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Benchmarking the energy use of historic dwellings in Bath and the role for retrofit and LZC technologies to reduce CO$_2$ emissions

Francis Moran

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Architecture and Civil Engineering

August 2013

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Conan Doyle, Scandal in Bohemia:

“it is a capital mistake to theorize before one has data”
Abstract

Historic dwellings in the UK make up 20% of all homes and are amongst the most poorly performing part of the English housing stock in energy use terms, with the lowest SAP rating and highest average annual CO\textsubscript{2} emissions.

The degree to which proposals to retrofit the UK housing stock can reduce emissions depends on current energy use and CO\textsubscript{2} emissions. Current methodology relies on national aggregated statistics to provide average energy use data; historic buildings as a subset cannot be segregated.

In order to assess realistic carbon reduction potential it is vital that performance of historic dwellings is established from disaggregated data sources or with validated and stakeholder accepted models that can accurately prescribe energy use in an affordable, easy to use and transparent manner. This research attempts to begin such orthodoxy.

The benchmark derived in this study suggests that historic buildings in Bath use less energy than predicted by national, regional, and local average energy use, but they are not low energy dwellings. They therefore require retrofit adaptations to reduce CO\textsubscript{2} emissions. Procedures to assess the potential for such measures are of primary importance as some adaptations impact on both fabric and aesthetics. It is therefore imperative that the contribution such alterations make towards reducing CO\textsubscript{2} emissions can be weighed against the change they may make to our built heritage.

Using the Passive House Planning Package modelling tool, predictions of energy use were provided and validated against actual energy use. The model demonstrated accuracy in predicting energy used when incorporating a reduction factor to reflect intermittent heating patterns. The model was then used to assess the retrofit adaptation measures with a suite of measures incorporating renewable energy technology, delivering CO\textsubscript{2} emission reductions approaching 80%. This approach can be applied beyond the UK as the model permits the use of local weather data sets.

In establishing a benchmark of energy use in domestic historic dwellings, this work assists in developing suitable and effective solutions that are replicable and durable, permitting built heritage to meet UK emissions targets through the provision of empirical data to evaluate any alteration to fabric or aesthetics against the benefit of carbon savings.
A summary of publish research output is at Table 1.

Table 1  Summary Published research output.

<table>
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<th>Chapter in Thesis</th>
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<tr>
<td>Developing a database of energy use for historic dwellings in Bath, UK.</td>
<td>December 2012 Energy and Buildings Volume 55, Pages 218-226</td>
<td>10</td>
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| Accepted Papers |
|-----------------|----------------|

| Submitted Papers |
|------------------|----------------|
| PV in Historic Dwellings. | April 2013 Energy and Buildings Manuscript number ENB-D-13-00491 Recommended for publication 9/7/13 | 11 |

| Presented Conference Papers |
|-----------------------------|----------------|
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| The use of Passive House Planning Package to reduce energy use and CO₂ emissions in historic dwellings. | UK Passivhaus Conference November 2012.⁴ Paper available on line. | 12 |

¹ http://www.euromedheritage.net/euroshared/doc/ACTES_THE04.pdf (page 30)
² http://gse.cat.org.uk/papers
³ http://www.salford.ac.uk/energy/research/retrofit-conference/retrofit-2012-papers-day-2

A summary of contribution to current knowledge is at Table 2.
## Table 2  Contribution to current knowledge

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<td>Benchmark energy use</td>
<td>Data set of 102 dwellings and their actual delivered energy use and carbon emissions.</td>
<td>The benchmark produced facilitates assessment of the performance of historic dwellings in Bath, permitting categorising dwellings into high, average or low energy users. Demonstrates benefit of energy efficiency retrofit (low energy users). Establishes a base line from which to monitor future performance and to gauge the direct benefits of retrofit adaptations in the surveyed dwellings Assists in developing target priority for district wide energy efficiency retrofit. Provides real time data for the evaluation of retrofit adaptations, both in financial and emissions terms.</td>
</tr>
<tr>
<td>12</td>
<td>Modelling energy use with PHPP</td>
<td>Using PHPP to predict energy use in 3 case study dwellings with a comparison to actual energy use. Modelling retrofit adaptations on the same case studies showing that energy and emission savings of 80% can be achieved depending on the original “as built” state of the dwelling.</td>
<td>Provides an assessment of energy use of dwellings. Applying a reduction factor based on occupancy the result aligns with actual energy use. Provides empirical data to evaluate the benefit of decisions that affect fabric and/or aesthetics Assessing the potential reduction in carbon emissions in dwellings and facilitating economic prediction of likely savings. Weighing loss of fabric arising from alterations against reduction in energy use and carbon emissions.</td>
</tr>
<tr>
<td>11</td>
<td>Photo Voltaic in historic buildings.</td>
<td>Considers the use of photo voltaic roof mounted panels in 5 case study historic dwellings. Showed that an average reduction of 19% in carbon emissions is possible. With demand matching to PV output this can rise to 23%.</td>
<td>Questions current orthodoxy of the “fabric first” approach that only considers low and zero carbon technologies once all measures to reduce heat loss through the dwellings fabric have been implemented. Demonstrates an effective means to reduce carbon emissions which, if required is fully reversible to permit the dwelling to return to it pre PV state.</td>
</tr>
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Acknowledgements

In preparing this thesis my thanks is expressed, in no particular order, to the following:

Nicole Solomons at the Marches Energy Agency for useful advice in the design of Questionnaires.
Thanawit Bunsit for instruction on statistics, questionnaires and the use of SPSS.
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All of this work would not have arisen without acceptance and encouragement for my research proposal by Professor Maria-Lena Nikolopoulou and Dr Dina D’Ayala.

A special note of thanks goes to Dr Sukumar Natarajan for his support, guidance and perceptive observations and input while I have travelled the long and winding road to completing this thesis.
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</tr>
<tr>
<td>BANES</td>
<td>Bath &amp; North East Somerset Council</td>
</tr>
<tr>
<td>BIPV</td>
<td>Building Integrated Photo Voltaic</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture Storage</td>
</tr>
<tr>
<td>CFL</td>
<td>Compact Fluorescent Lamp</td>
</tr>
<tr>
<td>CDD</td>
<td>Cooling Degree Day</td>
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<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CIBSE</td>
<td>Chartered Institute of Building Services Engineers</td>
</tr>
<tr>
<td>CLGC</td>
<td>Communities and Local Government Committee</td>
</tr>
<tr>
<td>DPC</td>
<td>Damp Proof Course</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change</td>
</tr>
<tr>
<td>EHCS</td>
<td>English House Condition Survey</td>
</tr>
<tr>
<td>EnerPHit</td>
<td>Energy Retrofit with Passive House Components</td>
</tr>
<tr>
<td>EPBD</td>
<td>European Performance of Buildings Directive</td>
</tr>
<tr>
<td>EPC</td>
<td>Energy Performance Certificate</td>
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<tr>
<td>HDD</td>
<td>Heating Degree Day</td>
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<td>FFt</td>
<td>Feed in tariff</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>IAQ</td>
<td>Indoor Air Quality</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode, a low energy lamp</td>
</tr>
<tr>
<td>LZC</td>
<td>Low &amp; Zero Carbon technology</td>
</tr>
<tr>
<td>MVHR</td>
<td>Mechanical Ventilation Heat Recovery</td>
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<tr>
<td>NCM</td>
<td>National Calculation Method</td>
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<tr>
<td>PPPP</td>
<td>Passive House Planning Package</td>
</tr>
<tr>
<td>RdSAP</td>
<td>Reduced Standard Assessment Procedure</td>
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<tr>
<td>SAP</td>
<td>Standard Assessment Procedure</td>
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### Definitions:

**Carbon factor**: the amount of carbon emissions caused by energy use. Measured in units of kg carbon dioxide per kWh of energy use.

**Energy efficiency**: to use less energy to produce the same level of service or output.

**Fabric**: the structure of a building, primarily includes the external envelope but also extends to include all elements that make up a building.

**Retrofit**: the implementation of adaptations that reduce energy use, improve energy efficiency, reduce CO₂ emissions and lower energy costs.
Chapter 1 Introduction

1.1 Research Context

We are entering a new low carbon paradigm (Royal Academy of Engineering, 2010), as a result the current thrust for research is how to decarbonise the built environment (Oreszczyn et al., 2010). It is clear that CO₂ savings in the existing domestic sector could make a significant contribution to the overall reduction of national emissions (CLGC, 2008). To achieve this, the scale of change needed in the built environment over the coming decades dwarfs anything achieved historically, and must be brought about over a timescale of 20–30 years (Oreszczyn et al., 2010). This suggests a high degree of urgency is required.

In meeting the EU’s legal target of 20% reduction in CO₂ emissions by 2020 and the UK’s 80% reduction by 2050, the building sector cannot avoid playing a major part alongside transport and commerce/industry. The 2011 Carbon Plan (DECC, 2011) sets out that if the UK is to play its part in the global effort to combat climate change, we will need our buildings to be virtually zero carbon by 2050. This is a bold statement and does not specifically exclude historic buildings. Accepting that the majority of the future 2050 domestic housing stock has already been constructed (Lowe, 2007) and that historic buildings are an integral part of the urban landscape, their CO₂ emissions will also have to reduce along with more modern dwellings.

Since the era when historic dwellings were constructed, the way we should use energy has changed radically, particularly in the recent decade. To some extent we are still on the learning curve on how to construct/adapt dwellings to emit less carbon. Recent retrofit design trends have gone back to basics revisiting passive design for heating and cooling. Historic buildings already incorporate some elements, e.g. thermal mass and large south facing windows (generally), but their overall design is neither intentionally passive nor conducive to being low energy. Currently there is a push to dramatically increase insulation and reduce infiltration levels, even going as far as proposing the use of mechanical ventilation with heat recovery. The latter approach is currently receiving a high level of interest in state of the art projects.
At the same time as the drive to radically reduce energy use there is a view by parts of the conservation community that historic building should remain largely unaltered, and the solutions to reduce their energy use should centre on reducing occupants expectations of thermal comfort. This may be an unrealistic expectation. Resistance to an assault on all fronts to reduce energy use in historic building is understandable and any energy savings clearly needs to be balanced against changes to aesthetics and loss of fabric.

It remains to be seen if this approach is really suited to historic buildings, yet we have to explore ways to bring these buildings into line with the perceived performance of more recent construction. We are at the dawn of an era that will see buildings designed to benefit from abundant fossil fuel with open fires in every room, evolve into dwellings that as well as having lower levels of emission will suit future climate scenarios - whether that will be colder winters or hotter summers, or perhaps even both. It is unlikely however, given current and predicted fuel options, that they will be zero carbon.

Regardless of the level of energy use reduction, this will be achieved through using modern techniques for analysis and modelling to predict how historic buildings will perform following adaptations using a combination of a range of currently available techniques. There will then follow a trial period (we are currently in this phase) where no doubt some mistakes will be made as these techniques are reviewed and adjusted to research findings. This is an on-going process.

1.2 Aims and Objectives

The primary aim of this research is that without knowing the base line of performance it is difficult, if not impossible, to assess accurately potential energy use reduction. This creates a need to establish a benchmark of energy performance that can improve or perhaps even optimise the energy efficiency of each individual historic building.

In this lies the crux of the problem; each historic dwelling is different if not unique; each one starts from a different level and pattern of energy use. Combine this with occupants with different comfort criteria and energy budgets operating buildings that vary considerably in fabric construction and performance, buildings that will have been altered in a number of ways since construction, that have varying degrees of planning protection, that have occupant changeover at frequent intervals, coupled with a lack of clarity on future climate, uncertainty on future energy prices, varying financial incentives and possible reduction in the future carbon intensity of delivered energy, and the result is an unclear roadmap to low carbon historic dwellings lined with uncertainties.
Retrofit is the future; historic buildings cannot side step the pressing need to reduce current levels of carbon emissions in the domestic stock. There is therefore an express need for a tool that can calculate accurately, in a user friendly and affordable way, extant energy use. From here it is a short step to predict likely energy reductions following retrofit adaptations including low and zero carbon technologies (LZC). It is vital that such a tool is accepted as trustworthy by stakeholders whilst at the same time, is adoptable by architects and retrofit specialists, who will be at the forefront of implementing retrofit at a national scale. This is not an explicit goal of this research but remains an aspiration that will need to be resolved in the near future.

1.21 Research Objectives

The aims of this thesis can be summarised as:

- Establish benchmark of energy use in historic buildings.
- Assess potential software models to predict energy use and to evaluate the benefits of retrofit adaptations.
- Model predicted energy use and validate against case studies actual energy use.
- Model reductions in energy use and CO$_2$ emissions arising from retrofit adaptations.

1.22 Thesis Outline

The framework to achieve this is:

- Critical review with a focus on improving energy efficiency in historic buildings.
- Data collection on energy use.
- Establish benchmark and energy use data to model retrofit adaptations.
- Evaluate suitable modelling software.
- Review suitability of LZC solutions for historic buildings in Bath.
- Quantify energy use and carbon savings potential.
- Analyse and discuss results.
- Outline requirements for future work.
These can be broken down into three parts, see Figure 1.

Figure 1  Outline Methodology
1.3 Contribution to the field

The key contributions from this thesis are:

- Establishes a benchmark of energy use in historic buildings.
- Gives an insight to the variation in energy use in similar domestic historic buildings and the possible effectiveness in applying retrofit adaptations to reduce CO\textsubscript{2} emissions.
- At the forefront of using Passivhaus Planning Package software to model energy use in historic buildings.
- Quantifies CO\textsubscript{2} emissions reduction against the background of effect on building fabric and aesthetics.
- Provides empirical data on the effectiveness of PV in reducing CO\textsubscript{2} emissions in historic buildings.

1.4 Thesis content

Chapters 2, 3 and 4 together address the complexity of reducing energy use in domestic stock. Together they amount to a critical analysis of the domestic energy use, with a focus on historic buildings. As the chapters proceed the complexity and breadth of this field will emerge. Recent research will be highlighted to show effective methodologies and the potential to reduce emission, in doing so gaps in knowledge are revealed that are collated in Chapter 13 (future work). Throughout these introductory chapters **markers will be placed** that will shape both the research question and the methodology to answer them as well pointing to other areas of research that are also needed to fill gaps in current knowledge.

**Chapter 2:** this sets the scene for energy efficiency in historic buildings and why there is a need to research this topic. It moves from the wider EU context to down to the City of Bath and why it is suitable as a research area. Reasons are given why we should persevere with this building group and not simply demolish them and start again, even in the face of a number of constraints.
Chapter 3: this chapter begins with climate change, moving from the broader scientific concerns to issues that affect decisions that need to be taken in the very near future and reviews the challenges this presents. The issue of what climate to prepare for and future carbon factors are explored; this suggests challenging current orthodoxy regarding prioritising actions for reducing domestic carbon emissions. Retrofit options for historic buildings are reviewed; this paints a complicated picture with many constraints for historic buildings. One clear observation is the urgent need for a usable, inexpensive, user friendly and effective means to deliver data upon which energy efficiency retrofit decisions can be made.

It concludes by establishing actual carbon emissions for Bath and in doing so highlights the scale of the problem for this heritage city.

Chapter 4: considers the potential to reduce carbon emissions in historic buildings. It touches on occupant behaviour and the carbon content of primary energy. The central focus is on retrofit adaptations and energy efficiency. It attempts to set retrofit in the wider heritage context, suggesting we are moving to, if not already in, a new era, one which may be a paradox, namely an era of low carbon historic buildings.

Chapter 5: provides a succinct summary of the complete critical analysis and concludes with the adopted research questions developed from the gaps in knowledge identified in the review of current orthodoxy.

Chapter 6: outlines the adopted methodology.

Chapter 7: deals with model selection to aid retrofit in historic buildings. Having selected the model explanations are given on a number of made assumptions.

Chapter 8: considers the range of LZC technologies and their suitability for historic buildings in the City of Bath.

Chapter 9: outlines the proposed retrofit adaptations and groups them for a three stage model analysis.
Chapter 10: this is a key chapter and deals with establishing a benchmark of energy use in historic buildings. This chapter has been published as a paper (December 2012) and is attached at Annex C.

Chapter 11: following selecting Photo Voltaic as a suitable LZC technology (in Chapter 9) further work was initiated to examine how this affects carbon emissions in case study dwellings. This chapter forms a paper that has been accepted by Elsevier Energy and Buildings, the submitted paper is at Annex D.

Chapter 12: this brings together Chapter 9, 10 and 11; it takes three case study dwellings and predicts energy use using both dynamic simulation and steady state analysis. It assesses these models against actual energy use from the benchmark survey. The chapter then continues with the Passivhaus Planning Package to assess retrofit adaptations to determine carbon emissions reduction potential. These results form a paper that has been accepted by Elsevier Energy and Buildings, the submitted paper is at Annex D.

Chapter 13: Conclusions and Discussion includes a critical analysis and contribution to the field of energy use in dwellings. Target areas for future research are also listed.
Chapter 2 Historic Buildings

The aim of this chapter is to outline the context why historic buildings should be firmly within the study of reducing carbon emissions in the domestic stock both in EU as well as the UK due to the distribution of buildings by age. The intention is to demonstrate why historic buildings should be studied and why the City of Bath is a suitable research location.

2.1 Historic or Traditional Buildings

Whether to use the term “historic” or “traditional” to define these buildings is not fully defined with stakeholder and research fields. There is no real clarity on the terms historic/traditional when referring to buildings. English Heritage uses the term both historic and traditional interchangeably when discussing older homes (Energy conservation in traditional buildings, 2008). Building Regulation (Part L1b, 2010), uses the term traditional building as a “construction with permeable fabric that both absorbs and readily allows the evaporation of moisture”. The Northern Ireland Environment Agency and the National Trust use the term historic building.

Regardless of the allotted typology name they are a finite and non-renewable asset that defines local landscape and creates a sense of place. The aesthetic properties of these buildings contribute to the culture and economy, both locally and nationally. In Bath, it is a particularly valuable asset that is recognised through its World Heritage status since 1987.

The term “historic” may be considered to imply a facet to the building that is of importance, this could be architectural features, characters/organisation associated with the building, its association with historic events or simply the materials used. The term historic building can also be indicative of architectural heritage and the building stock in general (Hasslar et al., 2002). Hasslar goes on to say that in the context of domestic dwellings their quantity, quality and diversity make them effectively a non-renewable resources, suggesting their retention for future generations.
Traditional can be defined as existing or part of something long established, whereas historic is something famous or important in history.

The term “historic building” as opposed to “traditional building” was chosen to address those dwellings that are constrained in their freedom to incorporate CO$_2$ emission reduction interventions. It also includes dwellings constructed using traditional building techniques and materials.

Chronologically, they can be defined as all buildings constructed prior to 1919, as this is the date generally accepted for the introduction of damp proof courses (DPC) and cavity wall construction in the UK (English Heritage, 2008). This research uses this definition though it is noted that there remains a large portion of the 1920-45 stock (the exact amount is unknown) that has the same characteristics (solid wall and no DPC) as the use of cavity wall construction only became widespread after 1945. Using the date of 1919 wholly focuses on solid walled buildings constructed with a permeable fabric that both absorbs and readily allows the evaporation of moisture; this suggests that retrofit adaptations should be sensitive to the natural movement of moisture in and out of this structure type.

The built heritage existing today has led to a body of conservation stakeholders concerned with the protection of the historically important fabric and aesthetics of historic buildings.

The notion of cultural heritage has been extended gradually from individual buildings to the architectural heritage and the building stock. An indication of the significance for historic buildings can be attained from Figure 2; this shows the EU distribution of dwellings by age.
The UK has the highest concentration of historic buildings with pre 1919 buildings making up 21.5% of the UK housing stock (Figure 3). They are solid walled, single glazed, a mixture of solid and suspended timber floors, with or without cellars/basements, inaccessible roof voids are not uncommon, can be high value properties and are nearly always difficult to treat to reduce energy use and CO₂ emissions. Add to this the high element of solid wall structures in the 1919-1944 stock and traditional buildings makes almost a 40% of the housing stock. In view of this, a simple analysis of the sheer numbers suggests that any proposals to reduce CO₂ emissions from our homes will have to include both historic and traditional dwellings.
A more tangible definition of historic buildings is provided by the Building Regulations (CLG, 2006):

a. Listed buildings.

b. Buildings situated in conservation areas.

c. Buildings of local architectural or historical interest referred to as a material consideration in a Local Authority's development plan.

d. Buildings within National Parks, areas of Outstanding Natural Beauty and World Heritage sites.
In Bath all four definitions apply, see Figure 4.

Grade I Listed

Grade II Listed
In the UK, a listed building is a building or structure which is considered to be of special architectural or historic interest. There are approximately 374,000 entries in the Listed Buildings Register in England, making up about 2% of the total building stock (English Heritage, 2010). This is not a large subset and the distribution varies.
Bath and North East Somerset Council (BANES) has around 5,000 Listed Buildings, 4,200 of which are in the city of Bath (BANES, 2004) accounting for 11% of the city’s building stock. The higher concentration presents challenges for the BANES carbon reduction plan if it is to meet the same levels of reductions as the rest of the UK.

According to the definition provided by the Town and Country Planning Act (1990), Conservation Areas are those areas that have been identified as having:

“Special architectural or historic interest, the character or appearance of which it is desirable to preserve or enhance” (Section 69).

Of the 25 million residential dwellings in Great Britain (English House Condition Survey, 2007) Bottrill et al. (2005) estimated that there are approximately 1.2 million residential dwellings in Conservation Areas, comprising almost 5% of Great Britain’s total housing stock and 24% of the historic housing stock. The aesthetic considerations of Conservation Area housing stock can limit the potential for reducing energy requirements and implementing low carbon technologies (Moorhouse et al., 2012) in historic buildings. This can be a frustration to home owners who have aspirations to reduce their energy bills in line with other home owners.

