristics. A larger sample size with a more varied representation of refurbishment works and building typologies would be need to make generalised statements of carbon savings.
- As life cycle assessments make predictions of future carbon emissions based on current conditions, some degree of uncertainty applies, especially as we look further into the future. This is the reason why a relatively short reference study period of 60 years is industry standard.
- The LCA results are very sensitive to construction and demolition emissions intensity assumptions. For this study, we assumed an emissions intensity of 23.7 $kgCO_2e$/tonne of waste, but this figure is currently subject to further research.

4.6 Case Study Findings

The main findings of the two case studies are discussed below. It should be noted that the Victorian Terrace Refurbishment is likely to be representative of a greater number of historic building refurbishment projects than the Chapel Conversion, which involved the relatively unusual reuse of a derelict ecclesiastical building and significant conservation and repair works, in addition to energy efficient upgrades. A review of the literature indicated that sixty years is a standard assessment period in many building guidance documents which allows for comparative analysis with other studies. For this reason, the results below use a reference study period of 60 years.

It should be borne in mind that the emissions performance of historic buildings is only one criterion to be considered when making design decisions about whether and how to refurbish and conserve them. This must be complimented by other relevant criteria such as heritage and cultural value, historic importance, material compatibility, moisture-related issues, accessibility, functional use, etc.

The life cycle carbon emissions for both the Victorian Terrace Refurbishment and the Chapel Conversion were comparatively lower using a 60-year RSP, due to the high embodied carbon emissions associated with the demolition and construction of the New-build. After 60 years, the Refurbishment remained more competitive with the New-build than the Chapel Conversion due to a greater focus on improved energy efficiency and a lower initial embodied carbon investment.

Focusing on the Refurbishment, the analysis shows that a typical energy efficient refurbishment project such as this has similar life cycle emissions to a New-build project over a 60-year reference period; these may be somewhat more or less depending on the internal temperature scenario assumptions (see Figure 8 and Figure 13). For an internal temperature of 21°C, life cycle carbon emissions were 59 tCO_2e in both Refurbishment and New-build cases; but considering operational emissions only (as the current building regulations do), the New-build results in lower emissions over the 60 years compared to Refurbishment: 42 vs. 58 tCO_2e respectively. Therefore, considering operational emissions only underestimates New-build emissions by 27.9% over 60 years and Refurbishment by only 2.1%. This demonstrates the importance of considering the total life cycle carbon emissions for historic buildings; this would be best effected by extending building regulations to take a whole-life approach.

The life cycle carbon emissions for the Chapel Conversion indicate that the New-build outperforms the Conversion after only 13-16 years. The derelict state of the building and the reconfiguration of the internal layout required a greater investment in products to bring it back into use, which therefore resulted in much higher embodied carbon emissions than the Victorian Terrace Refurbishment. This illustrates that one-off projects which do not target energy efficiency improvements and involve significant repair, conservation and conversion works will struggle to compete with alternatives from a carbon emissions perspective. Similar results for conversions were found by a US Study *'The Greenest Building: Quantifying the Environmental Value of Building Reuse'* (Frey *et al.*, 2011). In all but one case study, they found that refurbishments outperformed the new building alternatives. The exception was a conversion case study which they attributed to the large amount of materials required for conversion since the more materials will generally lead to higher embodied emissions. This may explain why the Chapel Conversion emissions were higher than the Refurbishment and the New-Build.

The Victorian Terrace Refurbishment and the Chapel Conversion together saved 266 tonnes of carbon compared to the Base-case. Both case studies indicate that life cycle emissions of historic buildings in their existing (Base-case) state is worse that both the New-build and Refurbishment and they must be made more energy efficient if they are to compete with new buildings on life cycle emissions savings.

The demolition of the Victorian Terrace Refurbishment and the Chapel Conversion would account 4.1% and 6.27% of the respective New-build's total carbon emissions. This is taking into account the reported 92.1% recycling rate of C&D waste. It is possible that demolition emissions may be even higher if the recycling rate was found to be lower. The New-build embodied emissions are sensitive to demolition emission intensities. Since there is little publicly available data and research on this topic, further research on this topic would help to confirm the assumptions made in this analysis.

In addition to looking at the effect of the reference study period on life cycle carbon emissions, internal temperature variations were also assessed. The 18-21°C range investigated had a significant impact on the relative performance of the different design. For example, this resulted in changing the number of years it will take for the New-build terraced building to outperform the refurbished buildings from 63 to 74 years, a 17% increase. Further research on the temperatures at which historic and modern buildings are actually operated is therefore recommended. This would give greater justification to assessing historic buildings using lower internal temperatures than those used in new or refurbished buildings and would weaken the argument for New-build, as demonstrated in Scenario_18-19-21.

The Refurbishment performs considerably better than the New-build both in terms of the MAC and SIR. This indicates that it would be more cost effective and attractive as a policy than the New-build and would be cheaper to make attractive to developers and homeowners.