Boardman (2007) takes a view that may be considered more pragmatic, stating that the heritage debate is important but at the same time questioned whether the listed residential buildings and homes in conservation areas, which together amount to 5% of the UK domestic stock, are sacrosanct. This misses the point, in that historic buildings are more than just listed buildings or dwellings in conservation areas. The House of Commons Communities and Local Government Committee report on Existing Housing and Climate Change (2008, p43) sums up succinctly the role of historic buildings in England:

“Approximately one in four homes in Britain were built 90 years or more ago, long before Carbon Emissions Reduction Targets, Building Regulations and Energy Performance Certificates were thought of. England has more than 370,000 listed buildings and a further one million unlisted buildings standing within 9,734 conservation areas. Beyond those buildings stand a further 4 million plus built before 1919, which, even if they are of no special architectural or historical interest, are often among the most prized and aesthetically attractive in the country, even if they are among the least efficient in terms of energy or carbon emissions.”
The importance of this view is linked to the lack of clarity regarding which and how many properties should be labelled ‘heritage’. Only one quarter of pre-1919 homes in the UK are in conservation areas or listed, but discussion from key stakeholders (plenary session, Towards a Green Heritage, 2009) suggested that almost all properties from this age band should be preserved as being of historical value to built heritage even though they have no protected status. This is of importance because the debate on heritage will influence the extent to which these homes can be retrofitted, in particular those measures that affect aesthetics and fabric.

2.2 Should historic buildings energy efficiency be improved?

There is perhaps a perception that the conservation community are resistant to change and that they promulgate the view that historic buildings should remain largely unaltered. No evidence was found to directly support the view that historic buildings should remain unchanged.

It is more likely that this view has been misinterpreted from stakeholder’s views that some assessments of energy use are based on theoretical models and produce results that often conflict with actual measurements, and, if such results are followed it may lead to unnecessary and potentially damaging interventions (English Heritage, 2014; SPAB (Society for the Protection of Ancient Buildings), 2014).

It may also stem from the view that energy performance of historic buildings is better than we are led to believe (English Heritage, 2009; SPAB, 2012; Sustainable Traditional Buildings Alliance (STBA), 2012), if that is the case then they may not be in urgent need of significant energy efficiency improvements.

There is also a preconception that occupants of historic buildings should lower their expectations of thermal comfort standards. Whilst the advice to “wear a jumper and turn the heating down” has been given (SPAB, 2011; Bath Preservation Trust and the Centre for Sustainable Energy, 2013) wearing additional clothing is no longer a main principle of reducing energy use in the home although it is possible that “future increased energy costs will nudge clothing customs in that direction” (Historic Scotland, 2011).

But there is more to thermal comfort than adequate clothing. A recent paper by Historic Scotland (2011) examines ways of providing thermal comfort without heating homes to modern standards (21°C in the main living area and 17-18°C throughout the rest of the dwelling (internal temperatures are discussed more fully in section 12.37).
The report proposes that the interior be maintained at a background temperature of 16°C and appropriate local supplementary heat-sources be provided, when and where desired, usually in the form of a radiant heater. The report summary concludes that creating thermal comfort with background heating and local supplementary warmth should more often be considered as a heating strategy, instead of relying only on technical upgrades of the building fabric and services.

Whilst the report acknowledges that modest background temperature with local supplementary warmth could create good thermal comfort (this has yet to be borne out by further trials and user feedback) and make energy savings compared with heating the whole interior to a temperature normally expected today, it cannot deliver alone the level of reduction in energy use to meet climate change targets.

English Heritage (2012) supports thermal upgrading of historic buildings provided it is carried out sympathetically and where proper assessment is carried out and documented. However, “reducing carbon emissions from buildings is not just about heating and insulating the building fabric. English Heritage (2010) takes the view that much can be achieved by changing behaviour, avoiding waste, using energy efficient controls and equipment, managing the building to its optimum performance, all of which is as relevant to older buildings as new ones”.

Cassar (2006) made the point that counters a resistant to change attitude, in that as historic buildings have undergone several extensive modifications during their lifetimes why should we be concerned about further changes. Particularly, as there is now a well-established framework to protect, review and regulate changes to historic building.

The publications over the last 5 years demonstrate that it is possible to reduce energy use and carbon emissions in historic buildings without compromising their historical and architectural character (Changeworks, 2008; English Heritage, 2012; Historic Scotland, 2012; SPAB, 2012; National Trust, 2009; STBA, 2012).
2.3 The City of Bath

In 2004, the city of Bath (separate but contained within the council district of BANES) had 37,600 dwellings (BANES House Condition Survey, 2004) with a population of almost 86,897 habitants (Office for National Statistics, 2010). Unlike listed buildings whose historic and/or architectural importance is measured by national criteria, conservation areas are determined at the local level. The extent of the conservation area in Bath is extensive, covering 75% of the City, see Figure 5.

Figure 5  Map City of Bath

Accessed 12/9/11

The implications of this is that a significant number of buildings will be subject to restrictions in introducing CO₂ emissions reduction interventions, although the planning constraints arising from being located within a conservation area are far less restrictive than those arising from a listed status.

The distribution of dwellings by age is at Figure 6. This shows that Bath has a higher than average concentration of pre 1919 dwellings, having 30% of all dwellings constructed before 1919 compared with the UK average of 22%.
The significantly higher proportion of pre 1919 buildings compared to the rest of England supports using Bath as a case study for this work.

In Bath, the Georgian period has left an urban scene that is effectively irreplaceable, whose status is protected and maintained by local and national planning regulations, as well as international restrictions arising from World Heritage status. This places constraints on retrofit adaptations for historic buildings that affect aesthetics and fabric. What is not known is the extent to which this will limit the potential for retrofit CO₂ emissions reduction adaptations.

2.4 Summary

This chapter has given a definition for historic buildings although our built heritage extends well beyond this classification. Data was presented to support and promote the study of historic buildings at both the EU scale and within the UK where there is the highest density of historic buildings.

Statistics for the City of Bath make a case for studying this city not only due to the high incidence of historic buildings, but because there are a number of constraints arising from World Heritage status, high numbers of listed buildings and a conservation area that covers 75% of the city.
Chapter 3 Carbon Emissions in the UK

The aim of this chapter is to outline the current status of energy use and carbon emissions in historic buildings and to place them within the wider field of the building stock. This will demonstrate the perceived contribution historic buildings make to CO₂ emissions through their energy use and how they compare with other buildings regarding energy efficiency.

At the outset climate change is considered. It moves from the broader scientific concerns to issues that affect decisions that need to be taken now (or at the latest in the very near future) and reviews the challenges this presents. Questions of what climate to prepare for, coupled with the future trajectory of energy carbon factors, are considered.

The question of whether historic buildings are energy efficient is considered. This is partly answered with data on their carbon emissions and where they arise within the home. The current high carbon factor of grid electricity suggests challenging current orthodoxy that centres on a fabric (heat) first approach first to reduce energy use.

Retrofit options for historic buildings are reviewed. In essence this is complicated and although solutions are known, the path to low carbon historic buildings is less clear. Part of the solution is an urgent need for data on actual energy use.

An equally essential component is the identification of a usable, inexpensive, user friendly and effective means to deliver data upon which energy efficiency retrofit decisions can be made.

The chapter concludes by establishing actual carbon emissions for Bath and in doing so provides additional evidence for using the City of Bath as a case study.

3.1 Climate change and current emissions

There is clear scientific and political consensus that climate change is the greatest long-term challenge facing the world. The Fourth Assessment Report by the Intergovernmental Panel on Climate Change (2007) confirms the urgency of the problem and states clearly that the principal cause is the rising concentration of CO₂ in the atmosphere, mainly because of humanity's growing use of fossil fuel (Royal Commission, 2000).
UK climate policy is based on advances in climate science and evidence of Greenhouse Gas Emissions and is aimed at limiting a global rise in temperature to 2°C and a low probability (less than 1%) of a 4°C increase (DECC, 2009). This review does not include what other research has amply covered as to why we need to reduce CO₂ emissions. The body of work is such that the need to tackle climate change is now accepted knowledge. Rather, it accepts that the UK building sector will have to make a contribution to tackling this challenge, alongside the sectors of transport and commerce/industry. What is unsure is what future climate scenarios we should plan to expect.

The building sector accounts for 40% of the EU’s energy. The European Council adopted in 2007 ambitious energy and climate change objectives for 2020 – to reduce greenhouse gas emissions by 20% (Energy 2020, 2011). It also gave a long-term commitment to the decarbonisation path with a target for the EU and other industrialised countries of 80-95% cuts in emissions by 2050 (Energy 2020, 2011).

In advance of this approach the Climate Change Act of 2008 commits the UK to reducing carbon emissions by 80% by 2050 against 1990 levels. Lowe (2007) puts the problem of climate change in stark terms, identifying only two issues:

1. The scope for reducing CO₂ emissions.
2. The time scales to achieve this reduction.

Unfortunately this over simplifies the challenge we are facing. For example, Gaterell and McEvoy (2005), point to the uncertainty of what scenario to prepare for in terms of future climate. Based on current climate change scenarios, UKCP 09 (Jenkins et al.) and UK Climate Projections (Murphy et al., 2009), predict that SW England (Bath) will experience a rise in annual average temperature of between 2 - 4°C by 2080. More importantly, the findings highlight the challenge in identifying appropriate measures now that will remain effective under the widest range of climate uncertainty.

This raises the question: should we continue to improve the efficiency of heating dwellings in winter or would it be more beneficial in CO₂ emission terms, to take heed of climate change scenarios showing that increased temperatures in the future? This is likely to create a growing demand for cooling, prompting a move to air conditioning to provide summer comfort. This is important because cooling mainly uses electricity (whereas most heating in the UK is currently provided by gas), which as an energy source is currently more than twice as carbon intensive as gas, and it is this aspect that may lead to increased overall CO₂ emissions (Day et al., 2009; Li et al., 2012; Gupta et al., 2012).
An observation here is that any possible demand for electrical cooling would align with the output of installed photo voltaic systems. Data shows that there has been a steady rise in annual cooling degree days (CDD) since 1960, see Figure 7.

There is an alternative approach here. That is to consider the high thermal mass of historic buildings and how this parameter can be utilised to limit the effect of increased future heat gains. This is an important area of further work, particularly as internal wall insulation, if adopted, dislocates part of the buildings thermal mass.

The increase is greatest in the South East; in Bath (South West) it is 18%. This figure for the South West may be an underestimate as the data shows that CDD’s have plateaued in the South west since 1988, whereas the majority of the England has seen a steady increase.

Figure 7  UK Cooling Degree Days
http://ukclimateprojections.defra.gov.uk/23049
Accessed 06/01/13 © Crown Copyright 2009
In line with increased CDD’s, annual heating degree days (HDD) have reduced by 15% in the South West since 1960, see Figure 8. Contrary to future predictions, for now at least, cooling energy use may not be a concern. Collins et al. (2010) states that demand for gas will reduce by 20% by 2050 without any alteration to the existing stock (simply due to warmer winters). Even if a shift to higher incidence of domestic cooling developed, work by Bell (2004) shows that by 2050 heating will still be the largest source of emissions in the home.

Figure 8  Heating Degree Days

http://ukclimateprojections.defra.gov.uk/23048
Accessed 06/01/13 © Crown Copyright 2009

Figure 8 also shows that the variation in climate across the UK, with a difference approaching 40% in HDD’s (CIBSE, 2006) from the north to the south. This may mean more stringent solutions in northern dwellings to meet the same energy use targets.

Regardless of the likely effects of future climate change, English Heritage Report England (2008) takes the view that:

“it is possible to respond to climate change and improve the energy efficiency of older buildings without destroying their distinctive character and value”
While using emotive words this statement is useful in that it acknowledges that there are options to reduce carbon emissions in heritage buildings, although there is no indication of what would be acceptable levels of reduction in overall energy use, and what alterations to built heritage would be suitable.

Kelly (2009) considers that there is already enough scientific evidence (regarding predicted climate change) to provoke us into action. But there is no clear plan or policy for domestic dwellings. The absence of this gives way to the temptation to follow every possible action; this does not always bring the desired effect. Examples are first generation biofuels (Laney, 2006) and the inappropriate use of micro wind turbines in urban areas (Encraft, 2009). It may be possible to add air source heat pumps (if they are inappropriately fitted to poorly insulated and high infiltration dwellings) and biomass boilers (there is no general agreement on the carbon cost of biomass fuel and there are also concerns regarding emissions) to this list; this is considered further in Chapter 8.

In the case of historic buildings there is debate on the long term performance of external walls following internal wall insulation, particularly where the equilibrium of moisture movement through walls is restricted and overall wall temperature is reduced. The debate centres on the concern that there is the possibility that actions attempted in haste, though well intentioned, may have long term negative effects in terms of our built heritage. This must be avoided, yet action is required. It raises a question, namely, should we be prepared to make mistakes in attempting to increase our knowledge before rolling out solutions at the district scale.

3.2 Carbon Factors

Domestic emissions are not only a function of energy use; it also depends on the carbon factor of the energy use. Here there is uncertainty, as it is unclear what the effect on CO₂ emissions will be as the carbon intensity of gas and electricity will change in coming decades. Recent trends for electricity have been in a slight downward direction, see Figure 9, although they have plateaued for the last decade.
It is likely though, given current renewable energy targets, that electricity will see the greatest reduction in carbon intensity in the coming decades, see Figure 10, but this is not guaranteed (current predictions seem very ambitious and are likely to be reliant on developing Carbon Capture and Storage (CCS) in the UK).
The carbon factor for electricity will influence certain LZC carbon technologies and their ability to displace grid electricity. An example is micro CHP (Combined Heat and Power) which is emissions economic at a high carbon factor, whereas heat pumps are more likely to be emissions economic as the carbon factor of electricity decreases.

The future carbon factor for gas shows less reduction, see Figure 11, gas is shown as non-electricity.

Figure 11  Historic and projected carbon intensity

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This shows that in the coming decades a small decrease in the gas carbon factor is expected. More importantly it shows grid parity between domestic gas and electricity in 2025. This is only 11 years away and would seem to be a very challenging target.

The prospect of grid parity of electricity with gas raises questions, regardless of when it is achieved, as the life of a gas boiler is 10-30 years, see Figure 12. This suggests that in the very near future, decisions of plant choice to provide heating will be influenced by changes to the carbon factor of the fuel it uses during its lifetime (something that we have not considered previously), the impact of which may see an increased reliance on electric heating as this will result in lower overall emissions. This is an area that is suitable for further detailed research.
Given the duration of this plant, and that gas efficiency (seasonal) is in the region of 80-90% for a condensing boiler (electricity efficiencies approach 100% from delivered energy), it may mean switching to electricity several years ahead of grid parity otherwise gas boilers will emit higher CO₂ emissions than simply using electric heating (most likely heat pumps) mid-way through their expected life expectancy.

3.3 Reducing Energy Use

As CO₂ emissions are the product of using energy coupled with the carbon intensity of that energy, the approaches to reduce them are clear. Either use less energy to maintain present comfort and service levels (in other words improve energy efficiency) or reduce/eliminate the carbon content of the energy by improving generation efficiency and/or shift to low carbon sources.

To a large extent reducing energy use, improving energy efficiency and reducing CO₂ emissions are aligned, if a dwelling uses less oil, gas or electricity (from fossil fuel sources) it will emit less CO₂. The introduction of micro renewable energy technologies distorts this picture as although they may be low or zero carbon they do not necessarily imply a reduction in energy used. So, it is possible for overall energy use to remain unchanged (or even increase), while total CO₂ emissions are reduced.
This is a reason to move directly to considering only CO₂ emissions when looking at domestic energy.

Regardless of the level of energy used, routes for action can be summarised to:

1. Demand reduction (do we need the lights on?).
2. Convert energy into comfort with minimal waste (e.g. a low energy light).
3. Use low carbon energy (e.g. renewable/decentralised energy generation).
4. Influence occupant attitudes to energy use (e.g. energy meters and energy price).
5. Reduced service levels (wear more clothing?).
6. Decarbonisation of grid gas/electricity before delivery (Government policy).

All but the last are applicable at the local scale, and to some extent they help achieve the last by reducing/managing demand. The application of 1-4 above can be considered retrofit. The term retrofit in the context of reducing energy use and CO₂ emissions is the implementation of adaptations that reduce energy use, improve energy efficiency, reduce CO₂ emissions and lower total energy costs.

Reduced service levels are an area that sees the meeting of the conservation of buildings and the conservation of energy. There are two opposite views. From a stakeholders point of view the priority is the preservation of the historic building stock through minimal loss of fabric and visual aesthetics through straightforward and reversible measures such as additional roof insulation, efficient boilers, low energy lights, window shutters and curtains, draught proofing, good controls and low background heating temperature. On the other hand there is the occupants desire to reduce energy bills and provide healthy comfortable living conditions.

The central premise of reduced service levels is achieving thermal comfort with significant reduction in energy costs through radiant heat sources while maintaining the remainder of the dwelling at a lower overall background temperature (Humphreys et al., 2011). There is still work required to further develop the effectiveness or even acceptance of such an approach:

1. Thermal simulation to predict savings.
2. Development of suitable radiant heating devices.
3. System development and associated controls for background heating.
4. User experience/acceptance.
However, within these approaches is a complex pattern of interconnected factors, which are expanded by Summerfield et al. (2009), see Figure 13.

Figure 13  Factors affecting domestic energy use
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The reality is further complicated as this illustration does not show constraints such as planning issues, access to finance, short term residency, tenure type, or on the positive side, the contribution Low and Zero Carbon technologies (LZC), controls, home energy monitors and smart metering\(^1\) can make, see Figure 14.

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\(^1\) A smart meter, primarily for electricity use, is a two way communication unit between the consumer and the supplier. It can provide real time energy consumption information to benefit the consumer who will be aware of the energy use, and suppliers who can manage/develop network supply in a more cost effective and carbon efficient manner.
Despite the complexities, there are a range of available adaptations; the buildings age regarding technical performance can in certain instances be irrelevant as techniques applicable to the recent stock perform for the most part equally well within historic buildings (e.g. efficient boilers, loft insulation, low energy lights and draught proofing). However, some options are contentious in terms of their effect on either aesthetics or fabric alteration/performance, examples are:

- External/internal wall insulation (aesthetics/interstitial condensation/fabric decay).
- Floor insulation (fabric damage).
- Building mounted renewable energy technologies (fabric damage/aesthetics).
- Double/secondary glazing (fabric damage/aesthetics).
- Low infiltration rates (occupant health/fabric decay).
- Mechanical ventilation heat recovery systems (fabric alteration).

Figure 15 shows a summary of current retrofit options with a weighting for impact on fabric and carbon emissions reduction potential.
There are also unique factors appertaining to historic buildings such as the state of conservation, the performance of the fabric, traditional original components such as windows and doors, lack of access to parts of the structure, restrictions arising from what degree of our built heritage should be preserved and planning constraints that vary depending on the building classification and location in the UK. These all have to be considered in order to develop compatible solutions that can meet both energy efficiency and fabric conservation/protection.

Figure 16 shows a 450mm roof void over a first floor bedroom in an 1850’s dwelling. The ceiling is original lath and plaster and the roof has a lead covering. There is no insulation present. What are the options in such instances? Take down the ceiling plaster and insulate whilst maintaining ventilation to the underside of the roof? Lift the roof covering and construct a warm roof? Spray in insulation but how to guarantee complete coverage and maintain ventilation? The answer will, of course, depend on a range of factors including fabric condition, cost, the degree of disruption permitted, other works being carried out and any relevant planning and building regulation constraints.
Such issues are more sensitive in listed buildings than in conservation areas, yet there is much that can be done to reduce energy use that is not contentious, e.g. draught proofing sash windows and external doors, installing appropriate levels of insulation in roof and floor spaces, efficient heating boilers, effective heating controls and low energy lighting and influencing occupant behaviour. But these measures alone make only partial progress towards the ambitious 80% CO$_2$ emissions reduction target.

LZC can help bridge this gap (Jenkins, 2012). It is worth noting here that heritage stakeholders are not anti-low carbon technology, the Heritage Counts Report (English Heritage, 2009) promotes the use of micro renewable energy in the historic environment without harming its character. However such adaptations alone are also unlikely to bring about the scale of CO$_2$ emissions required to meet the overarching need to tackle climate change. This demonstrates what is widely known; that there is no individual solution to this problem and that the incremental contribution provided by individual adaptations can collectively make a sizeable reduction in energy use.
Whilst the research available covers a wide range of building typologies there remain areas of uncertainty with regard to historic buildings. There is little evidence to show the net affect that energy reduction interventions would have on reducing the CO$_2$ emissions from historic dwellings in particular. This situation is exacerbated by the paucity of real data on current energy consumption to accurately predict energy savings. Furthermore there is uncertainty on long term fabric hygroscopic performance, particularly when insulating walls, internally or externally. This is an area worthy of further detailed research.

Jenkins (2012), using the TARBASE model, reported CO$_2$ emission reductions approaching 80% in historic buildings, but only following application of an extensive suite of retrofit adaptations involving LZC technologies. Although reporting the results as total CO$_2$ saved rather than normalising for floor area, the results are positive. This methodology shows potential, yet the experience in England at producing low energy buildings, new or retrofit, consistently delivers buildings that consume more energy than the design suggests (from observation). Furthermore, a lack of accurate post occupancy reporting on the performance of buildings (Gething and Bordass, 2006) highlights the difficulty in effectively retrofiting the entire housing stock.

Achieving such demanding reduction targets (80%) will be dependent on the amount and pattern of extant energy use. This is challenging as high-quality empirical evidence on the actual performance of our existing building stock has been largely absent from the debate to date (Oreszczyn and Lowe, 2010). This is a gap in current knowledge. The reality is that there are little benchmark data on traditional and historic buildings energy use.

This downside is now recognised, Oreszczyn and Lowe (Lords, 2005) who have for some time considered that the monitoring of the energy performance of the built stock should be based more on real delivered energy and stock data rather than inferred data. The Royal Academy of Engineering (2010, p18) have restated this approach: “it is essential for the establishment of benchmarks and standards……and the validation of new designs and techniques”.

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A benchmark can provide the following:

- Convey to designers performance targets for dwellings based on surveyed data.
- Convey to occupants how much energy a dwelling uses.
- Facilitate comparison to local aggregated data.
- A means to influence occupant behaviour by providing comparison to similar properties.
- Target appropriate retrofit measures that reflect occupancy patterns and dwelling performance characteristics.
- Assessment of the benefits arising from retrofit adaptations to occupants, designers, suppliers and installers.
- Prioritise where to direct resources to bring about the greatest carbon emissions reduction.