The Refurbishment was found to have the greatest life cycle carbon reduction potential for the 2030 and 2050 policy target years, as illustrated in Figure 9. For the Chapel Conversion, New-build and Conversion achieve similar carbon reductions in 2030, but by 2050 the New-build is best (Figure 16). The Base-case results in significantly higher carbon emissions for both case studies and policy target years, indicating that that continuing to operate buildings in their current state will not be attractive to policymakers.

The embodied analysis of the Refurbishment highlighted that wood fibreboard and other natural timber products have negative embodied emissions. Given that timber-based insulation products tend to be vapour permeable, it may justify further research into the performance (e.g. hygrothermal, durability, economic), potential technical risks and detailing of natural products for historic building refurbishment to support the development of guidance on the low carbon refurbishment options for historic and traditional buildings.

The analysis assumes that space heating systems for both the New-build and Refurbishment/Conversion are fossil-fuelled. The standards for new buildings will soon require that such systems are phased out in favour of very-low carbon technologies such as heat pumps. Historic building refurbishment practice will need to change in order to be able to compete with these developments.

Some of the main case study findings are summarised below. These are largely based on the more representative Terrace Refurbishment case study, so additional case studies are necessary to confirm and strengthen these conclusions.

- Deep energy efficient refurbishment of historic buildings is necessary if they are required to achieve performances similar to new buildings.
- The life cycle emissions assessment of the terraced dwelling (including the embodied carbon benefits of the existing structure) presents a more complete picture of environmental performance than operational assessment; operational emissions underestimated life cycle emissions by approximately 30% for New-build but have almost no impact on Refurbishment emission estimates. This demonstrates how existing regulations, which consider operational emissions only, disadvantage historic building refurbishment in terms of carbon emissions assessment.
- Shorter reference study periods (e.g. 60 years) best highlight the emissions benefits of historic building refurbishment.
- Historic building refurbishment was found to achieve the best economic performances in terms of marginal abatement costs and savings-to-investment ratios.
- Refurbishment was found to achieve the best carbon reductions for the 2030 and 2050 policy target years.
- Conversions may have higher embodied emissions than regular refurbishments due to more materials being used.

5 Recommendations

As climate change mitigation policy continues to grow in importance, securing and communicating opportunities to improve the energy efficiency of the English historic building stock through low carbon refurbishment is going to become more critical to its long-term survival. In order to actively influence the direction of debate and policy in this area, it will be important to measure and monitor the performance of energy refurbishment projects on an ongoing basis and to use the ensuing knowledge to develop guidance, tools and measures to reduce the emissions impacts of the historic building stock. As this scoping study has shown, life cycle assessment is a viable way to collect and analyse the data needed to inform policy change.

The recommendations from this research have therefore been organised under the following five categories: decision support, data collection, data analysis, guidance and specific considerations for further research.

5.1 Decision Support

It is recommended that before a large-scale LCA study of historic buildings is undertaken that a tool is developed or amended to speed up the process of the calculations. The research did not identify a 'one-stop-shop' web-based tool for assessing the performance of different refurbishment options for historic buildings at the concept-design stage. Such a tool could greatly increase the quality of designs with regard to minimising damage both to the environment and to the buildings themselves. Tasks for developing such a tool for historic building practitioners would include:

- Establishing user needs;
- Reviewing existing commercial and open-source tools with respect to these needs; and
- Developing and maintaining a tool incorporating the guidance.

The development of this tool could either be carried out in-house or in collaboration with an existing commercial company with a compatible product. The former would involve using freely-available databases (e.g. ICE, EPDs) and existing energy and emissions simulation tools (e.g. MIT Design Advisor) that might be offered either for free or at a cost. The latter would involve extending and amending existing building energy/emissions tools (e.g. One Click LCA) to include all life cycle stages and to comply with Historic England's guidance.

It would be desirable to accompany the development of a suitable LCA tool with a training programme for historic building professionals on the use of LCA for the refurbishment of historic and existing buildings.

5.2 Data Collection

This research has demonstrated that there is a lack of national and international data on the life cycle performance of historic building refurbishment and that it is difficult to find secondary sources of data which are suitable for this purpose. This can be done in conjunction with developing a suitable tool. The design and development of an ongoing data collection programme is therefore required to gather the evidence for identifying suitable refurbishment technologies, developing guidance, providing knowledge for policymaking, identifying research needs, and for guiding Historic England's strategy in this area. Key tasks include:

- Establish the strategic and operational aims of such a programme to Historic England;
- Identify the critical variables necessary to achieve these aims (e.g. cost, energy performance, durability, etc.);
- Identify suitable data collection channels (e.g. secondary data from existing programmes such as historic building grant-aid programmes or primary data collection programmes commissioned by Historic England);

- Develop data collation, cleaning, storage and retrieval processes; and
- Establish a resource management process for planning, monitoring, reviewing and improving data collection processes.

5.3 Data Analysis

While several separate components exist, there is not a complete LCA methodology which can be applied to analyse the life cycle emissions impacts of refurbishment projects for historic and existing buildings. The methodology presented here is a start, however it will be necessary to formally establish and operationalise such methodologies which can be used to analyse the data for a variety of strategic needs including: knowledge for policymaking; identifying and monitoring energy efficient refurbishment technologies; establishing research needs; producing and updating guidance for practitioners; and developing support tools. Data analysis tasks include:

- Identify the objectives, scope and output parameters for the LCA methodology for emissions from historic building refurbishment projects;
- Formalise a suitable methodology;
- Operationalise this using a suitable computer platform; and
- Apply this to case study data and collate findings for key stakeholders.

5.4 Guidance

There is no consolidated guidance documentation available to practitioners for assessing the life cycle emissions impacts of refurbishment options for historic buildings, either at the concept or detailed design stage, although a number of different standards and guidance documents have been identified for different life cycle stages or for new buildings. Given that the greatest impact on emissions can be made early in the design process, the necessary guidance should focus on the concept-design stage. This should be based on current relevant guidance and research, as well as on the results of the data collection and analysis tasks outlined above. Tasks for the development of LCA guidance include:

- Collate and review existing standards and guidance;
- Identify relevant material and product documentation from chosen databases and sources (emissions intensities, costs, thermal properties, hygrothermal properties, etc);
- Produce step-by-step guidance based on this information and the methodologies used in the data analysis; and
- Implement a procedure to regularly update guidance and supporting data.

Historic England's existing guidance on improving the energy efficiency of traditional buildings could be supplemented with guidance on the embodied carbon of building materials suitable for different types of historic buildings. For instance, the guidance could review and compare the environmental impacts of different types of hygroscopic insulations, such as wood fibreboard, mineral wool, lime plasters with cork and hemp, etc. However, as discussed in Section 2.2.2, if EPDs are being used to compare materials, the methodology of EPDs should be fully reviewed to ensure that the data is reliable, consistent and spans life cycle modules A1-D. Ideally, these EPDs would provide the GWP data in several functional units, preferably in kg of CO2e/m^2 as this functional unit is often used in LCA studies.

5.5 Further Research

Some areas of further research identified during this study include:

- Collecting and analysing a greater number and variety (in terms of construction, materials, use, etc.) of representative refurbishment case studies;

- Collect data on the life expectancy of historic building materials;
- Testing, developing and deploying low-carbon heating systems and designs which are compatible with the needs of historic buildings and their users (e.g. electric, radiant, heat-pump, biomass systems);
- Research into the revision of existing regulations and policies (e.g. Environmental Impact Assessments, building regulations, planning processes, procurement processes, etc.)
- Testing and demonstrating low-embodied carbon refurbishment materials and processes which are compatible with historic building needs (e.g. natural moisture-permeable insulating materials, by-products and recycled materials); and
- Obtaining better data on demolition emissions.

Ongoing data gathering and analysis, as well as user feedback from guidance and the decision support tool, will also support the development of a broader research programme.

6 Conclusions

This study aimed to identify suitable methods and tools for the assessment of the life cycle carbon emissions of different concept-stage energy efficient refurbishment designs for historic buildings. This was done through the assessment of the life cycle carbon emissions of a two completed refurbishment case studies, which were compared to a Base-case and New-build. Intended users of these tools and case study findings include historic building professionals (designers, specifiers and conservation consultants), policymakers and historic building owners.

The report describes the different phases and principles of life cycle carbon assessment, life cycle cost assessment and marginal abatement costing, all of which are important concepts for designers, building owners and policymakers respectively. Based on a review of current research and industry best practice in the field, a detailed methodology has been presented to assess the life cycle impacts of different concept-stage designs for historic buildings including refurbishment and demolish-and-replace.

This methodology was applied to two case studies: the conversion of a historic chapel for residential use; and the refurbishment of an end-of-terrace Victorian house, which is typical in terms of materials and construction method to many Victorian era buildings in England. The findings highlight that the energy efficient refurbishment of historic buildings is necessary to achieve performances similar to new buildings. It was found that existing regulations, which consider operational emissions only, disadvantage historic building refurbishment in terms of carbon emissions assessment. If embodied emissions were omitted from the LCA study, the total emissions of the New-build would be underestimated by nearly 30%. A sensitivity analysis of reference study periods indicates that the shorter 60-year reference study period best highlights the emissions benefits of historic building refurbishment; this period also aligns well with standard building design practice. The Victorian Terrace Refurbishment was found to achieve the best carbon reductions for the 2030 and 2050 policy target years of the options considered and was also found to achieve the best economic performances in terms of marginal abatement costs and savings-to-investment ratios.

The Chapel Conversion result supports the assumption that conversions, which require more materials, will generally have higher embodied emission. This case study is not a typical refurbishment case study as more materials were required to convert the derelict building into a dwelling. It demonstrates that the level of intervention affects the embodied emissions of refurbishments and building conversions that require a large quantity of new materials can reach the emissions levels of new builds. The carbon intensity of refurbishment works can be reduced by using low carbon materials and systems or by recycling and reusing high carbon materials. For instance, wood fibreboard and other natural timber products have negative embodied emissions; many are also vapour permeable and therefore suitable for traditional buildings.