Historic dwellings as a subset of housing have received even less attention and there is little information on their actual performance. This therefore suggests a research question to establish energy use benchmarks for a selection of historic dwellings and to use existing tools, if suitable, to measure and quantify the CO₂ emissions reductions possible following technical retrofit interventions. This is necessary, because without the consolidation and assessment of current energy use, the scale of possible CO₂ emissions reduction from retrofit intervention cannot be evaluated.

This view is also supported by English Heritage (2009) which considers high-quality research to deepen our understanding of how to make historic buildings more energy efficient as a means to facilitate the historic environment sector to meet the challenges of climate change. This is an area that is gaining attention yet there remains no comprehensive academic output in this field.
In response, English Heritage (2009) has begun a long-term research programme called ‘Hearth and Home’². This includes a broad programme of research, practical advice and policy development. It remains to be seen how effective this will be as the declared intent is to use the findings to inform English Heritage’s advice on improving the thermal efficiency of such buildings without compromising their architectural and historic significance. This suggests that the potential for emission reduction may be less than optimal.

Although we may not be entirely sure of the best route ahead for historic buildings with regard to reducing the energy use, it has been recognised for some considerable time that using relatively easy and cost-effective strategies are key (Rogers, 1974 & 1975). In the intervening period, this view has been further supported by numerous studies that have shown with increasing levels of accuracy, the extent of energy efficiency that is achievable in our homes (Johnston, 2005; Natarajan et al., 2007).

Yet, inaction remains. Though many of the technological solutions are available and well understood they are often not applied (Bell, 2004). The question as to “why not” is not answered, but Bell (2004) argues that Building Regulations offer a route to improve this by using the trigger point of building works to improve energy efficiency at a marginal cost.

Given the sheer number of historic buildings, this laissez-faire approach is not succeeding as most buildings may never have to apply for building regulation approval. Even if this were not the case, until recently, the UK had some of the most lenient regulations in northern Europe (Lowe et al., 2008). This suggests an alternative approach is required, but beyond a declared recognition of the problem (Thorpe, 2010), there is currently no firm policy in place on how to upgrade and retrofit the entire existing housing stock (at the time of writing the “Green Deal” ³ has recently been implemented).

² The Hearth and Home project will monitor the energy usage of a group of occupied Victorian terraced homes to work out best practice in measuring energy efficiency, to evaluate the cost-effectiveness of energy-saving options, and to provide guidance on measures to reduce domestic fuel usage and carbon emissions.

³ The “Green Deal” is the UK coalition Government’s flagship carbon emission reduction policy. The purpose of the Green Deal is to encourage as many people as possible to take up measures to make their homes more energy efficient.
3.4 Carbon Emissions and Historic buildings

It is recognised that historic buildings have both advantages and disadvantages:

Advantages:

- Locked in embodied energy.
- Built with sustainable materials.
- Natural hygroscopic performance for controlling/buffering moisture levels.
- Build quality can be good.
- High thermal mass - can mitigate summer overheating.
  - good for continuous heating pattern.
  - passive design to capture solar gain.
  - not all in external walls (i.e. large solid internal walls).
- Aesthetics and cultural value generally appreciated.
- Flues can help with night purging for cooling/MVHR routes.

Disadvantages:

- Quality of stone in external walls varies.
- High thermal mass - slow to heat up with intermittent occupancy.
- High levels of infiltration (draughts).
- Large windows on all elevations (generally).
- Rooms in roofs with little or no insulation.
- Parts of structure difficult to access to upgrade, e.g. parapet roofs, bay window roofs.
- Open flues that increase infiltration.
- High ceilings.
- Large floor areas.
- Planning restrictions for alterations.
- Their historic nature can make repairs/improvements expensive.
Boardman’s (2005, 2007) response to achieve large reductions in CO₂ emissions in the domestic stock argues for increased rates of demolition for the worst performing elements of the housing stock, this focuses heavily on historic buildings. This argument does not consider the relationship between embodied and operational energy. Embodied energy is the energy/carbon required to construct the original dwelling and the energy/carbon emissions that arise from any alterations that are proposed. Operational energy is the energy/carbon arising to provide comfort service to the occupants.

There may be a perception that in terms of total carbon, it is more beneficial to demolish a historic building and rebuild a new dwelling (embodied energy from existing and new dwelling plus lower operational energy), than to refurbish the dwelling to a better standard (embodied energy from original dwelling and retrofit plus lower operational carbon emissions).

There is good evidence to challenge this view. Firstly, demolition and rebuilding to current standards does not lead to reduced emissions compared to a comprehensive energy efficiency retrofit that takes into account the embodied energy in the existing structure (CAMCO, 2012). Furthermore, it has been shown for some time that adaptation and retrofit can significantly reduce energy use (Bell, 1998). There are also numerous recent examples of advanced, low carbon refurbishment where the cost of retrofit is less than demolition and rebuild.

A study of a major energy efficiency retrofit of an historic building in Canada (Bin et al., 2012) reported that the recuperation of embodied energy attributable to the retrofit adaptations were offset by savings in operation energy within 2 years. In this study the very quick recuperation of additional embodied energy was due to the initial high energy use of the historic building.

A similar study (Dodoo, 2010) that considered retrofitting an 1990’s apartment block to Passivhaus standard, found that the additional embodied energy was offset through reduced operational energy within 4 years. However this is not always the case. Optis et al. (2009) found that additional embodied energy payback varied from 2-72 years.

Even if research shows that deep retrofits are energy positive they not universally popular with conservation stakeholders. Asides from the high costs they generally involve high loss of fabric, either actual or visual (where it is covered up e.g. internal wall insulation); this suggests providing evidence to weigh up the perceived benefits against actual fabric loss and making rational decisions that contribute to the higher intention of tackling anthropogenic climate change. If this could be demonstrated then the price may be worth paying.
The challenge is to establish the performance of historic buildings. A common measure of the energy performance of a dwelling is the rating derived from the Standard Assessment Procedure (SAP)\(^4\), this is the National Calculation Method (NCM) for England as mandated by the European Energy Performance of Buildings Directive (EPBD).

The English House Condition Survey (EHCS, 2007) uses SAP ratings to reveal a close correlation between the age of a building and its energy performance. Homes built before 1919 have an average SAP rating of 39 (Band E), the effect of this is demonstrated by their average 9 tonnes CO\(_2\) emissions for heating and lighting—twice those of the post 1990 stock (Figure 17).

![Figure 17  SAP and CO\(_2\) Emissions by building age](source: Data from EHCS 2007, p 106)

From Figure 17 it can be seen that houses built before 1919 accounted for higher levels of CO\(_2\) emissions per dwelling, evidence of their poor energy efficiency. To put this into perspective in energy use and emission terms, using Elmhurst SAP 2009 software, a SAP rating of 39(E) equates to approximately 320 kWh/m\(^2\)/yr and 81 kg CO\(_2\)/m\(^2\)/yr.

Within these statistics it is recognised that there are differences in typical size between older and newer homes, which is why such data should be normalised by floor area to allow direct comparisons to be made, see Figure 18.

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\(^4\) SAP rating is calculated from an estimate of annual heating, hot water and internal lighting costs per m\(^2\) of a property. The SAP scale runs from 1 to 100, with 100 being the best (BRE, 2005).
Figure 18  Floor area by building age
Source: Data from English House Condition Survey, 2007.

Combining data of average floor area and CO$_2$ emissions by age of dwelling still shows that pre 1919 still have the highest emissions, see Figure 19.

Figure 19  CO$_2$ emissions normalised for floor area
Source: Data from CO$_2$ emissions and floor areas from EHCS, 2007.
The relationship between SAP and carbon emissions means that at the lower end of the SAP scale (where energy performance is worst), improvements bring about a relatively larger carbon saving than at higher SAP levels. There is a caveat attached to this, however, as SAP merely demonstrates carbon savings possible in principle, and does not take into account what can feasibly be done to improve each dwelling type, which in the case of historic buildings can be both restricting and challenging.

SAP is simply a compliance tool for planning and energy assessment purposes. It assumes a standard heating pattern and occupancy and only uses regional weather data for some calculations. The results are therefore not an indication of actual energy use. **This suggests the need to develop/demonstrate an assessment methodology appropriate to the performance of historic buildings, the way they are operated (particularly heating patterns) and where they are located.**

Regardless of the true energy consumption of a dwelling, the key point here is that the greater carbon savings are therefore, on average, achieved by raising the energy performance of the lowest performing dwellings. EHCS has shown this includes historic and traditional buildings, **leading to the conclusion that this portion of the stock may warrant early attention and can play a significant role in meeting CO₂ emissions reduction targets.**

**In the field of built heritage there are difficulties in moving from the concept of performance to having confidence in a tool for the accurate assessment of a buildings energy use and CO₂ emissions. There is little published work in this respect, and as a result this is suitable as a research question.** English Heritage considers SAP ratings for traditional and therefore historic buildings, as unsuitable (English Heritage, 2007) as it over estimates energy use (compared to actual energy bills). This remains a perception as no evidence is provided to support this view as there has been no large scale comparison of SAP modelled data with metered results.

An alternative is Reduced Sap (RdSAP), which (by using less technical information) was introduced to speed up the Energy Performance Certificate process for building purchases/rental agreements. This method is also not recommended by English Heritage, as RdSAP starts with the assumption that “traditional building types are less energy-efficient than modern ones”, an assumption that English Heritage disputes (Ibid, p.5).

Cheng et al. (2011) reported that “one of the major weaknesses of building physics based models lies on the generalisation of occupant behavioural patterns.” This may be a key factor that leads SAP to overestimate energy use in historic buildings.
It is clear that we need a way to effectively model the performance of historic buildings, and although research papers frequently suggest introducing new ways of modelling measures to reduce carbon emissions, time is against us. **We need a usable, inexpensive, user friendly and effective means to deliver data upon which energy efficiency retrofit decisions can be made.** One option is to simply validate current models to reflect the actual performance of historic buildings. This is integral to the modelling process (Ryan *et al.*, 2011) and may deliver usable results in a shorter time frame. This problem is not insurmountable and must be dealt with.

Despite data showing higher CO$_2$ emissions from the historic building stock there are differences on how the energy efficiency of these buildings is viewed; their energy efficiency is either regarded as good (English Heritage, 2008) or poor (SAP; EHCS; Boardman, 2007). Chris Woods, head of building conservation and research of English Heritage, at the ANBF (Association National Buildings France, Bordeaux, 2008) said:

“we do challenge the presumption that old buildings are inherently inefficient and this seems to be built into most models of thermal efficiency. On the contrary, in many ways the opposite is true.”

To counter the view that traditionally constructed buildings are much less energy-efficient than modern structures, English Heritage (2009) cites the research of energy use in traditional Court buildings (Wallsgrove, 2008) to promote the view that traditional buildings can be more energy efficient than modern counterparts.

The Wallsgrove analysis included a large sample group of different building types constructed over different time periods. The study concluded that pre 1900 Court buildings were the most energy efficient when considering total energy usage per square metre. This may be a significant finding that would have more standing if it had been subject to peer review. As it is aimed at the commercial sector (there is no equivalent study in domestic dwellings) there is no evidence that the findings would be applicable to the domestic building stock, the converse may even apply:

“**While there is considerable variability, the oldest homes generally performed less well than newer housing regarding their condition and energy performance**” (EHCS, 2007).

Research into the energy use of historic buildings (10 dwellings) in France (Cantin *et al.*, 2009) reported lower energy consumption for historical dwellings compared to more modern dwellings. This result is against what would be expected given the SAP assessment of traditional buildings in the UK.
However, closer examination of the data shows that both the internal temperatures for the older buildings and the occupancy rates were lower (no heating was supplied during nil occupancy periods in the historic buildings), neither of these factors were normalised in the results analysis.

### 3.5 Energy Use and CO\(_2\) Emissions in the UK

Context is required to outline the contribution the domestic built stock makes to energy use. At the global level, 33\% of all carbon emissions can be attributed to existing buildings (Vorsatz et al., 2007), consequently it is accepted that the building stock will have a major role in mitigating climate change in the short to medium term.

Though total energy use for the domestic stock is available, the problem is how this energy use varies between dwellings. **Despite 3 decades of research in this area there is very little hard knowledge of how people actually use energy in buildings** (Lords, 2005). The principle information available is the total delivered energy to the built stock (Digest of UK Energy Statistics). From this national data, delivered and useful energy demand is inferred from a range of data about the stock (such as the English House Condition Survey and floor space data from the Valuation Office) and computer modelling of energy flows in buildings.

Within the UK, using available aggregated data for 2009 (DECC, 2011), 26 million homes emitted 29\% of UK CO\(_2\) emissions (Figure 20). In view of this, the current target of reducing carbon emissions by 80\% by 2050 will not be achieved unless carbon emissions from the built environment are urgently addressed (Royal Academy of Engineering, 2010).
In the UK, on an annual basis, new buildings add less than 1% to the total housing stock, while significant renovations are completed on 1-2% of the existing buildings (Jennings et al., 2011, Ascione et al., 2012). Therefore, ensuring effective retrofit adaptation of existing dwellings will be more carbon effective than focusing attention on new build. Within this statistic lies the observation that given the time between a dwelling’s renovation is in the order of 40 years plus (Figure 12), it is vital that homeowners are encouraged to take up all energy efficiency options when the window of opportunity is presented. The challenge of climate change and the fact that 2050 is only some 440 months away makes an argument that rather than accept any improvement as a step in the right direction these dwellings should be optimised with regard to returning minimal CO$_2$ emissions, as it is likely they will only receive one large retrofit refurbishment during this period.

It is accepted that the majority of homes in England that will be standing in 2050 have already been built. However, the exact percentage can only ever be an estimate, consequently figures vary (85% Palmer et al., 2006; 80% Sustainable Development Commission, 2006; 70% Lowe, 2007). Regardless of the exact numbers, it will clearly be necessary to make existing buildings energy efficient rather than focusing primarily on new dwellings. Also, it would seem unlikely that the UK will be able to achieve large reductions in national emissions without the savings in the existing domestic sector being at least as large as those likely to be required in the economy as a whole (Johnston et al., 2005).
Within these overall emissions an understanding of how they arise is required; the breakdown of average UK domestic energy by end use in dwellings since 1970 is at Figure 21.

Figure 21  Domestic Energy by End Use 1970-2011

Accessed 2/1/13 © Crown Copyright 2009

This shows that cooking and hot water energy use has declined whilst lighting/appliances and space heating have increased (the variation in heating from year to year is a reflection of variation in annual HDD’s).

Figure 22 shows that breakdown of energy use in the UK for 2010.
This magnitude of heat shown is unsustainable (given current and near future carbon factors) if we are to meet emission reduction targets (The Carbon Plan, DECC, 2011). Space heating and hot water together account for 82% of all domestic energy use, the vast bulk of this is provided by gas (Owen, 2006), lighting and appliances accounting for only 15% of the energy used.

On first inspection the contribution from lighting and appliances to energy use may appear small and of secondary importance. However, the effect of inefficient primary electricity generation on the carbon factor for electricity increases the contribution it makes to CO₂ emissions (Figure 23).
This shows that space heating remains the largest source of emissions, but the importance of tackling emissions arising from lights, consumer electronics and appliances is clearly demonstrated. Given predictions for reduced heating (given the downward trend in HDD’s) and increased cooling loads (higher frequency of CDD’s), it is possible that within the next decade or two emissions from domestic electricity use will exceed that of heating. The effect of this may be lessened by the reducing carbon factor for electricity (requires additional research and the use of CCS). This is at odds with current orthodoxy when reducing domestic energy use which pushes a fabric first approach to reduce heating load. Given that electricity use is currently unaffected by fabric (most heating currently by gas in the UK) there is no reason why reducing electricity demand could not run in tandem with the fabric first approach.

Therefore, if reducing CO₂ emissions is the priority, domestic electrical activity should be considered alongside space heating to make significant gains, although the magnitude of this change will diminish as the carbon intensity of the UK national grid decreases in the coming decades. This is significant, because unlike heating and hot water, the options to reduce CO₂ emissions arising from electricity use are limited (detailed in Chapter 11). This may be an area where LZC technologies may have a role to play regarding tackling emissions for electrical use in the home. The breakdown for domestic electrical use emissions is at Figure 24, this shows there are several areas to focus attention on within the home to reduce CO₂ emissions.
Figure 24 Breakdown of Domestic Electricity Use 2010
Source: Data from Department for Energy and Climate Change DECC Energy Consumption in the UK, Domestic Energy Tables (2010).

3.6 Carbon emissions of historic buildings in Bath

The aggregated figures for the UK are not necessarily representative of Bath. Using data from DECC for 2009 Local Authority Carbon Dioxide figures, the total CO\textsubscript{2} emissions for Bath and North East Somerset (BANES) in 2009 were 967,000 tonnes, of which the domestic stock is responsible for 41% of the total emissions, see Figure 25. The average for the domestic stock in the UK is 29% (Figure 20).
Figure 25 CO₂ Emissions by Sector BANES 2009

Source: Data from DECC 2009 Local Authority Carbon Dioxide figures.

Figure 26 shows CO₂ emissions (also shown normalised with Heating Degree Days) for 2005 to 2010 (latest data as of January 2013). In this period normalised emission from the domestic sector in BANES has shown a decline of 26%.

Figure 26 CO₂ emissions BANES

Source: Energy data from DECC 2012.
The reason for the higher percentage of domestic emissions in BANES compared with national domestic emissions is unclear. One might be tempted to presuppose that this may be due to the higher proportion of historic dwellings (which are generally considered to have higher energy use than modern dwellings) in Bath compared to the national average (Figure 6). It is worth noting that in BANES 66% of dwellings were constructed before Building Regulations governing energy use were introduced (1968).

Other explanations may be a lower concentration of industrial output and a higher prevalence of tourism. This will require further work to fully account for this variance.

The significance of the higher proportion of older dwellings is clear when their contribution to CO$_2$ emissions is considered. This can be demonstrated by using data on emissions from DECC (2007) and using the English House Condition Survey$^5$ (EHCS, 2007) which can be used to show that pre 1919 dwellings accounted for 39% of all CO$_2$ emissions in the domestic sector in 2009, see Figure 27. (Chapter 10 shows such an assumption could be misleading as it based on aggregated energy use figures that deliver average energy use data).

Regardless of their exact energy use, the high proportion of historic stock suggests these buildings will have to play a significant role in meeting future emission reduction targets in BANES, even with restrictions that arise from their heritage status.

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$^5$ The EHCS is a cross sectional study of approximately 8000 dwellings and their occupants. Data was collected by face-to-face interview, house inspection and surveyor property inspection.
Figure 27  BANES CO₂ Emissions by Volume, 2009

This shows that in BANES an 80% reduction in CO₂ emissions cannot be achieved without involving historic dwellings. More importantly, failure to achieve 80% reduction in any dwelling, historic or otherwise, means that another dwelling must exceed 80% reduction by an equal amount if overall targets are to be met.

3.7 Summary

UK climate change policy dictates that the building sector will have to make significant carbon emission reductions. Reduction targets have been set but variations in predicted climate scenarios means there is a challenge to identify appropriate measures now that will remain effective under the widest climate uncertainty.

The contribution the domestic sector makes to carbon emissions was outlined. A case was made that despite the benefits of reduced HDD’s (reduced heating load) and the likely carbon levy for increased CDD’s (increased cooling load), even with a reduced carbon factor for grid electricity, an overall rise in domestic carbon emissions is likely.
Grid parity of electricity with gas in carbon emissions seems a decade or two away. This will require consideration soon (given heating plant lifetimes) on the appropriate selection of heating plant to ensure whole life carbon benefits remain favourable. Current models will need to adapt to reflect plant lifetime emissions with varying carbon factor scenarios.

The energy efficiency of historic buildings was questioned, conflicting views were put forward. Solutions for reducing energy use are known but they are complicated, fabric and aesthetic issues in historic buildings add an additional layer of constraint. A considered response is required to ensure that only appropriate and effective actions are implemented. Meeting 80% carbon reduction targets appear unobtainable without the use of LZC technology.

The significant contribution electricity currently makes to domestic carbon emissions, which seems likely to increase, throws uncertainty on pursuing the current fabric first approach to tackling household emissions; this suggests rethinking the appropriateness of current orthodoxy. Given the constraints outlined in reducing emissions in historic buildings, the suggestion is made that measures to reduce emissions from electricity can run in tandem with fabric first measures.

The main theme of this chapter was the lack of knowledge on actual energy use, particularly in historic buildings. The need for a benchmark of energy use was clearly established.

Alongside this it is clear that SAP’s ability to provide reliable predicted energy use is not accepted by key stakeholders for historic buildings. This highlights the need to adopt/develop a better tool to evaluate the benefits of retrofit measures that are based on accurate calculation of extant energy use.

The evidence for using Bath as a case study was shown as it has higher than the national average number of historic buildings and a higher level of domestic carbon emissions.
Chapter 4 Historic Building Adaptation Potential

This chapter considers the potential to reduce carbon emissions in historic buildings. It touches on occupant behaviour and the carbon content of primary energy. The central focus is on retrofit adaptations and energy efficiency with a review of the potential for reducing energy use and by proxy, carbon emissions, through retrofit and the adoption of Low and Zero Carbon technologies (LZC).

The wider context of built heritage is considered, in particular the conservation of energy and how it aligns with the conservation of built heritage. The underlying theme suggests we are moving to, if not already in, a new era, one which may be a paradoxically called an era of low carbon historic dwellings.

4.1 CO$_2$ emissions reduction

The potential to reduce heat and power demand of a dwelling are influenced by a range of factors (expanded from key points in Peacock et al., 2008):

- Behavioural, e.g. occupancy patterns, income, thermal comfort levels, attitudes towards appliance usage and selection, uptake of energy efficiency measures.

- Technical, e.g. how the dwelling is constructed, its rate of heat loss, the number/type of appliances employed.

- External, e.g. unit costs of gas and electricity, carbon intensity of network electricity, operational response of the electricity supply industry to distributed generation and climate.

- Policy, e.g. grants available for the implementation of micro-generation and energy-saving technologies.

Examples of domestic CO$_2$ emissions reduction has been demonstrated by a number of completed schemes. The York scheme$^6$ (Bell, 1998) showed two decades ago the application of cost effective improvements in existing houses.

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$^6$ A project involving around 230 early 1970s local authority dwellings which were in need of modernisation.
The 230 dwellings studied were 2 storey cavity wall brick buildings including terrace, end terrace and semi-detached units, constructed in the 1940/50’s. Improvements included improved roof insulation, cavity wall insulation, replacement timber windows with low-emissivity double glazing and draught seals, condensing gas boilers and draught proofing. Figure 28 shows the York mean energy use after improvements compared with the Great Britain mean. Energy use was measured as total delivered energy to the dwelling before and after the retrofit. The energy use was disaggregated using NHER/BREDEM model to establish hot water energy use.

The graph also shows that there is a potential for further improvements through the adoption of solar hot water, photo voltaic panels and combined heat and power units. The reduction in hot water energy seem ambitious, the project anticipated achieving this through fitting showers and basins with aerating taps, the application of thermal insulation to hot water delivery and primary pipework and by further increasing the thickness of thermal insulation applied to hot water cylinders along with the use of a solar hot water system.

![Figure 28 The York Energy Demonstration Project](image)

Source: Data from York Scheme, Final Report

These findings suggest retrofit adaption schemes have a very important part to play in reducing CO₂ emissions and improvements in the region of 50% can be achieved at modest cost using well proven (early 1980s) technology. The possibility of additional improvements is also identified and is perhaps necessary, and could see emissions fall by a further 30–40%.
Bell (1998) states the obvious in that many of the measures have been available for decades and their cost effectiveness is well established, yet they are not applied in sufficient volume. **The reality is that a large gap exists between the potential and achievement; this gap will need to be bridged/reduced if carbon reduction targets are to be met.**

The main conclusion from Lowe (2007) was that apart from those dwellings of high heritage value, delivered energy for space and water heating can be reduced by at least 50% by improved envelope performance and by increasing the efficiency of gas-fired heating. However, there is no mention of what would be possible from heritage buildings, even if the scope for envelope improvement is limited, suggesting a viable research question.

### 4.2 Energy Efficiency

It has been shown that buildings are complex systems, historic buildings maybe more so. As such they can be examined from several different directions. Energy efficiency is a term that can reflect a building’s performance, but this necessitates that there is something to compare with. The measurement or audit of a building energy use would permit this. **The development of a benchmark of energy use would assist in this regard.** This is not currently available for historic dwellings.

Eyre (2010) sub-divides energy efficiency into:

- Practical potential: Retrofit and occupant behaviour.
- Economic potential: Reduced bills, increased home value.
- Technical potential: Installed heating plant, lighting and appliances.
- Thermodynamic potential: Fabric insulation and infiltration.

The potential for the residential sector CO₂ emission reductions through the implementation of energy efficiency measures and renewable energy technologies has been well demonstrated (Boardman *et al.*, 2005; DTI, 2007; Lomas, 2010; Shorrock *et al.*, 2007).
The pursuit of energy efficiency is also not new; technical advances, effective research and more recently, occupant awareness, all promote improvements that in essence “get more from less”. In the domestic scenario this can translate into reduced fuel bills and less CO\textsubscript{2} emission per unit of energy used. But there is a reluctance to take up these measures because energy efficiency involves a trade-off between additional investment and a future reduction in energy costs (Schipper et al., 1992) for the dwelling which occupants may, or may, not still reside in for the return on investment period. The recently introduced “Green Deal “in the UK aims to bridge this gap by tying energy savings to the property rather than the bill payer, thereby delivering savings to the current and future occupants.

Throughout the development of our built heritage there are many examples of getting more from less, from chimneys consisting of a simple hole in the roof to walls with multiple flues, from internal wooden shutters/curtains to save heat loss to sliding sash windows, and from open fires and wood burners to sealed internal programmable heating systems and more recently the use of low energy lighting and LZC technologies.

Historically the driving force was more one of convenience and comfort. Today reducing energy cost is a significant consideration for householders; this has more recently been highlighted by continuing increases in the price of energy to provide service comfort. Fortunately reducing energy use reduces costs, this be used as a proxy for reducing carbon emissions. As we are now moving towards a new, low carbon era for historic buildings it only remains to decide how fast we travel in this direction. In response to this we now need to reduce the CO\textsubscript{2} emitted from our homes; this is a new approach and is to some extent out of line with cultural norms with regard to our built heritage. It poses the question whether the term kWh/m\textsuperscript{2} or kg CO\textsubscript{2}/m\textsuperscript{2} (measurements of energy use and carbon emissions respectively) in relation to dwellings will ever be as familiar as mpg/kml is to car economy. At the moment the best that can be expected is familiarity with the EPC (Energy Performance Certificate) issued for house purchases and flat rental agreements. It is still too soon to see robust evidence of domestic dwellings with a good EPC attracting a higher price or rent, although this is a reasonable expectation.

The use of kWh/m\textsuperscript{2} to compare energy use throws up an issue of the relevance of the parameters reflecting energy use. If the data set includes both modern and older buildings it is accepted that there will be variations in volume as modern buildings tend to employ smaller standardised ceiling heights. Normalising by volume, though possible, is largely ignored in both research and industry and is therefore of little benefit as there is no comparative data.
Normalising for occupancy also presents problems, as arises from difficulties in measuring this parameter, low occupancy, limited heating regime or fuel poverty\(^7\) will always deliver a low kWh/m\(^2\) figure. In the absence of alternatives, normalising for floor area prevails as a universally accepted parameter.

Interest in energy efficiency varies. In recent decades it has tracked the rise and fall of oil and energy prices. With a doubling of gas prices in the last 6 years and a 75% rise in electricity prices (DECC, 2012) and the prospect of higher energy prices (Wright, 2008), there was, until the current economic crisis, renewed interest in this area by occupants. Figure 29 shows average electricity and gas prices for the UK (adjusted for inflation using the GDP market prices deflator). Caven et al. (2012) suggests that rising energy prices may be more likely to reduce energy use and CO\(_2\) emissions rather than the present climate imperative by determining the speed and extent of retrofitting.

\[\text{Figure 29 Average Electricity and Gas prices}\]

Source: DECC annual energy price statistics, Annual Data table (2012)


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\(^7\) A dwelling is in fuel poverty when more than 10% of household income is expended on energy in the home.
Promulgating energy efficiency to reduce CO₂ emissions is welcomed yet there is some debate as to the effectiveness of this approach, the problem being the rebound or take back effect (discussed more fully in section 4.3). By achieving the same level of service/comfort through using less energy the occupants can either choose to maintain present comfort/service levels, thereby reducing overall cost and emissions. Or, they can choose to take increased levels of service/comfort, by using the energy saved but with the same total expenditure and no decrease in CO₂ emissions.

In practice a path between these two extremes is chosen. This would indicate that energy efficiency interventions will produce CO₂ emissions reductions but not at the scale expected. Shorrock et al. (2005) concluded that 30% of savings from heating-related measures would be taken in improved comfort instead of energy savings. This would mean that the reality of an 80% reduction in energy use following retrofit would in fact translate to a saving of between 55-65%. This is assuming all energy supplied is from fossil fuel sources. This issue could be offset if the take back used LZC produced energy.

Patterson (1996) states that despite continuing (and possibly increasing) interest in policy on the subject of energy efficiency, “little attention has been given to defining the term” (p.377). A problem is that energy efficiency has different meanings at different levels of tackling climate change, for example at the national level energy efficiency is used as a measurement of energy intensity (the ratio of national energy supply to national GDP).

There are a range of possible energy efficiency definitions but a starting point could be:

‘To use less energy to produce the same level of service or output’.

Essentially, energy efficiency is the term given to making more efficient use of electricity, gas, other fuels and renewable energy sources while still maintaining a similar level of service.

A difficulty arises in determining the energy used. Is it consumed delivered energy or should losses in generation and delivery be included (primary energy)? This would have a sizeable effect on calculated CO₂ emissions as it would reflect losses arising in energy generation. More importantly, failure to consider generation losses puts electricity generated by LZC technologies at a disadvantage in gauging its true contribution to reducing CO₂ emissions. For this reason, when considering the impact of energy use, there is an argument to consider the primary energy consumed alongside end-use demand (Allen et al., 2008). Yet this presents difficulties.
One drawback is that the carbon factor for purchased electricity changes with time, both daily and annually, since it depends on the generating mix. This would make retrospective comparison to past/future work and to data from other countries open to inaccuracies. Whereas using delivered energy allows direct comparison of energy data statistics such as annual energy use table produced by DECC. In addition, if occupants are to understand how their behaviour affects their energy bills, adding energy that is lost before they even receive a single kWh will only add to increased confusion over energy bills (discussed in Chapter 10).

Energy efficiency improvements do not necessarily equate to actual reduction in energy use and CO\(_2\) emissions. Hong et al. (2006) found that the impact of energy efficiency refurbishment on the space heating fuel consumption were not as expected. The potential improvement in energy efficiency from the installation of draught proof stripping, insulation and a gas central heating system was not observed, as fuel consumption was not reduced.

The use of normalised space heating fuel consumption was expected to take account of the rebound effect. The alternative explanations considered were that either the factors used to normalise the data were incorrect or that the theoretical model was too simplistic. This is of concern and is at odds with numbers of case studies on individual buildings that report significant reduction in energy use and CO\(_2\) emissions. It may well be a good example of the rebound effect where all the energy savings were taken back as increased comfort.

The same research has also shown that there can be carbon consequences as a result of energy efficiency interventions. Hong et al. (2006) observed that despite the introduction of measures designed to increase building airtightness the air infiltration rate rose. This was attributed to the installation of central heating systems where the introduction of unsealed or poorly sealed services penetrations increased the buildings ventilation rate. There is no reason why this problem could not be resolved by the use of appropriate sleeves and quality control to confirm they are correctly installed. Therefore the lesson here is to identify problems, rectify as early as possible and feed lessons learnt into future work. This will require improved site practices and more importantly, post occupancy evaluation to identify failings and areas for improvement - an approach that is rarely adopted. This shows the importance of post installation monitoring and the associated feedback in the design methodology for retrofit.
The research also found, through the use of thermal imaging, that though considered installed, the insulation did not achieve 100% coverage. The finding that the energy efficiency improvements implemented were not achieving the theoretically expected reduction in heating fuel consumption has implications on developing tools to assess potential CO₂ emissions reductions. Can such tools reflect a realistic assessment of the effectiveness of the measures proposed? It may be that 100% effectiveness is not possible; could the use of refurbishment case studies assist in defining a coefficient to reflect poor workmanship, inadequate detailing and inappropriate materials? Should we accept this or can we “train” out these issues?

This is not the only work on improvements failing to deliver expected energy savings. Oreszczyn et al. (2010) cite the Warmfront project (carried out on 3,000 existing dwellings and one of the most comprehensive studies of energy use, thermal comfort and health) failing to achieve expected reduction targets. The data collected, which were extensive, indicated that the introduction of modern heating systems and additional insulation/draught proofing did not improve the energy efficiency of the building anywhere near to theoretical expectations. The paper stated in this regard that:

“this study has therefore revealed conclusively that there is a serious problem with the impact of traditional energy efficient improvements, and yet is unable to offer a definitive analysis of what the problem is, nor a way of solving it” (p. 111).

This is a worrying statement and may suggest that these findings would be just as applicable to improvements in energy efficiency in historic buildings. It highlights the challenge ahead in reducing emissions from the existing housing stock.

Despite the perceived benefits of energy efficiency the reluctance to take up such measures is summed up by Graham (2007, p.20) on consumers’ attitudes to energy:

“Economists find it puzzling that consumers do not appear to act rationally in relation to energy efficiency improvements, given the economic, social and environmental gains that can easily outweigh the costs. Many studies have explored this paradox, and shed some useful light into it. There remains considerable scope for further public engagement work in this area”.

Given the emphasis in the UK placed on the current “Green Deal”, time will tell if this observed and unexplained consumer behaviour remains extant.
An explanation was postulated by Jenkins (2010) who considered that the lack of take up of energy efficiency improvements to reduce CO₂ emissions is related to the perceived lack of immediate threat in the UK from climate change. There may also be other factors, such as the likelihood of moving home, lack of access to finance, uncertainty on how to arrange energy efficiency measures and fear of disruption from alteration works. This area requires further work to determine a solution to motivate an increased take up of energy efficiency measures.

But energy efficiency is not the complete answer as it does not address the fundamental problem of consumption; this involves demand reduction and is a specialist area seen as having significant potential in meeting proposed CO₂ emissions reduction targets (MacKay, 2009).

4.3 Occupant Behaviour

Buildings do not use energy on their own; there is the contribution occupants make to energy use. In looking at domestic energy use, research has shown that it is impossible to ignore the importance of social and behavioural considerations (Sonderegger, 1978; Palmborg, 1986; Dall and Toft, 1996). Therefore, in order to estimate the predicted potential for CO₂ emissions reduction an understanding of how occupants affect energy use and emissions from the home is required. This in itself is a detailed area of investigation, one that has only recently received recognition as a major area of research.

There are conflicting views on the extent to which user behaviour affects energy use, Roth and Broderick (2008) suggest that occupant behaviour has a major impact on building energy consumption, in that intervention to modify occupant behaviour could result in appreciable energy savings. However, Steemers and Yun (2009), in a paper that addressed to what extent building energy performance is determined by interactions between occupants, behaviour and systems in the US housing stock found that:

“behaviour has a less dramatic effect on heating energy than the physical characteristics of the climate, building and system.” (P. 629).

They also found that:

“economic and demographic factors individually play a rather limited role in determining domestic energy use” (P. 630).
The reality is that technical measures will not be enough in themselves (Roaf and Hancock, 1992); necessitating an element of behavioural change even if it is to arrest the continuous rise in use of energy in the home. A “solution fits all” approach is unlikely to succeed, whereas a common methodology that can be adapted to each individual situation offers more potential. **This is an important consideration when designing the methodology for this research.**

Janda (2009) in the paper *buildings don’t use energy people do* supports and strengthens this view. The paper argues that building users play a critical but poorly understood, and often overlooked, role in the built environment. In the face of climate change, purely architectural solutions are necessary but not sufficient, suggesting that technical interventions are insufficient on their own to bring about the CO₂ emissions reduction required. This is also an area for future consideration.

An intermediate view is taken by Schipper et al. (1992), who considered that approximately half the energy use depends on the characteristics of the building and its equipment, and the residents and behaviour influence the rest.

The reality is that it is impossible to divorce either the building users or the buildings characteristics (fabric and environment) from each other. This is demonstrated by the finding that the energy use difference between one property and the next can vary by more than a factor of 2 (i.e. one property uses twice as much as an identical one with similar occupancy) (Socolow, 1978; Sonderegger, 1978; Parker, 1996; Bell and Lowe, 2000; Moran, 2012).

In view of these findings, English Heritage’s view that it is just as important to change occupants’ behaviour as it is to improve energy performance (English Heritage, 2009) is appropriate and necessary.

These issues demonstrate the need to go further. One possibility is through the exploitation of/or utilisation of the occupant/building interface, to positively influence energy use through information feedback and building management systems. The potential impact of monthly feedback on energy use patterns is usually estimated to be 5–10% (Darby, 2006), but there are concerns that the initial savings can be sustained in the medium-to long-term (Dam et al., 2010). This is an emerging research field that may identify an effective interface between occupants and energy use.
The installation of LZC technologies may also affect the energy use behaviour; according to Keirstead (2007), the installation of Photo Voltaic (PV) panels and system performance monitors encouraged households to reduce their overall electricity consumption by approximately 6% and shift demand to times of peak generation. This work also looked at how to influence demand to match PV output. This demonstrates an emerging research area, which is further explored in Chapter 11.

Technical improvements do not always result in the expected energy savings (Hong et al., 2006). The other aspect to be considered is the take back or rebound effect that follows a retrofit to improve energy efficiency, whereby by some of the energy savings are taken back through increased comfort levels.

Sorrel’s analysis (2009) of the “Jevons Paradox” (economically justified energy-efficiency improvements will increase rather than reduce energy consumption) concluded that there was not sufficient evidence to support this claim as yet. Therefore further work is required to fully consider this effect.

Druckman et al. (2011) although looking at only one measure that directly concerned domestic energy efficiency, estimated that under conditions of ‘behaviour as usual’, the rebound effect is around 34% for the suite of three ‘green’ household abatement actions studied. This means that only 2/3 of the expected savings were achieved. Looking at specifically at a suite of energy efficiency measures in the home, Chitnis et al. (2013), found a similar albeit smaller effect, in the range of 5-15%. Interestingly for measures to reduce energy for heating the take back was 20% (work in section 12.47 indicates this equates to approximately 2°C of average internal temperature increase).

Regardless of the exact level of take back there is another element that is beneficial: the improvement of occupant’s health and wellbeing (Oreszczyn et al., 2006). This arises from increased internal temperatures arising from retrofit adaptations.

Arising from the benefits to occupants from improved energy efficiency is the issue of fuel poverty. The DECC 2009 Annual report on fuel poverty statistics household defined fuel poverty as a household that expends more than 10% of their income to heat their home to a comfortable temperature. In 2011 this amounted to 2.39 million households (DECC, 2013), there were no data on the breakdown of the dwelling age or typologies.
4.4 Performance of Historic Buildings

Boardman (2007) counters English Heritage’s view that traditional buildings have better thermal performance and considers the task of significantly improving the heat loss of the fabric as unachievable in the case of traditional and historic buildings without the introduction of insulation to external walls.

This premise is of concern to stakeholders as the introduction of interior insulation systems (assuming the desire to preserve external appearances) are viewed with reservation among conservation stakeholders in Europe, due to historic buildings sensitivity to decay. Internal wall insulation may have consequences: a lower temperature inside the masonry, an increase in the risk of condensation behind the insulation in winter and a reduction in the drying potential of the wall increases the hygrothermal stress of the wall leading to increased risk of frost damage and corrosion risk (Künzel, 1998, 2004). Yet, despite hygrothermal simulation tools (e.g. WUFI) there is uncertainty on the hygrothermal behaviour of building envelopes beyond predicting mould growth (Sedlbauer, 2000). The absence of tools for frost and corrosion damage prediction and the long term risk of interstitial condensation in building components highlight an important area of further work.

This does not mean that internal wall insulation is inappropriate. In the UK internal wall insulation has been applied for at least three decades. There is no academic research to suggest that the many installations to date are failing to any significant degree. But there are calls to ensure internal wall insulation takes sufficient account of heat loss through thermal bridges and the increases risk of fabric decay arising from reduced heat flow into walls (May, 2012).

On the other hand there is research to support the methodology to adopt internal wall insulation (Toman et al., 2009). The report is of interest as it considers the performances of mineral wool insulation without the presence of a vapour barrier. The paper followed computational analysis that showed good hygrothermal performance for the use of mineral wool with a field trial in a historic building in Prague.

The trial lasted four years and found that the relative humidity on the interface between the external wall and the insulation presented no condensation risk. The conclusion drawn was that the application of an internal wall insulation using mineral wool without a vapour barrier achieved good thermal performance with no interstitial condensation.
This is a positive finding as the installation of a vapour barrier in existing dwellings presents many challenges as details are difficult to implement. Particularly around joist penetrations into external walls, the junction of suspended floors and walls and the junction of ceilings and roof rafters. The current orthodoxy, where joists remain in walls, is to cut the vapour barrier and seal to the timber with tape. The long term performance of this detail type is largely unknown. This is an area where long term validation of the vapour barrier performance is required.

Some intervention techniques lead to aesthetic conflicts or modification of the original structural fabric e.g. replacement windows, secondary glazing, under floor heating. Even though these intervention techniques may be considered in principle “correct”, as they contribute to significant energy use improvement due to the predictions provided by theoretical/numerical models, the real emission behaviour of the adapted historic building is less clear. **This presents an opportunity to clarify this area through collating a data base of real time energy use and CO₂ emissions in historic buildings.** This will assist in informed and effective decision making on how best to proceed whilst accurately weighing carbon benefits against heritage alterations.

There are a number of elements that affect the thermal performance of any building. Recent work on windows in historic building by Historic Scotland (Baker, 2008) and English Heritage (Wood, 2009) generated interesting findings. In particular secondary glazing on sash windows can achieve thermal performance equivalent to a double glazed window. This fact is rarely promulgated with the perceived emphasis being on complete replacement windows.

The view that historic buildings have poor energy efficiency may not always be correct, in that English Heritage may have a point with regard to some elements of the performance of traditional buildings being better than more modern dwellings.

Work by Stephens (1998, 2000), showed that pre 1920 buildings were more airtight than buildings constructed prior to 1970 (Figure 30). The study was comprehensive, the data base consisted of 471 dwellings, the mean was 13.1 ach @50 pa. From the data provided the standard deviation was 5.56 reflecting the spread of results around the mean. What is clear is that there is potential to improve the airtightness of all UK dwellings.
The cohort of 63 historic buildings cannot be considered statistically representative as there is no indication of how they were selected and what the typology was. It would beneficial to carry out detailed research into the infiltration rates in historic building to establish their actual performance in this parameter.

![Figure 30 Airtightness of UK dwellings](image)

Figure 30 Airtightness of UK dwellings
(number over column indicates number of buildings)

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English Heritage’s view is also supported by findings by Salat (2009) which showed that the U-Value of pre 1919 building envelopes in Parisian buildings was better, or at least equal to, buildings built before 1975 (Figure 31). This data was established by modelling some 10,000 buildings in Paris.
Walls are an area of high heat loss on an historic building. Recent work undertaken by Historic Scotland (Baker, 2011) the Society for the Protection of Ancient Buildings (Rye, 2010) and English Heritage (Baker & Rhee-Duverne, 2012) has found a discrepancy between the U-value of these walls between the as measured value and the standard calculated value. This results in heat loss through walls being over estimated.