A number of existing computer application tools were identified and trialled for use in the life cycle assessment of concept-stage refurbishment designs for historic buildings. The research did not identify a single ‘one-stop-shop' tool, but a number of different applications were found which addressed different life cycle stages. These could be combined, adapted and/or extended to develop a more complete tool which meets the specific needs of historic building refurbishment life cycle assessment.

A number of recommendations are made based on this scoping study, which include: developing associated decision support tools such as computer applications; developing an ongoing data collection and analysis programme; and developing practitioner guidance which addresses the special needs of historic buildings. A number of specific areas for further research have also been identified.

The retention and reuse of existing buildings should be incentivised by legislation that regulates the construction industry to avoid the unnecessary waste of materials and the embodied carbon embedded within them. Further research into the carbon savings associated with the energy refurbishment of buildings and recycling of building materials will help to solidify this argument and emphasise the role historic buildings can play in climate change mitigation.

7 Appendices

7.1 Acknowledgements

We would like to thank everyone who provided case study data for the Victorian Terrace Refurbishment, the Chapel Conversion, and the New-build, and those who provided case study data that ultimately could not be used within the confines of this study.

We would also like to thank Historic England and the stakeholder advisory group for their feedback throughout the course of the research.

7.2 Acronyms

BE	Built Environment
BOQ	Bill of Quantities
BRE	British Research Establishment
CCC	Committee on Climate Change
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EC	Embodied Carbon
EE	Energy Efficient (Efficiency)
GHG	Greenhouse Gases
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MS	Mitigation Strategy
PCR	Product Category Rules
RSP	Reference Study Period
ICE	Inventory of Embodied Carbon
EPD	Environmental Product Declaration
MAC	Marginal Abatement Cost
SIR	Savings-to-Investment Ratio

7.3 Glossary

CO_2-equivalents (CO_2e): expression of warming effect of greenhouse gases in relation to the warming effect of CO_2. CO_2 is the baseline, with a warming potential of 1 and other greenhouse gases oh higher warming potential are expressed as a multiple of that.

Cradle-to-Cradle: an extension of cradle-to-grave, where the end-of-life is not disposal but recycling for further use.

Cradle-to-Gate: assessment of the partial life cycle of a product from resource extraction to the factory gate (before transportation to a consumer)

Cradle-to-Grave: an assessment of the life span of a product from creation to disposal, a linear process.

Cultural Heritage: Inherited assets which people identify and value as a reflection and expression of their evolving knowledge, beliefs and traditions, and of their understanding of the beliefs and traditions of others. (Drury and McPherson, Conservation Principles, 2008)

Demolition Energy: Energy used during the demolition of a building and the transportation to a landfill or recycling site.

Embodied Carbon: the carbon dioxide emitted during extraction, manufacture, transportation and construction of buildings as well end-of-life emissions.

Embodied Emissions: carbon emissions result from the production, transportation and installation of building materials and components on site. Embodied emissions also include emissions from maintenance, repairs, replacement and ultimately the demolition and disposal of building materials over the full lifetime of the building.

Embodied Energy (MJ/kg): the amount of energy consumed to extract, refine, process, transport and fabricate a material or product (including buildings). It is often measured from cradle to (factory) gate, cradle to site (of use), or cradle to grave (end of life).

Environmental Product Declaration: standardised documents used to communicate the environmental performance of a product

Gate-to-Gate: an assessment of only process in the LCA chain, which can be linked with other process to form a full evaluation

Heritage Asset: A building, monument, site, place, area or landscape identified as having a degree of significance meriting consideration in planning decisions, because of its heritage interest. Heritage assets include designated heritage assets and assets identified by the local planning authority (including local listing) (*National Planning Policy Framework (NPPF)*, 2019).

Heritage: All inherited resources which people value for reasons beyond utility (Drury and McPherson, 2008).

Historic Environment: All aspects of the environment resulting from the interaction between people and places through time, including all surviving physical remains of the past human activity, whether visible, buried or submerged, and landscaped or planted or managed flora (*National Planning Policy Framework (NPPF)*, 2019).

Life Cycle Assessment: an assessment of the environmental performance of materials, from the raw extraction, manufacturing, disposal and recycling. It is the ‘cradle-to-grave’ approach of environmental assessment of buildings.

Life Cycle Energy Analysis: an assessment of all the energy inputs in a building throughout its life span.

Life Cycle Impact Assessment: evaluation of the environmental impact of products throughout their life span after the calculation of their emissions or energy use.

Life Cycle Inventory: the compilation and quantification of the inputs and outputs of a product during its life.

Operational Emissions: carbon emissions that result from the day-to-day use of a building through energy consumption

Operational Energy: the energy consumed during the day-to-day use of the building to maintain comfortable conditions which includes appliances, heating, cooling and ventilation systems, lighting and domestic hot water systems.