The discrepancy between calculated and measured U-values of solid walls has a consequence when modelling heat flow and energy consumption; wall U-values are a key component in the estimation of whole building heat loss and subsequent estimates of stock and building energy performance. However, in general the U values of solid masonry still remains high (Building Regulations Approved Documents Part L1B and L2 B sets a U Value targets for retrofit of 0.30w/m²K). On average the in-situ U-values achieved 1.4W/m²K, compared with the 2.1W/m²K value recommended in official SAP assessments (Rhee-Duverne, 2012).
Figure 32 shows energy use in kWh/m²/yr and shows a similar improved performance in pre 1920 buildings compared with post second world war buildings. But this is only an indication of comparative performance as energy use is still much higher than more modern dwellings.

These findings, which although they are based on similarly constructed buildings, consist of typical Parisian buildings with multiple apartments and are not necessarily representative of the UK. This may be because these were built in volume and with haste, a possible explanation for the higher energy consumption. The post 1990 figure of 40kWh/m²/yr for heating is a predicted figure considered achievable with construction methods and retrofit options current at the time of publication.

Even if historic buildings are not the worst performing building type it does not detract from the pressing need to improve their energy use and reduce their CO₂ emissions as a part of the need to tackle climate change.
4.5 Conservation and Heritage

A review of energy efficiency adaptations for historic buildings cannot ignore conservation issues within this building group. Loulanski (2007) outlines the preservation approaches that have evolved as our built heritage has aged (Figure 33). What was once preservation became the subject of conservation. Today this is viewed as heritage. Given the pressing need to reduce CO₂ emissions, time may show that we have established a new approach, that of energy efficiency in buildings that were constructed without regard for their energy use. Perhaps we should consider a new emerging theme of “performance” whilst maintaining heritage to meet the challenge of climate change.

Figure 33 Steps in the evolutionary process
Source: Loulanski (2007)
Original Image © Cambridge University Press 2007

The emergence of this approach can be seen in a speech by Duncan McCallum⁸, policy director for English Heritage, who stated:

“it is no longer relevant to take a protectionist position, the language has now moved on as well as the thinking”.

Paradoxically, although accepting that building performance and energy use are now an issue, he maintained the prevailing view that traditional buildings “are low energy users in the first place”.

This view is largely contradicted by the findings and comments presented so far. At the same time, it would appear that there is greater potential for energy savings in the large stock of existing dwellings (including historic buildings) than in the relatively small proportion of newly built dwellings, because the energy performance of existing dwellings is much poorer than new dwellings and the stock of existing dwellings is very large.

In evidence to the House of Commons Communities and Local Government Committee (2008), the Environmental Change Institute at Oxford University argues for more robust intervention in older buildings than has perhaps been permissible to date:

“Heritage conservation needs to be balanced against climate change mitigation — more interventions should be possible in heritage/conservation buildings than are currently allowed. Re-creation of original features (e.g. cornicing on top of internal wall insulation) should be seen as desirable, not rejected because of the intransigent position of conservation bodies, which argues that no original features should ever be lost.” (Vol. I, P. 264).

It may be that we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to the current environmental imperative. Perhaps we should consider that “we may have to be prepared for visually intrusive measures on much loved buildings” (House of Commons Communities and Local Government Committee, Vol. II, P. 44). This view may gather momentum because the options to improve energy efficiency in historic buildings are limited and the imperative to tackle climate change (or at least reduce expenditure on energy) is high.

In a wider context the response could be radical. Can the historic settings across the UK be subdivided or classified? Could there be a trade-off between conserving, for example in Bath, set pieces such as the Royal Crescent, The Circus, Brock Street etc., and retrofitting at a local level, areas that whilst historic, are not considered as the principle face of Bath, such as Oldfield Park, Camden Road and Belgrave Terrace and areas surrounding the London Road to the west. This may be considered a contentious approach. Figure 34 shows the set pieces and Figure 35 shows typical conservation areas in Bath.
In terms of conservation is one dwelling more important than another? Is one permitted a higher degree of adaptation than another? How would residents respond if, in the face of increased energy costs, they were prevented from adopting energy efficiency measures permitted in other historic buildings?
This view is of course extreme, particularly as the present situation can be seen more as a meeting rather than a collision, of the conservation of energy and conservation of heritage. Cassar (2009) considers that the heritage environment must engage fully with the process of adaption to climate change that the whole of society is undergoing, otherwise there is a real risk that historic buildings may become redundant and the price of environmental obsolescence, demolition, in future will be too high.

To some extent the debate has begun. One question that will have to be decided is what level of heritage value can be altered to facilitate reducing CO₂ emissions. This will involve weighing up the perceived benefits of energy savings and CO₂ emissions reduction against loss of fabric. Loss of fabric includes actual alteration to/or removal of amounts of the original building. They vary in scale and nature from cutting service chases to taking down ceilings to reach inaccessible roof voids. It also includes loss of visual fabric. This can occur where a part of the original building is covered from permanent view but remains intact. an example is internal wall insulation in front of a plastered wall with stucco features.

Climate Change and the Historic Environment (Cassar, 2005) is the result of a study commissioned by English Heritage. This work identifies gaps in the research that can help our understanding of how traditional buildings perform as a complete environmental system, and at the same time accepts this will run in tandem as we take action to reduce their energy use. The work challenges traditional orthodoxy, accepting, that if we are to lose original features/change aesthetics in order to make historic buildings more energy efficient we must quantify and compare the performance of old and new measures before paying the price. This research will assist by providing the framework to quantify the energy and emission savings and the benefit arising from proposed changes to the historic environment.

The recent decade has seen the emergence of major case studies. Some involve large scale refurbishment and amount to reconstruction rather than adaptation. For example the Low Energy Victorian House (LEVH)⁹ project left little of the original interior features and amounted to a virtual complete reconstruction of the property other than the external walls. This is certainly not feasible either practically or financially, for the bulk of the historic stock.

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⁹ Low Energy Victorian House: a retrofit project in Camden, London. The project, led by Camden Council, refurbished a solid wall semi-detached Victorian house located in a conservation area to achieve a 90% reduction in the dwelling’s carbon emissions.
One criticism to date could be the effect of the disjointed and uncoordinated retrofitting of energy efficient and renewable energy measures. This could lead to a mixed street scene of different shaped and positioned materials/components that by their very disjointed development and appearance detract from the pleasing street scene seen today.

A radical way to counter this could be to insist that whole streetscapes or collective skylines are altered uniformly and simultaneously to achieve a harmonious result. Taking this to the extreme may mean including dummy Photo Voltaic or Solar Hot Water panels on roofs that are not ideally orientated or where occupants cannot afford the installation in order to maintain visual harmony see Figure 36. This shows an installed PV array in a conservation area in Bath. The second photo shows the street scape that might emerge if whole streets were to receive a PV array.

![Figure 36 PV installation and Street Replication](image-url)
Hassler (2006) discusses the diverse threats stacking up against our cultural heritage and touches on an interesting point in conservation, the precautionary principle. In other words, be aware of developing short term reactions that might lead to long term damage. At the same time the overarching need to reduce CO\textsubscript{2} emissions and the value we place on our built heritage means we do not have the time nor the wish, to make mistakes (it may take years or decades for building performance problems to come to light), yet we must make decisions today amid a degree of uncertainty, that with time will prove to be both effective and durable.

Although there is a good deal of peer reviewed information available on the background to climate change there is less on how to adapt historic buildings to minimise loss of fabric and to mitigate the effects of climate change. Climate change has to some extent merely highlighted long-standing issues, namely thermal comfort and high energy costs.

Until now stakeholders have resisted change, but the pressing need to reduce CO\textsubscript{2} emissions and research demonstrating possible improvements in energy use brings pressure to bear on decision makers and occupants alike to consider improving the energy efficiency of historic buildings.

Hassler’s and Cassar’s papers are perhaps most notable for what they do not discuss, that is the contribution of the built heritage to climate change in terms of CO\textsubscript{2} emissions. More importantly, they have resisted engaging in the debate to tackle this issue. This to a large extent reflects the interdisciplinary nature of this issue. The challenge will require a combined effort from disparate fields to provide acceptable workable solutions to reduce CO\textsubscript{2} emissions within the historic building stock.

Key stakeholders should, given the imperative to reduce carbon emissions, be required to clarify what energy efficiency improvements can be expected from both historic and traditional buildings. This will be a balance between householder aspirations to minimise fuel costs and contributing to UK CO\textsubscript{2} emission reduction targets and the desire to maintain the built heritage.

English Heritage’s view that we need to understand in more detail energy usage in all types of historic and traditional building stock is accepted. But there is less agreement on balancing the needs of building conservation with the needs of energy conservation. There is little time to conclude this approach.
Cassar suggests aligning the principles and practice of conservation in the 21st century more fully with sustainability principles. This will require aligning heritage conservation more closely with delivering acceptable CO₂ emissions and energy use whilst conserving our built heritage. Unfortunately, the dwellings that are the hardest to insulate can have the highest heritage value. Furthermore, evidence from the EHCS would suggest that these properties would make a larger contribution to reducing CO₂ emissions given the poor performance base they start from.

While committed to the Government’s energy efficiency aims, English Heritage is concerned that improvements should enhance, rather than harm, the special interest and performance of traditional and historic buildings (English Heritage, 2009). English Heritage has a statutory obligation to protect historic buildings, and it advocates a sensible and reasonable approach to energy improvements: in some cases it is not feasible or cost-effective to add every possible improvement, but a more restrained approach can still produce substantial energy savings. What we do not know is what level of reduction in CO₂ emissions would be reasonable let alone possible; this thesis will add knowledge in this area.

4.6 LZC (Low and Zero Carbon Solutions)

Renewable energy is the use of natural resources to provide energy that is low or zero carbon; as such it has the potential to decouple future energy use from future CO₂ emissions, an attractive proposition. The current government renewable energy strategy seeks to increase decentralised micro renewable generation (DECC, 2011). This approach is supported by Natarajan’s and Levermore’s (2007) view that:

“In any scenario, it is now clear, that energy conservation alone will very likely not deliver the required 60% carbon emission reduction. It is only through the aggressive use of energy export that emissions can be balanced” (P, 5735).

This would suggest the onsite generation of electricity and heat will be essential in meeting future CO₂ emissions reduction targets. In June 2011 DECC published a Microgeneration Strategy, which when coupled with the roll out of smart meters and the Green Deal, will encourage small scale power generation to reduce bills and make people more energy self-sufficient.
The focus of the Microgeneration Strategy will be electricity generation technologies less than 50 kW in size, and heat generating technologies less than 300 kW in size. This includes:

- Air, ground and water source heat pumps.
- Solar photo voltaics (PV).
- Solar thermal water heating (SHW).
- Biomass boilers.
- Micro wind turbines.
- Fuel cells.
- Micro hydro schemes.
- Hydro.

There is a growing acceptance that renewable energy technologies can achieve a significant reduction in CO₂ emissions beyond that from the standard energy-efficiency methods (Chwieduk, 2003). The National Trust (2009) in its response to the Heat and energy Saving Strategy considers that closer attention should be given to the contribution that historic buildings can, and need to make, to reducing CO₂ emissions.

They highlighted the availability and promotion of suitable low carbon and renewable energy solutions. Their experience suggests that there is an undue presumption that there are only very limited options for reducing the carbon emissions of older buildings, for example those in conservation areas. They challenge this presumption and have demonstrated ways to circumvent it by installing roof solar systems on Grade I & II Listed Buildings. Examples are at Figure 37.

Clumber Park- Solar Hot Water

http://ntenvironmentalwork.files.wordpress.com/2012/01/3-charis-fit-for-the-future-cdec-020412.pdf

© National Trust Images
Morden Hall Park- PV and SHW
© National Trust Images

Hanbury Hall- solar Hot Water
© National Trust Images
Gibson Mill PV
http://ntenvironmentalwork.files.wordpress.com/2012/02/picture-gibson-mill.jpg
© National Trust Images

Air Source Heat Pump (ASHP) on a domestic dwelling
http://www.google.co.uk/imgres?imgurl=http://www.modbs.co.uk/files/August_2012/10_Heat_pumps.jpg&imgrefurl=http://www.modbs.co.uk/news/archivestory.php/aid/10794/National_Trust_puts_its_trust_in_saving_energy_.html&usg=__5agtY9RORj_7J0b3zIdyHy34e9A=&h=240&w=250&sz=38&hl=en&start=31&zoom=1&tbnid=8_1dRMz1AIU8M:&tbnh=107&tbnw=111&ei=O-HwUOejNKSf4ASoYHYCg&prev=/search?q=national%2Btrust%2BPV%26start%3D20%26um%3D1%26hl%3Den%26sa%3DN%26gbv%3D2%26lr%3D1R2SNYK_en-GB%26tbs%3Disch%26mode%3Ddivns&um=1&tbs=1
© National Trust Images

Figure 37 National Trust LZC Installations
The National Trust consider the challenge is about winning hearts and minds, and cultural change across the public, local authorities and some of the heritage sector - in addition to education and training. They stated that they are keen to play a positive role in shifting current perceptions of the public, local authority staff, professionals and others by demonstrating and promoting the wide range of energy efficiency and renewable energy solutions that can be integrated with historic and sensitive buildings. A means to predict carbon savings from such initiatives will add weight to support LZC installations.

The recent introduction of Feed in Tariffs\textsuperscript{10} for micro electricity generation in the UK and the prospect of the same for renewable heat has led to increased take up of domestic micro renewable energy generation systems; micro generation is just as beneficial to historic buildings as the rest of the housing stock in terms of supply low carbon energy although the effects on aesthetics is debated. Figure 38 shows four PV installations on historic buildings in Bath.

Figure 38  PV Panels, Bath
(photo: top left Tony Crouch)

\textsuperscript{10} The Feed-in Tariffs (FITs) scheme was introduced on 1 April 2010. It allows people to invest in small-scale low-carbon electricity generation in return for a guaranteed payment from an electricity supplier of their choice for the electricity they generate and use as well as a guaranteed payment for unused surplus electricity they export back to the grid.
This shows varying aesthetic impact; the combination of roof lights and PV panels (top left) makes a good case for a degree of control to ensure visual harmony.

On the domestic stage there is a wide area of interest in micro renewable energy, for example Lowe’s UKERC research topic is “how can the energy demands of the existing building stock be reduced very substantially in a manner that is socially acceptable”. In response to this, Lowe considers retrofitting low carbon technologies to existing buildings as crucial to reducing future emissions. This research will assist by determining the contribution LZC can make to reducing CO₂ emissions in historic buildings.

Allen et al.(2008) state that if appropriately installed, micro-generation could provide a significant proportion of energy supply (with demand reduction), for example typical PV installations could provide 50% of electricity demand (DTI, 2006) and SHW systems are capable of supplying up to 50% of hot water requirements (DTI, 2001).

On the other hand, renewable energy technologies may not be the complete answer. The Royal Academy of Engineering (2010, p12) views it necessary to make advances in energy efficiency whilst at the same time recognising that the introduction of renewable energy generation does not address the issue of demand. It will be necessary to clearly outline how the use of renewable energy and the introduction of demand reduction together can significantly reduce CO₂ emissions.

The CIBSE (Charted Institute of Building Services Engineers) addressed this issue in their monthly magazine (January 2010), with the front cover page title “Bling or Bust?”. Although appearing to suggest that LZC’s in the home were more a question of glamour rather than substance, the article aimed to put the adoption of these technologies into perspective with the energy hierarchy approach of reducing demand and improving energy efficiency first. The article stated that “renewable technologies do have a valuable part to play in a vast array of projects, both large and small”.

There is a downside to this negative “Bling” image in that it fosters the current orthodoxy for improving energy efficiency by focussing on reducing the heating load, and only when this is achieved does it turn to dealing with the approximate 35% contribution electricity use makes to CO₂ emissions (Figure 23). The introduction of PV, though currently recommended as one of the last retrofit measures, can lead to reductions in CO₂ emissions through using considerably less delivered electricity (discussed further in Chapter 11). When primary energy production losses are considered the benefits increase.
Kelly (2006) considers that only with a balance between reducing energy use and increasing renewable supplies can the UK hope to meet its emissions reduction targets. Boardman et al. (2005) concluded that it is possible to achieve an 80% reduction in CO₂ emissions from all energy use in the whole UK housing stock by the end of 2050 with the introduction of micro renewable energy at the domestic level. In broad terms, two-thirds of the saving comes from reducing demand and one-third from the introduction of micro-generation. Given the higher capital cost of renewable energy technologies, demand reduction through energy efficiency and occupant behaviour changes has the added benefit of reducing plant size and increases take up by contributing to a reduction in the investment cost of renewable energy plant.

This broad academic and professional base clearly suggests the unavoidable use of LZC technologies if emission targets in the buildings sector are to be achieved. Considering the size of the traditional and historic building stock it is unlikely they can avoid playing a sizeable part in this respect. Historic buildings have varying degrees of heritage importance ranging from Listed to no protection at all. If stakeholders resist the adoption of micro generation technology on any historic building then another dwelling will have to go further in emissions reduction to make up this short fall, yet research shows that achieving an 80% is challenging in itself.

Boardman (2005) suggests that not all micro renewable energy technologies will have the same effect on historic buildings,

“The output from many LZC technologies, such as photo-voltaics and solar thermal, does not vary with the property on which it is positioned. However, with CHP (from fuel cells), the greatest output will be obtained if it is installed in less efficient buildings with substantial heat demands, as indicated by a low SAP rating” (P.373).

By producing both useful heat and electricity locally, combined heat and power (CHP) systems can potentially achieve lower overall carbon emissions than conventional heating systems and grid electricity (Carbon Trust, 2011). The report, which looked at 72 domestic installations using gas micro CHP units (this thesis only considers micro CHP), indicated carbon savings in the range of −4 to +14% depending on the annual heat demand. CO₂ emissions of 9% were reported by Peacock et al. (2005) for domestic micro CHP systems. The findings of these investigations indicate that CHP systems have the potential to reduce the carbon footprint of a single UK dwelling relative to the non-CHP base case of using a condensing boiler and grid electricity. More recent work by Barbieri et al. (2011) reported primary energy savings that is always higher than 20% in dwellings with an annual heating load of at least 120 kWh/m² (this is generally the case in historic buildings).
The Carbon Trust report also shows that cost effectiveness is improved by running the CHP for as many hours per day as possible. The high thermal output of micro CHP makes it less feasible in smaller dwellings/flats or well insulated properties where heat demand is low. Dwellings with an intermittent heat demand are also unlikely to be economic.

A key factor to the performance is the dwelling heat load as it influences the output of the CHP system. Subsequent work by Peacock et al. (2008) looked at how the dwelling heat load influenced CHP performance, reporting that reduced heat demand following retrofit fabric improvements delivered negative or marginal CO₂ savings. The research also commented that societal intransigence to alter the physical appearance of historic buildings inhibits the deployment of low carbon energy intervention strategies that could reduce significantly their annual CO₂ emissions, suggesting that these dwellings might represent the early (incentivised) market for current generation CHP systems (as CHP has little or no effect on aesthetics or fabric). This approach ignores the energy reduction hierarchy that advises reducing energy demand first, which when applied reduces the benefits of a CHP unit.

There may be situations where the use of micro CHP would benefit historic buildings and heritage properties, where the benefit of integrating heat production with electricity generation may transform inefficient high emission buildings into lower carbon dwellings. But this will depend on high levels of heat demand to achieve economic viability. We do not know if historic buildings fulfil this demand as we are unsure of patterns of energy use; it is unlikely that there is a sustained demand in summer months to make such systems viable in the domestic stock.

This potential for CHP is supported by Kelly (2006) but for different reasons, in that given that the majority of the energy requirements in the UK domestic sector are for space and water heating, the efficient provision of heat using micro CHP and/or solar thermal technologies may be more effective at reducing emissions than renewable electricity production.

There is a difficulty here, like energy use in buildings, the situation is complicated. It depends on international and national government energy policies, fuel prices, fuel carbon content, plant life expectancy, component replacement frequency and carbon cost, grid gas and electricity carbon factors and varying occupancy and heat demand patterns.
The Carbon Trust report considered the carbon factor of grid electricity and found that if this reduces in the lifetime of the CHP unit, the carbon savings may be negligible or even negative. In the worst case, this window of opportunity could therefore be limited to the next 5-10 years (if predicted Carbon factors are achieved), even if the performance of these micro-CHP systems can be incrementally improved.

It should be noted that future generations of micro-CHP systems based on fuel cells, which are expected to generate a much higher ratio of electricity to heat, will achieve significant carbon savings even for much lower values of the carbon intensity of grid electricity. They are therefore likely to have a longer window of opportunity in the UK than systems based on Stirling engines.

One approach is to perhaps consider the use of LZC technologies as part of a transition process. Their installation is generally reversible and has a finite life. The life time of a PV system or Air Source Heat pump is in the region of 15-25 years. As we cannot predict with any real confidence what will be the favoured technology in over two decade’s time it may be that they are removed and replaced by a currently unforeseen alternative. **What we do know is that current visually unacceptable energy technologies can be removed at a future date therefore restoring historic buildings to their original state.**

Cockroft and Kelly (2006) see the large scale deployment of renewable energy technologies coupled with greater energy efficiency as a means of combating increasing energy demand and reducing CO$_2$ emissions. Yet, despite a few exemplars, such as Woking and Kirklees councils 11 (Allen et al., 2008), decentralised supply and micro generation has not had a significant impact on the UK’s energy system.

Dincer (2000) points out that the understanding of the processes and sources of renewable energy are easy. This does not address the challenge that lies in the installation of an engineered device that does what it says, that is, it delivers low carbon energy at the level expected. At the same time attention is drawn to an often overlooked aspect regarding renewable energy technologies, in that despite having low operating costs their overall benefits are often not well understood and as a consequence are often evaluated as being less cost effective than fossil fuel alternatives. **This suggests that clarity is required to outline the contribution that can be expected of renewable energy technologies when applied to historic buildings and the reduction in carbon emission that would result.**

---

11 Woking Borough Council achieved a 49% reduction in energy consumption and a 77% reduction in CO$_2$ emissions between 1991 and 2004 through the introduction of decentralised and renewable energy generation. Kirklees Council in West Yorkshire now accounts for 5% of the UK’s installed solar PV capacity and has fitted over 160 houses with solar thermal water-heating systems.
Is PV and SHW just a new aesthetic? Historic buildings have withstood many changes in the past. Is the introduction of renewable energy technologies really such a problem? They are after all, fully demountable. One argument against them is that these interventions are simply a question of glamour because the really effective measures (insulation, improved energy efficiency and draught proofing) are simply unattractive, and from observation, often ignored. Here it is necessary to discern between heat and electricity. Heat demand correlates to fabric performance and infiltration rates whereas electricity demand does not (unless providing heating).

There is an argument that the application of LZC devices at the domestic level is not the best use of resources. Clearly a kW of PV installed in the south of England will produce more electricity annually than in the north of the UK. But these are policy issues; another example is money spent to increase insulation is better than investing in an oversized heat pump. These issues can be debated endlessly. However, when dealing with individual dwellings, professionals and householders can only operate within current financial and technically permissible parameters.

The current FiT encourages domestic PV - at the time of writing this amounts to 1.45 GW of installed peak capacity. Looking ahead this may present problems. Taking this further, with say 30% of all dwellings having a 2 kWp system, would mean a peak output of 15 GW on a sunny day in July. How would this affect the performance of the grid if 80% of this was exported at the same time?

The answer is we do not know. The same problem arises as the Domestic RHI (Renewable Heat Incentive) approaches. If 30% of homes had a 14 kW air source heat pump, the peak demand on a winter’s day could be 105 GW (it is accepted that this is a theoretical figure that would be reduced by variability within the grid). The highest output on the grid over the 2012/2013 winter in the UK was 56.8 GW (National Grid, 2013). Where would this additional generating capacity come from? These issues are not a reason to say LZC technologies are unsuited to reduce CO₂ emissions in dwellings, but more a demonstration of the disconnect between short term aspirations and long term effects, which could easily be overcome by overlapping a comprehensive energy policy with a low carbon strategy.
4.7 Summary

The benefits of adaptations to reduce energy use and carbon emissions are well documented. Energy efficiency is not new yet the take up of low energy solutions is not high, suggesting technical measures will not be enough. This is further complicated when the “take back” principle is applied. This highlights the importance for inter-disciplinary liaison to marry up retrofit with occupant behaviour.

The lack of take up of energy efficiency improvements to reduce CO₂ emissions is not wholly explained. Interest in energy efficiency has varied since the 1970’s. The steady rise in energy prices in the last decade is used to suggest that the speed of retrofit may be determined by the price of energy. This remains to be seen.

Issues in improving energy efficiency in historic buildings were outlined; areas where our knowledge is not complete were highlighted. Whilst there is no desire to experiment with historic buildings, retrofit options may have consequences on aesthetics, fabric performance and carbon emissions, therefore shared post occupancy evaluation is crucial to avoid unintended consequences.

Historic buildings were shown to have better performance than some more recent parts of the domestic stock. This should not be used as a defence to resist retrofit as their energy use remains high and can be significantly improved.

There is a clear need to bring together the conservation of heritage and the conservation of energy. It may be that we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to environmental imperatives in order to align heritage conservation with delivering acceptable CO₂ emissions and energy use. This view may gather momentum because the options to improve energy efficiency in historic buildings are limited and the imperative to tackle climate change (or at least reduce expenditure on energy) is high.

This chapter concludes by showing that the deployment of LZC technologies coupled with greater energy efficiency will assist in combating increasing energy demand and reducing CO₂ emissions. The presumption that there are only very limited options for reducing the carbon emissions of historic buildings is challenged. This is demonstrated by the National Trust which is at the forefront of a drive to show that LZC technologies can be applied to historic buildings.
Chapter 5 Critical Review Summary and Research Questions

The built environment cannot produce emissions without users. The various research threads are tied together by the desire to reduce the overall CO₂ emissions of the domestic building sector. This review gives a deep insight into domestic energy use, making us pause to acknowledge the challenging complex possibilities for CO₂ emissions reduction in the general domestic stock: couple this to the heritage restraints for historic buildings and the issue becomes an order of magnitude more complex.

In the case of historic buildings there is a view by stakeholders (English Heritage, Society for the Protection of Ancient Building’s (SPAB) and the Sustainable Traditional Buildings Alliance (STBA)) that this portion of the stock does not perform as badly as generally perceived. Little detailed and robust evidence was found to support this view; in fact the EHCS findings suggest the converse applies. The data presented coupled with the literature review indicates a strong potential for improvement. Perhaps a new approach to the study of historic buildings is required, one with a new perspective that overlooks or sets aside fabric loss, visual or real, in favour of optimising CO₂ emissions reductions.

Stakeholders have responded to pressures on the need to reduce the energy use of historic building with academic research to identify areas of concern regarding fabric performance (English Heritage, 2012; SPAB, 2012; STBA, 2012), to promote the performance of traditional building components (English Heritage, 2009a), to establish realistic data to assist accurate energy use modelling (Historic Scotland, 2011) and to provide best practice in retrofit (Historic Scotland, 2012, Changeworks, 2008; STBA, 2012).

17th, 18th and 19th (and 20th) century dwellings are a problem in the 21st century, yet the current research paradigm focuses on the generic building stock as a whole including historic and traditional dwellings; it is unclear how much CO₂ emission reduction can be reasonably expected from the sub set of historic dwellings. Though there is no agreed definitive prediction of energy savings in the domestic stock the outlook is broadly positive. This will require concerted action on a large scale to bring about any meaningful result. The main challenge lies in implementation of adaptations and the inter relationships between factors influencing energy use in buildings.
The overall position appears to be positivist in that although government statistics suggest historic and traditional buildings have high CO₂ emissions, solutions to the problem are known, action can be taken and the majority of these are straightforward measures. It appears that all the research is looking in the same direction, which is how to reduce CO₂ emissions in conjunction with the effect of user behaviour. Reductions are possible, how much in the case if historic dwellings is less sure. The challenge is how to quantify this with empirical research.

There is also a relativist view that in the absence of data there may be a preconceived opinion of the performance of historic buildings, leading to conflicting views as to the importance and potential of reducing CO₂ emissions in these buildings. Historic buildings have been shown to be a significant contributor to overall domestic CO₂ emissions. Using the date 1919 to define historic buildings does not include the large number of pre 1945 buildings that also contribute to the emission of traditional buildings in general.

This suggests that existing orthodoxy must be challenged; it is delivering little. We need to get into the detail of decarbonising these buildings, but first we need more information to make informed choices. The test will be how to make sustainable choices for historic buildings amidst complexity and uncertainty today that will be shown to be both effective and durable tomorrow.

It has also been shown that there is a role for renewable energy. What needs to be resolved is how, and what difference, this technology can make for this building type and to weigh this benefit against any changes to fabric or aesthetics.

Reviewing the current field of research leads to the question “where do we go from here” to make meaningful discoveries that will facilitate the overarching aim to reduce CO₂ emissions in our historic dwellings. One obvious direction is to collate data on the actual energy use of our historic buildings. Without knowing where we start from it is difficult to plan a route to emission reduction targets. From this it can be established if historic buildings have good or poor energy efficiency.

Another is to establish a model that accurately reflects as built energy use in historic buildings. More importantly, such a tool should be able to predict likely CO₂ reduction following technical interventions; the variation in dwelling types makes this challenging. Stakeholders remain unconvinced regarding the suitability of SAP or RdSAP for this purpose. Nevertheless a tool applicable and tailored to historic buildings is necessary in order that the real CO₂ benefits can be predicted.
CO\textsubscript{2} emissions arise from the dynamic performance of a dwelling. Reduction will be a function of fabric performance improvement, technical intervention, national energy mix and behavioural change, the bias in favour of either approach requires clarification. This necessitates a multi-disciplinary approach.

Despite the obvious attention to technical issues the larger picture of the Heritage Status cannot be forgotten. In Bath, it is the Georgian buildings that account for the large portion of Bath’s CO\textsubscript{2} emissions. There is no reason, as we enter a new low carbon paradigm, that these structures cannot remain and at the same time significantly reduce their CO\textsubscript{2} emissions.

The reality is that we need all measures; research has shown that we can reduce CO\textsubscript{2} emissions in our built stock. No one solution can bring about the required reduction individually, the problem is serious and all available resources will have to be employed. Defining the scope of the challenge to improve energy efficiency in historic buildings is not straightforward. Whatever form this takes it should include a more viable energy use with lower, if not minimal CO\textsubscript{2} emissions.

Retrofit action may have carbon consequences; this can be avoided and should be addressed through post installation monitoring to develop enhanced installation methods incorporating demand reduction, minimal waste and low carbon renewable energy technologies.

The general consensus, regardless of a dwellings age is that carbon emissions need to be significantly reduced, this means using less energy and using energy efficiently to provide service and comfort in homes. Attitudes to this orthodoxy are polarised.

On the one hand it can be argued that the “specialness” of age and character should not be obstacles to contributing to the effort society is undertaking to tackle climate change, historic building are have potential to reduce carbon emissions and there is good knowledge in achieving this. This is countered by those stakeholders charged with a duty or an interest in preserving built heritage, the defence provided is that historic building are not necessarily energy inefficient, the buildings perform better than modelling techniques predict and proposed alterations may lead to irreversible damage to these buildings.

The climate change imperative is pressing, reductions in carbon emissions are necessary across the built stock, in order to make decisions that prove to be valid and effective research must establish accurately the potential emission reductions that can be expected from the range of interventions open to historic buildings.
This review shows that there is a good deal of action that can be taken to reduce energy demand in historic buildings through improved insulation, reduced infiltration, more efficient technology, behavioural change and the use of low carbon energy from renewable energy sources.

These buildings have evolved continually since they were constructed, absorbing and adapting to technology where desirable and affordable. Open fires were once the only source of heating; today this has evolved into sophisticated central heating systems with multiple zones that can be controlled away from the home. There is no reason why historic buildings cannot continue to evolve in coming decades whilst preserving their own distinct and unique contribution to our urban landscape.

5.1 Adopted Research Questions

1. Quantify the energy use (thermal and electric) and CO₂ emissions for historic buildings in Bath.

2. Assess the potential for building integrated renewable energy technologies to reduce CO₂ emissions in historic buildings.

3. Quantify the reduction in CO₂ emissions following energy reduction adaptions and the application of LZC technologies.
Chapter 6 Methodology

This chapter describes the methodology evolution to answer the research questions derived from the literature review. It provides a description of the process in selecting the research strategy considering the merits, methods and procedures of available approaches to allow selection of one methodology over other options.

The chosen approach will centre on the premise that for any “solution” to be effective in delivering large-scale cuts, it must be replicable at district scale. This leans towards existing and near to market integrated retrofit solutions combined with a systemic approach for their application.

From the overall thesis methodology three research areas emerge. The methodology for these is within the relevant subsequent chapters.

6.1 Research Design

The main stages identified are based on Maxwell (2005), who though referring in particular to qualitative research, considered that the design of such research is dynamic; there is no reason why this could not be applied to quantitative research. Figure 39 shows the interactive approach proposed.

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![Interactive Approach](image)

**Figure 39 Interactive Approach**
6.11 Objectives

From the literature review and selected research questions the following objectives (goals) were identified:

- Benchmark energy use for historic buildings through data collection.
- Comparison of actual energy use to modelled energy use.
- What LZC technologies are suitable/appropriate for historic buildings?
- What contribution can LZC technologies make to reducing CO₂ emissions?
- Evaluate emission reductions following retrofit adaptations.
- What levels of CO₂ emissions can reasonably be expected.

6.12 Conceptual Framework

A roadmap (Conceptual Framework) was developed; the nature of the research questions created three distinct milestones, see Figure 40.

<table>
<thead>
<tr>
<th>Milestone 1: Data Collection</th>
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<tbody>
<tr>
<td>- What buildings to measure.</td>
</tr>
<tr>
<td>- How many buildings to measure.</td>
</tr>
<tr>
<td>- How to measure, what data to collect.</td>
</tr>
<tr>
<td>- Interview or questionnaire.</td>
</tr>
<tr>
<td>- What external data sources are available to provide comparative energy use.</td>
</tr>
<tr>
<td>- How to establish statistical relevance.</td>
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<td>- How accurate are the results.</td>
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<tr>
<th>Milestone 2: The Role for Retrofit</th>
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<tbody>
<tr>
<td>- What and how many case studies to use.</td>
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<tr>
<td>- What retrofit and LZC technologies to consider.</td>
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<tr>
<td>- Performance of selected LZC technologies.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Milestone 3: Modelling energy use and CO₂ emissions</th>
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<tbody>
<tr>
<td>- What software models are suitable and how to select which would be appropriate.</td>
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</tbody>
</table>

Figure 40 Methodology Roadmap
In summary, the designed methodology must first gather data to establish accurately energy use in historic buildings. Consideration should be given to define suitable retrofit adaptations that will facilitate a reduction in CO$_2$ emissions. Then, following model analysis, it should evaluate the model’s effectiveness at predicting energy use by comparison with the actual energy use and quantify the reduction in energy use and CO$_2$ emissions.

6.13 Validation

It was clear that validation would be necessary at all stages within the methodology. From the accuracy of any data collected on energy use, the accuracy of the data supplied to model energy use, to the reliability of the results provided by the selected model. Selecting case studies from the data collected presents an ideal opportunity to validate the model predicted energy use results against actual energy use data.

6.2 Methods

6.21 Data Collection

There exists however a contextual relationship between occupants and energy use, suggesting a mixed methodology approach. For data that can be measured accurately the quantitative approach applies. This is well known, understood and an accepted research paradigm. But there are areas that are more subjective, such as attitudes to energy use and renewable energy generation. Where such variables cannot be measured accurately a qualitative approach is necessary.

Two approaches were identified to generate a benchmark of energy use. One, a top down approach that uses aggregated data and energy use available from government statistics. Options include published energy use data from DECC that includes national, regional, local authority (down to clusters of 2000 meter readings) and local post code clusters (containing an average of 31 meter readings). To develop a database this energy use would need to be normalised by floor area. To establish this at regional level and above though possible would be a mammoth task. However, the use of post code cluster data and the use of GIS mapping and drive by surveys would permit the establishment of dwelling floor area to a reasonable level of accuracy. This is an area for future work as sub-national consumption gas energy use data is weather corrected and is available from 2010.
The other, is a bottom up approach that gathers the data directly from the dwellings themselves. To some extent the latter should be a validation of the former.

The use of aggregated data can provide a benchmark of energy use for dwellings in a defined area. This can only be an indication of average energy use, as data is not available to derive the benchmark of energy use of building typologies or historic buildings specifically (although it could be if the information was in the public domain). Nonetheless it is required to serve as a comparison.

Thought was given to how far the data collected should be disaggregated. A minimum that would be acceptable is the total energy used for heating, hot water, lighting and appliances. As the area of research is in an urban setting this could be further divided to look at gas/oil heating and electricity use. It was clear that in order to arrive at a representative benchmark the disaggregated approach was essential. This was considered appropriate as it had high potential to deliver the research question, namely establish a database for energy use in historic buildings. Therefore the chosen methodology will require the collection of actual energy consumption.

The options to gather data were limited. A survey seemed appropriate. The alternative was to call house to house or to seek opportunistic data through contacts or a limited form of advertising or through community groups. These alternatives were rejected, asides from not being random they may actually be self-selecting to promote efficient energy use.

There was a concern with relying on survey sourced data as targeting the identified building typologies with a postal survey can expect a low response rate. Experience for the Marches Energy Agency on the Sustainable Energy Communities in Historic Urban Areas (SECHURBA) project achieved only single figure response, even with follow up.

Following discussion with the Marches Energy Agency, the likelihood of a high response rate for survey derived data seemed unlikely. Yet, despite this, it remained the only option as it was recognised that any data collated must be statistically significant. Relying on opportunistic data sources would diminish the statistical significance.

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12 MEA conducted postal survey to assess carbon footprint of dwellings as part of a European Funded Project.
There were other factors that supported adopting a survey approach. This arose for two reasons, firstly collating data may take respondents some time if bills are not immediately to hand, and secondly, it was perceived that cold calling to obtain energy use information would be challenging to generate enough (if any) responses.

There were challenges in adopting a survey approach apart from improving response rates, what length to make the survey and the accuracy of respondents replies (particularly for providing empirical inputs with which the respondents might not be familiar). These are explained in Chapter 10.

6.22 Role for Retrofit

Retrofit includes a range of options, it was necessary therefore to include a review of the options and to sensibly group these to reflect a realistic district scale adaptation of historic buildings. This is covered in detail in Chapter 9. It was anticipated that due to the nature of the constraints arising from the heritage of the surveyed dwellings not all retrofit options would be suitable.

Initially, key areas of interest were the use of LZC technology and upgrading the thermal performance of the external envelope. The option for improving external wall thermal performance was limited to internal wall insulation as it was unlikely that alterations to the external appearance of historic buildings would be unlikely to receive planning approval. The options for LZC were more varied, therefore a review of these is considered in Chapter 8.

6.23 Modelling Energy Use and CO₂ Emissions

This was perhaps the most difficult milestone to define, it is also the most important as the results generated here will form the key findings in the research project. Chapter 7 contains the steps taken to determine model selection.
6.3 Adopted Methodology

The adopted methodology is represented in Figure 41.

**Figure 41 Outline Methodology**

- **Data Sources**
  - Survey
    - Survey of Dwelling energy use
  - National Statistics
    - District energy use
    - National energy use

- **Benchmark Energy Use (Data Base)**
- **Average Energy Use (Data Base)**
- **Select Case Studies**
- **Energy Use Model Review**
- **Selected Model**
- **Potential for reducing CO₂ emissions in Bath**

**Case Studies retrofit assessment:**
- Envelope performance:
  - Internal wall insulation
  - Windows/doors
  - Infiltration
  - Roof/floor insulation
  - Heating plant
  - LZC technology
  - Lighting
  - Controls

**Data Sources:**
- Survey of Dwelling energy use
- District energy use
- National energy use

**Selected Case Studies:**
- Survey of Dwelling energy use
- District energy use
- National energy use
6.4 Limitations

The following limitations were identified:

**Occupant Behaviour**: it was apparent that the role of occupants, though accepted as important, is a research field in itself. Therefore it is not explored within this thesis although there was an opportunity to gather data on occupant attitude to energy use and renewable energy adaptations; it was decided to explore this in future research due to time limitations.

**Aesthetics**: critical assessment of the aesthetic appropriateness of each LZC technology to historic building type was intentionally avoided. The aim of the research was to provide empirical data on retrofit adaptations to inform stakeholders considering aesthetics changes that deliver significant CO$_2$ emissions savings, thereby assisting in rational decision making.

**Fabric Performance**: the literature review showed that reducing heat loss through external walls is a key component of reducing energy use in dwellings. It also shows that the effect the application of wall insulation has on external walls is complicated and is the subject of detailed on-going research. No evidence was found to state that this would lead to fabric decay. This work evaluates the CO$_2$ emissions savings following this adaptation only, accepting that the effect of such measures on the long term performance of the fabric requires additional research.

**Cost**: Consideration of this would require detailed analysis to deliver a least total system cost arising from an optimum mix of demand and supply measures. Aside from time constraints, monetary evaluations are only valid for a very short time frame and can be very building specific. Another consideration was that information on cost benefit is dependent on typical dwellings and is generally only an indication. This work wanted to be precise, offering carbon benefits that are based on real time energy use in the case study dwellings. A final factor is that there are number of stakeholders and energy bodies (Energy Savings Trust, RICS, Local Council websites) that produce useful information that gives a reasonable indication of the cost benefit of domestic energy efficiency measures.

**Analysis of life cycle CO$_2$ emissions**: this is another specific research area and one that is receiving increased interest. There is no work to suggest that the proposed retrofit adaptations would be carbon positive (that is to say they would lead to increased total CO$_2$ emissions) in the lifetime of the materials and components selected. This aspect will not be explored, although it is an area where future research is required to ensure there are no carbon consequences of retrofit adaptations.
6.5 Summary

The design methodology plans to gather survey data on energy use, establish a benchmark of energy use in building typologies comparing this with regional data, select a suitable model, model the energy use and CO\textsubscript{2} emissions of case study dwellings and compare this with actual energy use and the benchmark data. It will then evaluate the benefit of retrofit adaptation packages to establish reduced levels of energy use and emissions reduction based on actual energy use.

The main considered elements were:

- Identify available data sources to develop generic regional and local benchmarks.
- Sample definition to achieve statistically representative results.
- Survey design.
- Creation of a database with benchmark energy use information.
- Statistical analysis of results.
- Parametric modelling of retrofit adaptations to include fabric elements and energy plant.
- Assessments of potential LZC technology retrofit options.

These are all covered in detail in the following chapters.
Chapter 7 Model Selection

7.1 Model Requirements

Establishing energy use for a dwelling and the changes that arise from retrofit adaptations requires software modelling, identified elements were:

- Collect delivered energy use data for minimum of 12 months to establish actual energy use.
- Model predicted gas and electricity energy use and carbon emissions.
- Consider balance of ease of: use v cost v output detail.
- Include appliance and plug in electricity use.
- Reflect as built building characteristics.
- Results based on weather data set relevant to case studies.
- Compare actual energy use from data base to model predictions.
- Model the energy and carbon savings for retrofit measures.
- Evaluate the contribution of a 2.0 kWp PV array (typical domestic sized array).

The constraint of time impacted on the selection of the model for analysis of retrofit adaptations. This led to selecting only one model to run for the full retrofit evaluation. To some extent this is not a constraint, as selecting additional models may have led to making a comparison between models and the pros and cons of each package. This would be an area of study in itself. The aim of this research is to evaluate CO₂ emissions savings in a clear manner in order to permit decision making when considering loss of fabric and aesthetics.

7.2 Model Options

There are numerous modelling tools available to assess domestic energy use. The critical analysis identified stakeholder concerns regarding the accuracy of modelling techniques to predict actual energy use in historic buildings.