Traditional Buildings: solid-walled buildings constructed using materials that allow the cyclical absorption and dissipation of atmospheric moisture from the building fabric and with techniques that were in use before 1919 (*Advice Series: Energy Efficiency in Traditional Buildings*, 2010)

U-Value: measure of the rate of heat flow through a material, expressed in W/m^2K. The lower the U-value, the lower the rate of transfer.

7.4 Energy and Emissions Databases

During this study, several databases and tools were considered for use in refurbishment projects. The specifications and reason for accepting/rejecting the databases/tools are presented in Table 16 and LCA Tools

Table 17.

Table 16. The databases considered in this study reviewed based on scope, accessibility, accuracy, cost and the LCA boundaries included.

	Criteria					
Database	**Scope**	**Accessibility**	**Accuracy**	**Cost (£)**	**Boundary**	**Assessment**
Ecoinvent	Life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, transport services.	Online guidelines available including guidelines for any updates. User need not know the origin of products. Database uses market activity dataset to detect where it is coming from. Guidelines on LCIA given. Software required – may be hard for first time users. International	Updated every year	3800 (Commercial single user)	Gate to Gate, Cradle to Gate	Excluded due to cost
ICE	Over 200 materials in 30 categories: bricks, cement, concrete, glass, timber, plastics, metals, minerals and stone	Excel sheet easy to use. Knowledge of complicated software not necessary. Applicable to UK	Updated at periodic intervals	Free	Cradle to Gate	Consider
Green Guide	Environmental impacts of construction materials often used in commercial, educational, healthcare, retail, domestic and industrial buildings. The elements covered are external and internal walls, roofs, ground and upper floors, windows, insulation landscaping and floor finishes. Gives ranking of different elements (A+ to E)	Easy to use online programme. Building type, category and element type are input into the programme and rating is given for different options. International	Annually updated	Free	Cradle to Grave (demolition not included, disposal included)	Consider

Embodied Carbon Database by WRAP	Focusses on whole buildings and their embodied carbon, not individual materials. Includes different building types.	Made for building professionals, engineers, architects, quantity surveyors. Applicable to UK	No information given	Free	Cradle to Gate	Consider
GaBi	Covers large range of sectors including the building industry	Guidelines online, difficult to follow for first time user. User must create connections in the supply chain manually. International	Updated every year	Cost not determined	No information given	Excluded due to cost
Exiobase	Covers large range of sectors incldung the building industry	PDF guidelines available for each version of exiobase. International	No information given	Free	No information given	Excluded due to pdf format
Okobaudat	Construction material database containing impact assessment of products. Mineral building materials, insulation material, timber products, metals, lacquers and sealants, plastic building materials, components of windows, doors and curtains, technical installations of buildings, others	Limited to German materials	Continuously updated (last update 30.04.19)	Free	Cradle to Grave	Excluded due to region

7.5 LCA Tools

Table 17. The LCA Tools considered for this study reviewed under scope, databases used, accessibility, cost and LCA boundaries included.

LCA Tool	Country	Scope	Database used	Accessibility	Cost (£)	Boundary	Assessment
SimaPro	USA	Software package for industry and academia for products and services at all lifecycle stages.	Ecoinvent, worldsteel, IDEA, US LCI, Swiss Input/Output database, ELCD, datasmart (US)	Seems limited to French businesses	Starting at 350 for business user	Cradle to Grave	Exclude due to complexity, cost
Athena LCA	Canada	Software contains two services: Impact estimator: Estimator allows the user to input energy simulation results to calculate their operating effects alongside their embodied effects. EcoCalculator (out of date): user needs only to input the square footage of any particular assembly to receive instantaneous embodied life cycle impact assessment results (operating energy is not included)	Own embedded database - North American data only	Not designed purely for engineers or architects. Some technical knowledge is required.	Free	Cradle to Grave (excluding operation)	Exclude due to region
BREEAM	UK	Assessment tool of an asset's environmental, social and economic sustainability performance, using standards developed by the BRE Group.	Green Guide	International	Free	Cradle to Grave (excluding demolition, inlcuding disposal)	Exclude due to excessively broad scope
IES Virtual Environment	UK	Allows user to quantify data for different categories (superstructure, substructure, services, etc.) and their elements. The tool calculates the embodied emissions of the whole building and expresses the data in graphs.	Unknown	Unknown	License required	Cradle to Site	Exclude due to complexity

MIT Design Advisor	USA	Simulates building energy use and operational emissions through a small number of inputs. It allows the user to compare the operational energy and emissions of different scenarios but is limited in its capability to measure embodied carbon.	None	Suitable for concept-design stage	Free	Only considers operational	Only useful for operational energy calculations
One Click LCA	Finland	Software for LCA of buildings to calculate life cycle emissions and to compare designs to find the optimal solutions. Contains materials specific to historic buildings.	International EPDs	Contains UK EPDs	from 790	Cradle to Grave	Suitable for historic buildings in UK & for concept-design stage but not for operational calculations

7.6 LCA Data Requirements

Building life cycle emissions analysis requires both building-related data as well as emissions intensities for fuels and materials. The latter are available from LCI databases. The former, building-related data required for a comprehensive life cycle assessment of a historic building energy and emissions efficient refurbishment, is detailed in Table 18. This includes information on the geometry and materials used for both the existing and proposed refurbishment/replacement options. In addition, information on existing and proposed services, occupancy and building use/management are required. For full life cycle cost analysis and marginal abatement costing, refurbishment and/or replacement construction costs are also required.

Table 18. Building-level data requirements and potential sources for case studies. All data related to that typically available at the concept-design stage. Red denotes required, amber highly desirable and green desirable.

Information Type	**Data Required**	**Possible Sources**		
		Existing	Retrofit	New Build
General	Building use, age, location, surrounding environment (overshadowing etc).	Owner/design team interviews. Google maps, survey reports.	Not required.	Not required.
Building Geometry and location.	Dimensions of building envelope, rooms and elements such as windows, walls, doors, chimneys, vents. Orientation. Building location.	Survey drawings. Energy Performance Certs. Maps.	Architectural/design drawings.	Architectural/design drawings.
Construction Materials and Systems	Types of materials and construction details employed including thicknesses and thermal specifications where available.	Survey drawings/reports. Energy Performance Certs.	Architectural/design drawings. Bills of Quantities.	Architectural/design drawings. Bills of Quantities.
Heating, Cooling and Electrical Services	Description of the heating, cooling, ventilation and electrical systems including any technical details and efficiency data.	Energy Performance Certs. Survey reports.	M&E design drawings/specifications. Bills of Quantities.	M&E design drawings/specifications. Bills of Quantities.
Occupancy	Number of occupants. Any available socio-economic data (age, occupation, etc.). Typical occupancy hours.	Owner/design team interviews.	Owner/design team interviews.	Owner/design team interviews.
Management	Any information on energy management practices. Any measures of thermal comfort.	Owner/design team interviews.	Owner/design team interviews.	Owner/design team interviews.
Energy End Use	Quantities used by fuel type (gas, oil, coal, electricity, etc.). Smallest time step available.	Bill data. Building management system log files.	Not available.	Not available.
Construction Costs	Cost of construction	Not applicable.	Bills of quantities. Quantity surveyor reports.	Bills of quantities. Quantity surveyor reports.

7.7 Energy Refurbishment Options for Historic and Traditional Buildings

Any refurbishment or conservation project must start with an understanding of the building's historic significance and heritage value. This will determine the appropriate approach and level of intervention for that particular building. Statutory designation as an individual listed building or as part of a conservation area will also set parameters on allowable refurbishment options, so building owners must seek planning permission where required before works start. Refurbishment options may also be limited by the existing building condition, material properties, construction type, risks related to cold bridging or moisture retention and special features or design characteristics of the original building that should be retained. Sensitive energy refurbishment works can be compatible with historic buildings, but a balance must be struck between achieving contemporary energy efficiency and comfort standards and retaining the historic character of the building.

7.7.1 Understanding Historic Significance

The historic significance of a building can be due to its age, its association with certain people or events, or to its special architectural style and characteristics. In England, buildings of special architectural or historic interest are 'listed' to provide statutory protection. In general, all buildings constructed prior to 1700 that retain most of their original features are listed, as are a large majority of buildings up until 1850. Historic buildings are awarded different levels of protection based on their significance, ranging from Grade II, to Grade II* to Grade I at the highest level. The most exceptional buildings are listed at Grade I, which comprises only 2.5% of all listed buildings, while 97.1% of listed buildings are listed at the lowest level Grade II, which primarily includes buildings of local or regional importance.

The listing process is designed to protect historically significant buildings from detrimental changes or demolition, though it does not mean that they cannot be changed at all. Before works begin, building owners must obtain listed building consent for specified works, which in terms of an energy refurbishment may not permit certain works that will change the look or character of the building (such as solid wall insulation). Historic England maintains an online record of all listed buildings and sites on its website. Building owners should also consult their local authority for more information on obtaining listed building consent.

The potential impact of energy refurbishment measures on the historic significance of a building should always be considered. The UK National Planning Policy Framework (NPPF) states that assessment should be commensurate with the level of significance, and if in doubt, professional advice should be sought (MHCLG, 2019). Further guidance and information on conservation principles and assessing the significance of historic buildings can be found in a number of Historic England publications, including *Managing Significance in Decision-Taking in the Historic Environment* (Historic England, 2015), *Making Changes to Heritage Assets* (Historic England, 2016) and *Conservation Principles, Policies and Guidance for the Sustainable Management of the Historic Environment* (Drury and McPherson, 2008).