Models can either be dynamic or steady state. A dynamic model is generally considered to be more accurate and capable of delivering a dynamic response of the building through the use of real time hourly weather data. Steady state models are generally considered less accurate as they cannot generally reflect the dwellings dynamic response to detailed weather variations.
At the outset it was recognised that SAP would have to be included as it is the UK NCM for compliance with EPBD. But stakeholder’s lack of confidence in its accuracy with regard to historic buildings highlighted in the critical review meant it was necessary to consider another model. Such a model would have to demonstrate potential to foster greater acceptance not only with stakeholders but with architect and designers.

PHPP was selected because of its transparency regarding how results are determined, relative ease of use and inclusion of appliance energy consumption and its affordability. The perceived disadvantage of not having been readily applied to historic buildings, although a retrofit standard exists, was viewed as an opportunity to explore its suitability for this sector of existing dwellings.

Both SAP and PHPP are steady state models. It was decided to also include a dynamic simulation model as it was important to determine the loss of detail in adopting a steady state model, which if not considered would lead to criticism of the results. A number of dynamic modelling options were considered. Table 3 shows only the salient advantages and disadvantages of the dynamic models considered. This list is not exhaustive.

While dynamic simulation software are considered likely to deliver more accurate results they are more expensive, time intensive, have complex data inputs, require a period of user training and are not specifically designed for small scale domestic use.
Table 3  Table of Comparison of dynamic models

<table>
<thead>
<tr>
<th>Model</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>IES</td>
<td>CAD data can be imported using plugins. Good interoperability with other platforms.</td>
<td>Not fully integrated into the design process</td>
</tr>
<tr>
<td>Energy Plus</td>
<td>Open source. Can import designs.</td>
<td>No visual interface to see buildings.</td>
</tr>
<tr>
<td>ESP-r</td>
<td>Capable of simulating innovative technologies. Buildings can be graphically represented in EPS-r. Open source.</td>
<td>Requires user energy knowledge and expertise. More suitable as a general purpose tool.</td>
</tr>
<tr>
<td>HTB2</td>
<td>Highly suitable for research and specialist interest groups (e.g. aspects such as heating control energy use feedback).</td>
<td>Excludes constructing 3D models of the designs. Complex software can require a considerable period of learning to exploit full potential.</td>
</tr>
<tr>
<td>TAS EDSL</td>
<td>Responsive and accurate tool for concept development. Easy to customise for areas of concern.</td>
<td>Not intended for detailed services layout design.</td>
</tr>
<tr>
<td>Ecotect</td>
<td>Suitable for early design stages. More suitable for use by architects.</td>
<td>Primarily intended as a conceptual design tool. Limitations for detail thermal analysis.</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>Suitable for unconventional energy systems.</td>
<td>User unfriendly input of the building data.</td>
</tr>
</tbody>
</table>

From this IES was selected not because its results would be more accurate than any other dynamic model, but because it is recognised as an industry accepted model, a licence for its use was available and the author had previous experience in it use.

In summary therefore, Integrated Environmental Solutions (IES) software, Standard Assessment Procedure (SAP) (2009) and Passive House Planning package (PHPP) 7.0 were assessed for suitability to model energy use, see Table 4 for their comparison. (More models could have been considered but time constraints prevailed).

It should be noted that it was not the intention of this study to make a detailed comparison of these models with one another but to consider the PHPP and its potential to develop stakeholder and architect confidence in its use for historic buildings.
## Table 4  Model Comparison

<table>
<thead>
<tr>
<th></th>
<th>IES VE</th>
<th>SAP 2009</th>
<th>PHPP Version 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic calculation method</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Steady State calculation method</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Monthly heat load</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Number heating zones</td>
<td>variable</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>NCM compliant</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Alternative weather data sets</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Software Cost</td>
<td>£££</td>
<td>££</td>
<td>£</td>
</tr>
<tr>
<td>Window orientation</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>Hard</td>
<td>Easy</td>
<td>Medium</td>
</tr>
<tr>
<td>Transparency</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Suitable for historic buildings</td>
<td>Y</td>
<td>N</td>
<td>Unknown</td>
</tr>
<tr>
<td>Potential to replicate</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Appliances electricity use</td>
<td>N(^1)</td>
<td>N(^2)</td>
<td>Y</td>
</tr>
<tr>
<td>Appliances incidental heat gain</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Evaluates solar hot water</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Evaluates PV array to CO(_2) emissions reduction</td>
<td>Y</td>
<td>Y</td>
<td>Y(^3)</td>
</tr>
<tr>
<td>PV generation based on dwelling actual location</td>
<td>Y</td>
<td>N(^4)</td>
<td>Y</td>
</tr>
<tr>
<td>Internal heat gain</td>
<td>User Input</td>
<td>5.9 W/m(^2)</td>
<td>2.1 W/m(^2)</td>
</tr>
<tr>
<td>Energy Use Reporting</td>
<td>Primary and delivered</td>
<td>Primary and delivered</td>
<td>Primary</td>
</tr>
</tbody>
</table>

Notes:  
1. revision in progress  
2. includes incidental heat gain only  
3. although not included in energy use and CO\(_2\) emissions results  
4. uses data for Sheffield, UK  
5. can be input manually from IHG sheet to Annual Heat Demand Sheet
It was also necessary to run the IES model to evaluate all the proposed retrofit measures in order to assess the extent of detail lost when opting for a steady state analysis only. This presented additional work that would extend significantly the research period. For this reason a fellow researcher, Tom Blight, was approached to contribute this element of analysis. As a result he is a co-author of the paper that emerged, see Annex D Paper 3.

7.3 PHPP

PHPP is a spreadsheet design and compliance tool produced by the Passivhaus Institute to model the performance of a proposed Passivhaus building. It is considered an accurate tool because it was systematically developed by comparing dynamic simulations to validated measurements in completed Passivhaus projects. Though not specifically designed to model energy use in historic buildings it is used for the retrofit of existing buildings (EnerPHit\(^{13}\)) and has targets for heating and non-heating energy use.

The Passivhaus Standard has a high degree of flexibility in that energy use targets can be met using a variety of design strategies, construction methods and technologies. Local regional weather data can also be inserted or imported; this study used the (free download) Severn Valley data set from the BRE\(^{14}\). It also allows occupancy to be prescribed, as well as starting conditions for the performance of the dwelling (including internal temperature, infiltration level, appliances and electrical goods).

Passivhaus methodology is primarily energy driven and focuses on minimal fabric and ventilation losses, maximum passive internal heat gains and solar gain in winter (requires attention to avoid summer over heating), the use of energy efficient MVHR (mechanical ventilation heat recovery) plant (requires a very low heat load) and incorporates LZC (Low and Zero Carbon) technologies to meet the remaining energy demand.

All of the PHPP model parameters seem at odds with the characteristics of historic buildings. However the intention was to predict actual energy use of these buildings. Whilst PHPP is concerned with very low energy dwellings there is nothing in its description to suggest that it is not capable of predicting energy use in less thermally efficient buildings that fall way sort of the PH standard.

\(^{13}\) PHI has developed the “EnerPHit – Quality-Approved Energy Retrofit with Passive House Components” Certificate for the refurbishment of old buildings. Max heat 25kWh/m\(^2\)a, max primary energy demand 120kWh/m\(^2\)a

\(^{14}\) Available to download via http://www.passivhaus.org.uk/page.jsp?id=38 (accessed 12/12/2012)
For this study the intention was not necessarily to meet the EnerPHit standard, but to assess the potential reductions arising from retrofit adaptation for the case study buildings. The prospect of applying PHPP to historic buildings may be considered as asking too much of a model that relies on high levels of thermal insulation, low levels of infiltration and MVHR with a constant and evenly distributed internal temperature in the heating season and applying it to draughty, thermally inefficient and intermittently heated historic dwellings. But it should be remembered the intention is to ascertain its suitability as an affordable, easy to use, accurate and stakeholder accepted means to empirically evaluate retrofit adaptations in terms of carbon emissions savings.

7.4 Model Limitations

There are limitations to using the PHPP, either as a result of the way the software operates, or from the methodology proposed in this study, these can be outlined as:

- It is not a dynamic modelling package, so suffers from limitations of quasi steady state approaches.
- Thermal bridges present little opportunity for amendment in historic buildings; they are also difficult to measure, though this could be done through thermal imaging. In this study, default settings were accepted which may underestimate the effect of thermal bridges.
- What airtightness to start from and what to reduce to (this is discussed further in Chapter 12).
- MVHR may be impractical in existing historic buildings (though it may be possible to consider the point use of MVHR for bathrooms and kitchens).
- The risk of possible summer overheating if internal wall insulation disconnects the internal air from large areas of thermal mass. (PHPP only uses whole house average temperatures rather than individual room temperatures to assess this risk).
- The potential for improving the performance of windows was limited to maintain heritage aesthetic appearance.
- Electricity generated by Photovoltaic (PV) systems, although calculated, is not counted against the primary energy target although the use of Solar Hot Water (SHW) is counted towards the gas primary energy use.
- There is no clear methodology for dealing with intermittent heating. Options are to reduce the internal temperature from 20°C (there is no data on how to establish the lower temperature, one possibility would be to use the BREDEM/SAP algorithms to calculate the decay and hence the average internal temperature and use this figure as the internal set temperature). Another more straightforward approach is to apply a reduction factor (annual heat demand worksheet).
The results may overstate the expected savings as the “take back” or “rebound effect” is not catered for (applies to all models).

PHPP methodology deliberately avoids the carbon benefit of PV generated electricity (or any other LZC electricity generating technology) to prevent poor standards of energy efficiency being offset by the use of renewable energy. Given the importance of built heritage and the challenges in tackling CO₂ emissions, this rigid position may prevent a large number of older dwellings meeting the EnerPHit standard. This study includes an assessment of the benefit of PV generated electricity on overall energy use and emissions.

It is worth noting that default energy use in PHPP is reported as primary energy, whereas the majority of other models and databases give delivered energy figures. This requires care when using conversion factors (that vary with time and from country to country), so results can be equally compared.

It was not possible to, due to time constraints, to model all building typologies. It was decided to focus on terrace dwellings as they have the highest incidence in Bath. This has limitations as the selected building typology may not be representative of other historic buildings in Bath due to difference in fabric, previous energy use alterations/improvements and the behaviour and attitude of the occupants. Despite this limitation, the case studies remain relevant as their performance will be representative in demonstrating the benefits of retrofit adaptations, e.g. demonstrating the effect of solid wall insulation or the use of PV solar panels.
Chapter 8 Low and Zero Carbon Technologies (LZC)

It is necessary to evaluate the carbon reduction potential of LZC retrofit adaptations in the scenario of historic buildings. The reason for exploring LZC technologies is that they have the potential to develop a “step-change reduction in energy demand” from dwellings (Hinnells, 2008).

The use of these technologies is available to all buildings, and aside from issues of aesthetics and possible alteration to the buildings fabric to accommodate their installation, they perform equally well on historic buildings.

The limitations in following a fabric approach in historic buildings may necessitate implementing a new orthodoxy that raises the possibility of LZC being considered alongside rather than after the current “fabric first” approach.

The options are now reviewed in order to justify inclusion in Chapter 12, Modelling Energy Use.

8.1 Condensing Gas Boiler

Is a condensing gas boiler a LZC? Some may argue that it is not. It is included here because it can be a low carbon means to provide heating and hot water (particularly compared to electricity and oil), even lower than some perceived renewable energy technologies, e.g. air source heat pumps.

A well installed and commissioned gas condensing boiler can reach plus 90% seasonal efficiency. This would require a heating system that returns hot water to the boiler lower than 45°C to take full advantage of the efficiencies that arise from recuperating the latent heat of evaporation from the exhaust flue gases (which is why a vapour plume is seen from condensing flues).

In an historic building this may be possible with existing radiators as following retrofit adaptations the heat demand may be lower and the radiators therefore become oversized. An alternative, though challenging in historic buildings, is to use under-floor heating.
Further efficiencies can be obtained through the use of controllers. As a basic measure it should include a thermostat (as of 2010, 6 million homes did not have a room thermostat, English Housing Survey, 2011). A programmer that is “user friendly” is also required. A further gain can be made using a weather compensator (tracks external air temperature to heating return temperature, aiming to keep this as low as possible to meet dwelling heat demand).

8.2 Photo Voltaic Panels (PV)

As this research considers specifically the city of Bath, only grid connected or utility-interactive systems are considered. The panels can either be mounted on the dwelling, normally the roof, or grounded mounted in proximity of the dwelling. In the case of ground mounted systems there are fewer planning restriction when located within the buildings curtilage. Where aesthetics are an issue this is a preferred solution.

When mounted on a roof there are two options, directly fixed to the roof structure or integrated into the roof, commonly called “building integrated” photo voltaic (BIPV).

There are 3 main types of PV panels:

- Multicrystalline silicon: These modules consist of many randomly oriented crystals of silicon. Typically each module converts 8-12% of the solar radiation into electrical energy.

- Monocrystalline silicon: These modules consist of a pure single crystal of silicon wafer. Typically each module converts 15% of the solar radiation into electrical energy.

- Amorphous silicon: These modules are constructed with very thin layers of material (as little as 1/1000 mm thick). As the amorphous silicon has no long range crystal structure modules it has low efficiencies of between 4 and 6%.

In the case of listed buildings, the main limitation arises from aesthetics; in that roof mounted PV technologies are located where they are not visually obtrusive. In Bath, this suggests that elevations away from the main facade, concealed valleys and external buildings are suitable sites. Figure 42 shows PV installation on dwellings in and around Bath.
For conservation areas there is less restriction and they are currently subject to permitted development rights. This means they can be located on any facade, even if visible from the front of the building.

One option to address aesthetic issues is to use BIPV, see Figure 43 (narrow horizontal band above dormer roof). As the PV modules form part of the roof the most economical way to install these is when in the process of reroofing a property, otherwise the costs for removing the roof covering for installation makes them less financially viable.
Although the “Heritage” PV slates in Figure 43 have a similar appearance to natural slates the difference is still discernable, and so therefore still has a visual impact (English Heritage, 2012a). It should also be noted that the expected life of the PV slate will be much less than that of a natural slate (20-25 years producing electricity/40-50 years as a tile years versus 100 plus years for slate).

Historic Scotland (2009), takes the view that in order to protect the integrity of the building it is usually desirable to mount photovoltaic modules as panels over existing slates, rather than replacing historic fabric with look-alike photovoltaic materials in the form of slates.
Regardless of the visual merits of BIPV there is a technical downside. The key issue is overheating of the PV module/slate that reduces the efficiency of electrical output, therefore careful attention needs to be given to ensure adequate ventilation.

A critical issue on historic roofs is the fixing method employed. Figure 44 shows a bracket fixing drilled directly through the slate roof covering into a rafter below, the bottom right image shows the cable entry from the PV panels into the roof space using a lead cover flashing. These details satisfied the installation of a PV system on a listed building in Bath.

Figure 44 Roof mounted PV fixing on slate roof

Other options include cradle brackets, see Figure 45.
Output is dependent on available roof area and orientation. But output may be of little benefit in reducing carbon emissions if it is not aligned to demand. This is explored further in Chapter 11.
8.3 Solar Hot Water (SHW)

The same principle for PV applies to SHW in terms of location. There are two principle types of the solar collector in the UK, see Figure 46. The Energy Savings Trust (EST) found little difference in the solar fraction of either system in a recent field trial (EST, 2011).

Solar thermal collectors can contribute 50% to domestic hot water in a standard installation. (DTI 2001; Jenkins et al., 2012). The EST (2011) reported that properties with well-installed and properly used systems provided around 60 per cent of a household’s hot water.
The PHPP gives a solar fraction of 55% with flat plate collectors and simple solar storage; this can rise to a solar fraction of 60% for stratified solar hot water storage with a domestic hot water heat exchanger. The use of an evacuated tube collector increases the solar fraction further, see Figure 47.

![Figure 47  PHPP SHW performance](image)

For this analysis simple solar storage with an evacuated vacuum tube was selected; this was sized to contribute 60% of hot water demand. As SHW is a well-established technology, in both new and retrofit situations, it was decided that no additional performance information was required to develop the contribution this technology can make to historic buildings energy use.

### 8.4 Heat Pumps

Heat pumps are a proven high-efficiency heating systems with numerous European examples of best practice in both new build and retrofit (Hewitt, 2011). Best efficiencies are obtained in well insulated houses with underfloor heating (appropriately sized radiators can perform very close to underfloor heating) and low infiltration rates. All of these present challenges in historic buildings retrofit but are not insurmountable.
In Bath, the option is between air source heat pumps (ASHP) and ground source heat pumps (GSHP). The River Avon could present the potential for a water source heat pump but this would only be possible for properties adjacent to this water source.

In the retrofit scenario, GSHP were discounted for two reasons. In Bath there is a significant concentration of known archaeology and archaeological potential where ground disturbance is likely to be harmful. Also, drilling long boreholes is always challenging in an urban scenario, more so when there is a significant concentration of known archaeology. In addition vertical boreholes need to have regard to the Avon Act (1982) which protects the source of the Bath hot springs.

A recent UK study by the Energy Saving Trust (2010) found that the performance of ASHPs was disappointing. Explanations were attributed to several factors, including inadequate design and sizing of the heat pump systems, and the greater knowledge and experience of European installers resulting in better installed systems. This is probably a reflection of the relatively small number of installations completed in the UK and that it is an emerging technology. Figure 48 shows a 14kW heat pump installed on an historic building near Bath.

Figure 48  Mitsubishi Ecodan 14kW ASHP serving detached historic building.

A follow up in-depth consumer survey of participants in the EST heat pump field trial showed that the majority of users were very satisfied with their ground source or air source heat pump systems (Caird et al., 2012) showing that despite installation issues it has the potential to provide acceptable comfort conditions.
It was decided not to investigate the potential for an ASHP to contribute to CO$_2$ emissions. The EST trial shows that while we are still on the learning curve for this technology it can deliver heating at a lower carbon cost than gas. Any future reduction in grid carbon factor will increase the advantage of a heat pump system. For a heat pump to be effective it first requires a fabric first approach; this analysis will determine how far retrofit for improving the fabric performance can reduce the heat demand, setting future criteria for considering the benefits of heat pumps.

8.5 Biomass Boilers

These were not considered as being suitable to include in this study for several reasons.

One is the on-going debate regarding the use of biomass for the provision of heating and hot water to reduce carbon emissions from domestic dwellings. Researchers and practitioners have also disclosed concerns surrounding the sourcing, processing, transporting of biomass fuel, and increases in NO$_x$ and particulate emissions as a result of biomass boilers. A recent report by the ACEB (2010) concluded this may actually lead to higher CO$_2$ emissions. More recently, CIBSE (2012) has also questioned the low carbon benefits of this technology.

A different position is taken by SAP (2009) which suggests carbon emissions from biomass fuel are around a tenth of those from burning gas. The recent negative publications are mainly technical in nature and are contradicted by other research. Keirstead at al. (2012) reported that biomass offers significant carbon savings with acceptable levels of urban air pollution when compared with a gas boiler reference case.

In terms of general air quality guidelines, existing regulations are in place to limit adverse health effects related to combustion of biomass in populated areas. The combustion of biomass is often linked to emissions of pollutants such as PM (particulate matter), NO$_x$ and SO$_2$ (based on fuel composition) and CO (based on combustion quality) (Görgen et al., 2007; Villeneuve et al., 2012).

This research has not considered biomass as a suitable candidate for its application at the district scale, primarily because of possible negative side effects of atmospheric particulate pollutants though options to consider it on an individual basis are appropriate. Another consideration was that Smoke Control Areas in many urban locations require the installation of appliances from an exempt appliance in accordance with the Clean Air Act 1993. An approved list is available from DEFRA (2012).
8.6 Combined Heat and Power (CHP)

The majority of domestic scale systems available in the UK are based on the Stirling engine, which generates between 1-3 kWe of electric power and 6 to 12 kWth of heat (EST, 2010). Micro-CHP is viewed as an emerging technology with a limited range of products available at present.

For micro CHP to be effective it requires a constant (all year) source for the heat produced when generating electricity. In a dwelling the heat load is seasonal. This leaves the hot water load, which although fairly constant is not high. For this reason this work has not explored the effect of CHP systems; moreover it has sought to explore the benefits of fabric thermal performance, the benefits of which reduce the suitability of CHP (as discussed in Chapter 4). Where this is not possible or does not bring significant reduction in energy demand the use of CHP is clearly an area for future research.

Another possible consideration is the possibility to amalgamate hot water loads to provide sufficient demand in a mini heat network; this may present an opportunity in multiple occupancy units.

8.7 Wind

Now accepted as not suitable in the urban setting and is unlikely to meet embodied energy costs (Warwick Wind Trials, 2009) so was not considered further.

8.8 Hydro

As no water source is available to individual dwellings this was not considered further. The presence of the River Avon presents an opportunity for hydro generation at the city scale; this would be an area for future research as part of the potential for renewables generally in the BANES area.

8.9 Summary

From the review of LZC technologies both SHW and PV will be included in the retrofit options. Efficient gas boilers will also be adopted.
Chapter 9 Retrofit Adaptations

The adopted methodology aims to reflect typical Bath dwellings and retrofit options that as well as being effective are affordable. This Chapter sets out the retrofit that will be modelled in Chapter 12.

9.1 What is Retrofit?

The traditional definition of retrofit is to provide the same level of comfort using less energy (similar to energy efficiency); this paper focuses on emitting less CO₂ emissions as the key parameter. This distinction is important, as using LZC produced energy, although not necessarily significantly reducing energy use, may deliver sizable CO₂ emissions emission reductions in the dwelling, particularly when offsetting high carbon factor delivered energy, e.g. current grid electricity.

Energy use can be divided into heat and power. In dwellings energy is used through components to achieve overall comfort and service conditions. The reduction of energy use and by proxy, the reduction of CO₂ emissions, can be driven by improving energy efficiency, fabric thermal performance or by using LZC technologies in conjunction with intelligent and user friendly controls. The effectiveness of these approaches are shaped by occupant behaviour. This aspect is not considered in this study.