7.7.2 Energy Refurbishment Guidance for Historic and Traditional Buildings

Energy efficiency works can pose unintended consequences, especially for buildings of traditional construction. The installation of non-vapour permeable insulation or linings plus increased airtightness can lead to the retention of moisture, which when excessive can cause issues with damp and mould growth, and eventually structural damage. It is therefore important that the design of energy and thermal efficiency improvements are informed by hygrothermal assessments (Arregi and Little, 2016; Little, Ferraro and Arregi, 2015; Browne, 2012) and undertaken using vapour permeable materials/finishes and are balanced with adequate levels of ventilation (Currie, Williamson and Stinson, 2013; Borderon, Nussbaumer and Burgholzer, 2016; Pickles, 2016d; Walker and Pavía, 2016).

For the purpose of this study, inappropriate refurbishment options for traditional and historic buildings have been eliminated from consideration based on guidance provided by Historic England through their *Energy Efficiency and Historic Buildings* advice series. This series includes guidance on a variety of refurbishment options and issues, including *Draughtproofing Windows and Doors* (Pickles, 2016a), *Insulating Solid Walls* (Pickles, 2016d), *Insulating Suspended Timber Floors* (Pickles, 2016e), *Insulating Pitched Roofs at Rafter Level* (Pickles, 2016c) *and Ceiling Level* (Pickles, 2016b) and *Application of Part L of the Building Regulations to Historic and Traditionally Constructed Buildings* (Pickles, Brocklebank and Wood, 2017). The latest publications in the series, *How to Improve Energy Efficiency (McCaig, Pender and Pickles, 2018)*, advocates for a 'whole building approach' to energy efficiency improvements which is designed to:

- Avoid harm to the heritage significance;
- Provide effective, cost efficient, proportionate and sustainable solutions;
- Ensure a healthy and comfortable indoor environment for occupants; and
- Minimise the risk of unintended consequences.

Section 3 of *How to Improve Energy Efficiency* subdivides practical energy efficiency measures suitable for historic buildings into 4 sequential sections:

Understanding what you've got

> This pertains to assessing the building, its heritage value, current condition, occupancy patterns, heating systems, location, orientation and setting and so forth.

Green Actions (low cost/low risk)

> Green Actions are low cost/low risk energy refurbishment measures that should be considered for every building. Green measures may include reducing draughts, optimising natural light, insulating roofs at ceiling level, repairing renders and repointing mortars with permeable lime-based materials, and repairing or reinstalling thermal features such as internal shutters, thermal curtains and rugs.

Amber Actions (medium cost/medium risk)

> Amber Actions entail some cost and involve some risk and therefore should be considered on a case by case basis. Amber measures may include installing secondary glazing, replacing heating systems, insulating roofs at any level other than ceiling level, replacing render on external walls or plastering internal walls, insulating existing solid floors or draught-sealing suspended timber floors.

Red Actions (high cost/high risk)

> Red Actions should only be implemented after careful consideration and may not be appropriate for historically designated buildings. Red measures require careful design, correct materials, good detailing and extremely high standards of workmanship in order to avoid damage to the historic significance or fabric of the building. Great care must also be taken to avoid any moisture-related risks. Red measures may include insulated flat or low-pitched roofs, insulating solid walls internally or externally, replacing original window frames and glass, replacing existing solid ground floors and insulating suspended timber floors from above or below.

Historic England has also published several detailed energy refurbishment case studies through their Research Report Series. These cover design issues such as hygrothermal modelling (Baker, 2015; Browne, 2012), understanding the true U-value of historic building fabric (Rhee-Duvern and Baker, 2013; Rye and Scott, 2012) improving thermal efficiency through maintenance (Rhee-Duverne and McCaig, 2017), and mitigating moisture-related and unintended risks both before and after refurbishment (Rhee-Duverne and Baker, 2015; Historic England, 2014).

Further guidance on the energy refurbishment of traditional and historic buildings is provided by Historic Environment Scotland through a series of Refurbishment Case Studies, Technical Papers, Technical Advice Notes and Short Guides (Jenkins and Curtis, 2014; Jack and Dudley, 2012; Snow, 2012; Historic Environment Scotland, 2013; Currie, Williamson and Stinson, 2013); the Sustainable Traditional Building Alliance *Responsible Retrofit Guidance Wheel* (STBA, 2017); and European Standard EN 16883:2017 *Conservation of Cultural Heritage - Guidelines for Improving the Energy Performance of Historic Buildings (*European Committee for Standardization, 2017).

Numerous guidance documents have also been published on moisture-related risks of poorly designed or inappropriate energy refurbishment upgrades for historic and traditional buildings, including *Heath and Moisture in Buildings* (May, McGilligan and Ucci, 2017), *Moisture in Buildings: An Integrated Approach to Risk Assessment and Guidance* (May and Sanders, 2017), *Responsible Retrofit of Traditional Buildings* (May and Rye, 2012) and *Hygrothermal Risk Evaluation for the Retrofit of a Typical Solid-Walled Dwelling* (Arregi and Little, 2016). Specifiers should be aware of the risks and consult the appropriate guidance in tandem with the recommendations put forth by the Final Report.

Before any refurbishment works are undertaken, it is important to understand your building in terms of actual energy performance as well as historic significance. These two factors will determine the level of intervention that is required and permitted by the protection status of the building. Actual thermal performance of the building will be affected by its condition, maintenance schedule, effect of works over the years, orientation, whether it is sheltered or exposed to the elements, and so forth. Well maintained historic buildings often perform better thermally than expected, meaning post-refurbishment energy savings may be less than anticipated.

7.8 Relevant Standards

Table 19. General and building-specific LCA standards and guidance documentation.

Ref.	Title	Description	Publisher	Date	Type
1	BS EN ISO 14044:2006+A1:2018 Environmental management. Life cycle assessment. Requirements and guidelines.	Describes the practical implementation of 14040 standard.	BSI	2018	Standard
2	ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures	Establishes the principles and specifies the procedures for developing Type III environmental declaration programmes and Type III environmental declarations.	ISO	2006	Standard
3	BS 13790:2008 Energy performance of buildings - Calculation of energy use for space heating and cooling	Gives calculation methods for assessment of the annual energy use for space heating and cooling of a residential or a non-residential building, or a part of it.	ISO	2008	Standard
4	BS EN 15804:2012+A1:2013 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products	Gives guidance around core product category rules relating to Environmental Product Declarations (EPDs) for construction products and services	BSI	2013	Standard
5	BS EN ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework.	Outlines the requirements and principles involved in the LCA process for application generally to products and systems.	BSI	2006	Standard
6	BS EN 15978:2011 Sustainability of	Describes an LCA calculation method to	BSI	2011	Standard

	construction works - assessment of environmental performance of buildings - calculation method	estimate building environmental performance - can be applied to both new and existing.			
7	BS EN 16883:2017 Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings	Guidelines for improving the energy performance of historic buildings.	BSI	2017	Standard
8	PD 156865:2008 Standardized method of life cycle costing for construction procurement: a supplement to BS ISO 15686-5 Buildings and constructed assets - Service life planning - Part 5: Life cycle costing	Outlines a structured approach (with examples) to the whole life cycle costing of buildings and structures.	BSI	2008	Standard
9	PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services	Applicable to organizations assessing the life cycle GHG emissions of products.	BSI	2011	Standard
10	Publication C767: Minimising risk through responsible sourcing: a handbook for the construction industry	Guidance on assessing risks in construction procurement. Presents best practice on how to minimise social and environmental impacts. Covers sustainability, materials and labour.	CIRIA	2017	Guidance
11	Publication C695 Guide to sustainable procurement in construction	Guidance on sustainabile construction procurement including purchasing, relevance of BS 8903,	CIRIA	2011	Guidance

		planning and implementation.			
12	Guide to understanding the embodied impacts of construction products	How to assess the environmental impact of construction products over their life cycle, and what effect European Regulations and emerging European Standards will have.	Construction Products Association,	2012	Guidance
13	Green Guide to Specification	The Green Guide to Specification is a guide to which helps quantify the environmental impacts of building materials and systems. It contains over 1,500 specifications for several generic building types. First produced in 1996 it is continuously updated.	BRE Group	2019	Guidance
14	Life Cycle Assessment of Buildings: A Practice Guide	Practical guide for building professionals on use of LCA with online supports including technical guidance documents, building-related LCA resources and building-specific LCA tools or software.	The Carbon Leadership Forum, University of Washington	2018	Guidance
15	Whole life carbon assessment for the built environment	Provides a standard "whole life carbon assessment implementation plan and reporting structure" for buildings with the aim of improving the reliability of whole life carbon assessments in the construction sector.	RICS	2017	Guidance

16	BS EN 15978:2011 Sustainability of construction works - assessment of environmental performance of buildings - calculation method	Provides a calculation method for new and existing building environmental LCA. Involves defining object of assessment, system boundaries, inventory analysis methods, indicator choice and procedures for calculation, reporting and defining data needs.	BSI	2011	Standard
17	FB 85 Material resource efficiency in construction. Supporting a circular economy	Assesses the benefits of construction material resource efficiency on reduced costs and environmental impact across all construction project phases. Refers to existing tools and methods (including, for example, BREEAM).	BRE Group	2016	Guidance
18	Building Applications Guide BG 52/2013 Life cycle assessment: an introduction	Provides an introduction to LCA and outlines a structured approach to assessing the life cycle energy requirements and environmental impacts for application to buidling products, processes, assemblies, services and buildings.	BSRIA	2013	Guidance
19	Introduction to LCA of Buildings	Provides a high-level overview of LCA in the building design process and its implementation in practice. It is designed for use with building LCA tool, LCAbyg.	Danish Transport and Construction Agency	2016	Guidance
20	Embodied and whole life carbon assessment	Describes implementation of "Whole life carbon	RIBA	2017	Guidance

	for architects	assessment for the built environment" (RICS, 2017) over RIBA work stages			
21	Circular economy guidance for construction clients: How to practically apply circular economy principles at the project brief stage	Aimed at helping clients include sustainability in project briefs for non-domestic buildings. Consists of a set of high-level circular principles, presented to aid circular thinking and improve sustainability performance.	UKGBC	2019	Guidance

7.9 References

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