9.2 Adaptation Options

The potential retrofit adaptations were divided into three packages and are summarised in Table 5. The Technology Strategy Board (2009) “Retrofit for the Future” recognises that it can be very challenging to improve existing dwellings to the point where space heating useful energy is below 40 kWh/m²/yr. To reach a level such as the 15 kWh/m²/yr in Passivhaus may depend on the building undergoing major refurbishment to the point where the roof and ground floor are replaced and the external walls are insulated.

For this analysis it was decided to adopt measures excluding major refurbishment, they are grouped into 3 distinct packages:
Retrofit Package 1 (RP1): considered adaptations that are generally low cost and straightforward. Underfloor insulation was included although possibly difficult and not low cost, it is necessary to achieve maximum draught proofing as well as to improve insulation levels. This package includes 12 interventions that were modelled collectively as a standalone retrofit step.

Retrofit Package 2 (RP2): upgrades the thermal performance of the external wall fabric. Internal solid wall insulation was included as a separate measure to investigate the potential contribution this element makes to reducing energy consumption. External wall insulation was eliminated due to the potential negative effect on aesthetics, although there may be scope for this approach on rendered dwellings or on some rear elevations that are of little or no heritage value. As there would only be one opportunity to improve this aspect in a dwelling an ambitious U-value was adopted.

This approach may require further research to consider possible implications. One issue is that driving rain and absorbent stone may create a risk of fabric decay. Hemp batts and sheep’s wool were selected to permit moisture movement through the wall construction as they have good vapour permeability and hygroscopic performance. Increased thermal performance of the internal face will, of course, lead to reduced external wall temperatures which will carry an increased risk of future frost damage in certain wall types and in certain locations. Another issue is that this construction amounts to 150mm and will reduce internal floor (in the selected case studies in Chapter 12 this amounts to 4-5% as these are relatively small properties).

Retrofit package 3 (RP3): Following the review of potential LZC technologies (Chapter 8) this package assessed the potential for Photovoltaic Panels (PV) and Solar Hot Water (SHW) to reduce CO₂ emissions.

A more detailed explanation of the retrofit measures is at Table 5:
Table 5  Details of retrofit packages

<table>
<thead>
<tr>
<th>Serial</th>
<th>Adaptation</th>
<th>Specification</th>
<th>Target</th>
<th>EnerPHit Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Roof insulation</td>
<td>Minimum 270mm fibre glass</td>
<td>U= 0.14 W/m²K</td>
<td>0.12 W/m²K</td>
</tr>
<tr>
<td>2</td>
<td>Insulation to timber suspended floor</td>
<td>100mm foil backed polyisocyanurate board with breathable vapour membrane above insulation</td>
<td>U= 0.27 W/m²K reduced infiltration</td>
<td>0.15 W/m²K</td>
</tr>
<tr>
<td>3</td>
<td>Draught proof</td>
<td>Seal uncontrolled air ingress routes</td>
<td>q50 9.6 ach @50pa ( see section on infiltration)</td>
<td>&lt;1.0 ach @50pa</td>
</tr>
<tr>
<td>4</td>
<td>Window thermal performance</td>
<td>Either replaces single glazed sash windows with double glazed units or overhaul window and fit secondary glazing (dependant on the condition/heritage value of the window). No works to existing double glazing was considered, allocated U = 3.0 W/m²K Double glazed sash window U= 2.23 W/m²K Secondary glazed unit U=2.30 W/m²K</td>
<td>0.85 W/m²K</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Central heating boiler</td>
<td>Upgrade to efficient condensing boiler designed to take advantage arising from low return temperatures. Include thermostatic radiator valves</td>
<td>Seasonal COP 90%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Central heating pump</td>
<td>Low power high efficiency pump</td>
<td>Auxiliary electricity power reduced from 100W to 25W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Insulate all service pipe runs and eliminate dead legs</td>
<td>40mm foam insulation, no runs in cold spaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Washing machine</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fridge freezer</td>
<td>Upgrade</td>
<td>A++ energy rating</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Dish Washer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Clothes Dryer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Lights</td>
<td>CFL or LED</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Internal wall insulation</td>
<td>Comprising timber stud frame with 100mm sheep’s wool or Hemp batts insulation with 40mm wood fibre boards, finished with 12mm lime plaster.</td>
<td>U= 0.24 W/m²K</td>
<td>0.3 W/m²K</td>
</tr>
<tr>
<td>1</td>
<td>Solar Hot water (SHW)</td>
<td>Evacuated tube system</td>
<td>60% hot water demand</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Photo Voltaic (PV)</td>
<td>2.05 kWp</td>
<td>850 kWh/KWp/pa 40-90% used within dwelling</td>
<td></td>
</tr>
</tbody>
</table>

A dead leg is a length of pipe between the hot water store and the draw off point; this should be kept as short as possible to minimise the quantity of heated water that cools to room temperature.

These outputs are established in Chapter 11.
U-value calculations were carried out using the PHPP U-value calculation sheet and compared using Build Desk v3.4 software. U-values for the existing thermal elements were based on generic materials from the software library in both sets of software. These were found to be broadly comparable, PHPP U-Value calculations were chosen.

The make-up of the existing thermal elements was based on reasonable assumptions, site inspection, and historical evidence.

The proposed detail for internal wall insulation and examples of actual installation from similar projects is at Figure 49.

Notes:
Void 0-20mm reflects variations in surface of internal wall.
Studwork position in ensure no contact with external wall without the presence of a damp proof course/membrane.
Phenolic boards but jointed with foil tape.
Wood fibre boards screwed to studwork at 450mm centres.
Studwork ready to receive insulation.

Note that insulation will be inserted through first floor void between joists.

Note internal face of limestone wall rendered to seal cracks and reduce infiltration.

Note: try to avoid service penetrations on external walls joists, introduces cold bridge and air infiltration route.

Studwork with sheep wool insulation.
Sheep’s wool fitted to wall.

Fibre boards being fixed to studwork.
Abutment detail window reveal. (Wood fibre will be fixed on reveal up to window frame).

Wood fibre boards ready to receive lime plaster (note timber lining fixed around window in this instance).

Figure 49 Proposed details internal wall insulation
Figure 49 is included to provide general detail only and does not address the numerous onsite abutment details that require detailing. The photographic examples provided are not definite solutions. In retrofit adaptations each dwelling will require specific detailing as there a large number of variations in the construction details of this dwelling type. From experience, no design for low energy survives contact with retrofitting historic buildings, as there are always numerous individual site detailing issues that arise as work proceeds.

9.3 Summary

The proposed adaptations are in 3 distinct packages. RP1 is generally what can be done at a DIY level or with a small amount of professional help if required. RP2 is sequenced separately as it is an expensive, intrusive and a potentially controversial measure. RP3 incorporates two well understood LZC technologies that were selected from the review in Chapter 8.
Chapter 10 Benchmark of energy use in historic buildings

This chapter sets the parameters considered in designing and distributing the survey results. It then presents a benchmark of energy use established from the survey data.

First, it is necessary to define a benchmark; the Concise Oxford English Dictionary (2012) gives the definition of a benchmark as:

‘a standard or point of reference against which things may be compared or assessed’

10.1 Design Constraints

At the outset it is recognised that resources, time and budgets are finite. There is therefore a trade-off to be made between a small sample in-depth study and one that encompasses a larger sample size but examines the population in less detail. Time dictated that the data be collected within a 12 month time frame in order to then consider a case study analysis. It was also necessary to collect energy use for the dwellings to cover a common time frame to eliminate the effects of degree days on energy use between dwellings although the data could be normalised for this if required (discussed section 10.8)

10.2 Data Sources

Aggregated data was collected from a range of National Statistic sources:

- UK Energy Research Centre (UKERC).
- DECC National and Regional energy use figures.
- Digest of UK Energy Statistics (DUKES).
- Homes Energy Efficiency Database\(^\text{17}\).
- OFGEM.

\(^{17}\) HEED is designed to help monitor and target carbon reduction and fuel poverty work. HEED is a national database which tracks house-by-house the sustainable energy characteristics of the UK’s housing stock. It collects datasets on energy efficiency and microgeneration installations such as cavity wall insulation and solar hot water, along with property survey information such as Energy Performance Certificates. Now with date-stamped information describing over 1 in 3 of the UK’s homes, HEED represents a powerful resource for the UK’s sustainable energy network.
DECC has developed energy consumption data to regional and local authority level\textsuperscript{18}.

Gas and electrical energy consumption data are available below LA (Local Authority) area with the aim that this will enable councils to monitor and target small areas for interventions as part of LA initiatives to improve energy efficiency\textsuperscript{19}.

The availability of energy use in these publications has limitations. A key concern is that they focus on providing total energy use by fuel, i.e. gas or electricity use. This in itself does not reflect the energy efficiency of dwellings. It is necessary to normalise the energy use to a relative parameter, e.g. floor area to deliver kWh/m\textsuperscript{2} (energy used) or kg CO\textsubscript{2}/m\textsuperscript{2} (CO\textsubscript{2} emissions), allowing direct comparison between dwellings and to the rest of the domestic stock.

This opens an area of debate; historic buildings tend to have taller room height so should normalising for volume be considered? Also, buildings in themselves do not use energy, the occupants do, so should we normalise for occupation? Normalising by area meets current comparative norms and is sufficient to gauge the overall energy performance of a dwelling. Extending this to occupation, while challenging, was considered unnecessary to answer the research questions, although it may develop in to an area for future research as the influence of occupant behaviour is considered. A key factor is that occupancy is not just the number of people residing at an address, it should encompass their pattern of use, down to number of hours and time of day they require comfort conditions.

\textbf{10.3 Sampling Frame}

It was necessary to define what historic buildings are to be examined, so that when scaled up the sample group will be a statistically significant sample of the Bath building stock.

\textsuperscript{18} http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/regional/regional.aspx

\textsuperscript{19} http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/regional/electricity/mlsoa_llsoa/mlsoa_llsoa.aspx
For the sample to be representative of the housing stock in Bath it is necessary to first classify the stock distribution by typology, see Figure 50. There was no data for the distribution of typology for historic buildings. As historic building make up 30% of the Bath building stock it seemed reasonable to reflect the observed distribution within the survey distribution. This assists in returning a weighted random selection of sample of buildings that reflect the building stock population by typology.

![Figure 50 Building Typology Bath](image)

**Source: BANES House Condition Survey**

The constraint or restrictions placed on buildings in the form of statutory listing and locations within a World Heritage site and/or conservation area affects at least 75% of Bath’s dwellings (Figure 5). In the survey only homes within the conservation area were considered.

**10.31 Sample Size and Normalisation**

To derive results from which the energy use characteristics of all historic buildings in Bath can be inferred to a known margin of error required the sample population size to be calculated.
The selection of strategy for sample size considered the population size, the variability of the parameters being considered and the desired level of confidence. The simplified formula by Yamane (1967) was considered suitable to calculate sample sizes:

Number of buildings in Bath: 37,600
Number of pre 1919 buildings: 11,280

Accuracy of sample size is determined using the equation:

\[ n = \frac{N}{1 + N(e^2)} \]

Where:
- \( N \) = Population
- \( n \) = number of sample
- \( e \) = error (not less than 0.1)

With a total population (\( N \)) of 11,280 dwellings, 99 responses is the lowest number of returns required to achieve a 90% confidence level or a 10% error level. Returns in excess of this increase the accuracy of the survey.

The Yamane formula assumes a uniform distribution of the data and a 95% confidence level (95% of samples should lie within 2 standard deviations of mean). The data is confirmed for normality in section 10.10.1

10.32 Target Address Selection

The next step was to decide which buildings to target with the survey. This was decided on a random basis. In order to maintain statistical relevance random street selection using the random number generator within MS Excel was employed. Within each street 20 surveys were distributed.
Thought was given on how to improve the survey response rate as it was uncertain if enough data could be gathered. Initiatives employed were:

- Covering letter on University headed paper to lend academic credence to the data request.
- The address of a University member if respondents wished to complain about the survey.
- A SAE envelope for reply.
- An incentive in the form of feedback on energy use for those respondents who requested this.
- The guarantee of anonymity.
- The offer of assistance if required to complete the survey.

10.33 Confidentiality

The following issues were identified from guidance provided by the EPSRC (Engineering and Physical Sciences Research Council) and ESRC (Economic and Social Research Council)\(^{20}\):

- Data storage: how and where, how long and controlled by who.
- Confidentiality and data protection.
- Legislative requirements.
- Intellectual property.
- Secondary data sets, comply with access requirements.
- Participants consent to interview.
- Methods of data collection.
- Benefits to respondents and participants.
- Expected outcomes, impacts and benefits to research.
- Access to subsequent researchers.
- Data preservation.
- Consent forms.
- Future use and presentation of data.

\(^{20}\)http://www.esrcsocietytoday.ac.uk/ESRCInfoCentre/Images/ESRC_Re_Ethics_Frame_tcm6-11291.pdf
Accessed 12/12/11
http://www.epsrc.ac.uk/funding/managing/Documents/goodpracticeguide.pdf
Guide to Good Practice in Science and Engineering Research (EPSRC) Contents
Accessed 12/12/11
As comparisons are made between occupants there are issues of ethics in how the data is used. This centres mainly on ensuring confidentiality when giving feedback on energy use. This was dealt with in an explanatory letter and within the cover sheet of the questionnaire (Annex A).

By engaging occupants to contribute to the study there may be expectation of a quid pro quo relationship. Occupants may want to know their overall energy use, and in the future how to reduce it. There was a danger here not to influence energy use so that accurate data arose.

It was decided to offer feedback if required. The results will be presented once the data is collected.

### 10.4 Survey Design and Development

The questionnaire aimed to identify energy use in the dwelling. There was also an opportunity to gather data on influencing factors or variables relevant to reducing CO\textsubscript{2} emissions. The delivery of the questionnaire is a one off opportunity so the range of parameters should be given proper consideration, as no repeat would be possible.

It was accepted early on that it would not be possible to collect adequate data to calculate SAP for the respondent dwellings for two reasons. Apart from the information required proving difficult for respondents to provide accurately, it would also enlarge the survey to the point that would dissuade respondents from replying at all.

The questionnaire was trialled both as a pre-pilot and a pilot study. The pre-pilot was conducted on eight researchers within the University of Bath and 4 home owners already contributing to an extant energy use study. This enabled the development of the questionnaire to ensure clarity, removal of ambiguities and improved comprehension.

The pre-pilot sample identified those areas where data collection would add to the breadth of research and give weight to any findings. The initial intention was to keep the questionnaire short in order to mitigate against participant saturation and disturbance (Dejan et al., 2009). On the other hand, this was an opportunity to gather research data beyond what was strictly required for the study. Based on the response rate of the pilot study regarding the survey length it was established at 9 pages. Whilst not short it was decided to proceed on this basis as this was a “one off “opportunity for data collation.
The questionnaire sought information on a range of parameters which would help to analyse energy consumption. These included: type and quantification of energy use, typology, construction material, orientation, building age, heritage protection classification, level of insulation, window type, level of draught proofing, number of open flues, number of floors, heated rooms and bathrooms, heated floor area, heating plant and age, heating pattern and set temperature, loft conversion, number and age of occupants, appliances and income.

The pilot questionnaire was distributed to 30 dwellings selected to represent the overall distribution of building typology in Bath. They were hand delivered with a covering letter and a pre-paid return envelope with a second class stamp. The response rate was 26% (8 completed returns). This was higher than anticipated.

On delivering the questionnaire it was discovered that a residential address was not always a domestic dwelling. In three cases the property was a Bed & Breakfast establishment and one was undergoing refurbishment and one was unoccupied. In such instances the questionnaire was not delivered and these buildings were not included in the response rate.

SPSS is a statistical package that is used for data analysis and was chosen to complete the statistical analysis of the data collected. On entering the data into the SPSS software for the pre pilot study two issues arose:

1. Ambiguity in one question relating to occupants’ attitudes to constraints governing options to improve energy efficiency.

2. The realisation that the type of energy for cooking was not included.

The questionnaire was then amended and is included at Annex A.

In total, 600 household energy use questionnaires were hand delivered from March-July 2010. Prepaid envelopes were provided for reply, a return rate of 25% was achieved.

The distribution of collected data is at Figure 51, each marker represents 5-8 data sets.
10.5 Survey Feedback

Interestingly, providing energy used was a complicated question for some respondents to answer due to difficulty in reading utility bills and lack of access to information through having either changed supplier or being unable to access paperless billing. Consequently, initially a total of 54% of respondents provided complete energy use data. In a number of cases assistance was given to derive this information, increasing the response rate for energy use to 68%. This resulted in 102 data complete sets of energy use comprising a twelve month period.

In several instances respondents returned years of utility bills for my use. One resident visited had 25 years of fuel bills; this provided a useful insight into price changes over that period.

In several cases the high cost of gas was noticed, in one case simple advice to switch supplier saved the occupant £600 a year.
10.6 Validity and Reliability

For the survey data the energy use was normalised for internal heated floor area based on the data provided by respondents. There is room for error here, as the subsequent analysis relies on respondent input that cannot be verified. This was checked by a follow up of 12 replies (11.7%) to verify the data provided. The error margins in the replies were found to be less than 5% for floor area and 6% in the energy used data.

10.7 Region Average

For comparison, average energy use per dwelling was established using DECC Sub-national Local Authority gas and electricity consumption statistics from 2009. An average floor area for urban dwellings of 80m² was established from EHCS 2007 Summary Statistics; the results are shown in Table 6. To allow direct comparison between individual dwellings all energy used discussed in this thesis is delivered energy to the dwelling and is reported in kWh/m²/year and CO₂ emissions as kg CO₂/m²/year.

Table 6  Dwelling 2009 average annual energy use

<table>
<thead>
<tr>
<th></th>
<th>GB</th>
<th>England &amp; Wales</th>
<th>England</th>
<th>South West</th>
<th>BANES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh</td>
<td>15838</td>
<td>15300</td>
<td>15306</td>
<td>13650</td>
<td>15295</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>198</td>
<td>191</td>
<td>191</td>
<td>171</td>
<td>191</td>
</tr>
<tr>
<td>kg CO₂/m²/yr</td>
<td>38</td>
<td>36</td>
<td>36</td>
<td>32</td>
<td>36</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh</td>
<td>4152</td>
<td>4149</td>
<td>4136</td>
<td>4448</td>
<td>4343</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>kg CO₂/m²/yr</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td><strong>Gas &amp; Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh/m²</td>
<td>250</td>
<td>243</td>
<td>243</td>
<td>227</td>
<td>245</td>
</tr>
<tr>
<td>kg CO₂/m²/yr</td>
<td>66</td>
<td>64</td>
<td>64</td>
<td>62</td>
<td>65</td>
</tr>
<tr>
<td>Delivered energy Carbon Factor</td>
<td>kg CO₂/kWh (Carbon Trust)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the available regional energy use data the average for domestic gas and electricity use combined for BANES in 2009 was 245 kWh/m²/yr. This is slightly higher than the South West average but in line with the England average.
10.8 Survey Results

Table 7 shows the principle details of the buildings surveyed. A table of the data collected is at Annex B. The dwellings were all pre 1919, solid wall, pitched roof homes. The flats were in converted houses.
### Table 7  Survey Parameters
(n=102)

<table>
<thead>
<tr>
<th>Dwelling Parameter</th>
<th>Value</th>
<th>Count</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typology</strong></td>
<td>Flat</td>
<td>8</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>Terrace</td>
<td>49</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>End Terrace</td>
<td>9</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>Semi-Detached</td>
<td>25</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>Detached</td>
<td>11</td>
<td>11%</td>
</tr>
<tr>
<td><strong>No of Storeys</strong></td>
<td>1</td>
<td>11</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>56</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>17</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Occupancy</strong></td>
<td>1</td>
<td>18</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>&gt;6</td>
<td>2</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Demographics</strong></td>
<td>Children&lt;16</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(total=251)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17-60</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61-80</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;80</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td><strong>Classification</strong></td>
<td>Grade I</td>
<td>4</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Grade II</td>
<td>54</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>Conservation Area</td>
<td>102</td>
<td>100%</td>
</tr>
</tbody>
</table>
Three properties used electricity for heating and hot water. Gas, oil, biomass and coal use were grouped together to derive heating, hot water and cooking use. As cooking accounts for less than 3% of energy use in domestic dwellings (DECC, 2010) this was only considered in the regression analysis. Where electricity was used for heating (3 dwellings), 82% was attributed to heating and hot water in accordance with energy consumption by end use (DECC, 2010).

Where gas energy use was provided for prior to 2009, the data was corrected using the 20 year average degree day data for the Severn Valley divided by the degree day data for the months in question (CIBSE TM41, 2006).

10.9 Statistical Analysis

Excel and SPSS software were used for statistical analysis. Excel provided mean energy use and SPSS was used to provide a simple linear regression model to assess the independent variables that influence the energy performance of the historic dwellings data set. From this a multiple linear regression model was developed.

Tests for Normality for all delivered energy (gas, electricity, oil, biomass and coal), normalised for heated floor area, are at Figures 52-54. Floor area is recorded as measured heated internal floor space including stairways. The graphs were created using SPSS and show a normal distribution (bell shaped curve) in all cases (necessary to apply the Yamane formula).

Several tests were used to consider normality. The histogram gives an indication of the shape of distribution. A more sensitive test is the Q-Q Plot which is a plot of the percentiles of a standard normal distribution against the corresponding percentiles of the observed data. If the observations follow approximately a normal distribution, the resulting plot should be roughly a straight line with a positive slope. Tests for Normality include results for the Kolmogorov-Smirnov and Shapiro-Wilk tests, where n<50, the Shapiro-Wilk test is considered more reliable. A significance result of >0.05 is considered a normal distribution for both tests (the appropriate test result is highlighted in the colour yellow in the result table).

For all delivered energy and energy for heating, hot water and cooking, the data was shown to have a normal distribution.
However, initial results showed that the distribution of data for electricity use was not normal. Looking at the Q-Q plot and the histogram it was evident that there were a number of data points beyond 50 kWh/m$^2$/yr (outliers). This is high domestic energy use figure, in these data points electricity was also used for underfloor heating for bathrooms and conservatories as well as a 7-8 kW Aga stove that was in constant use. Therefore there was a contribution to heating that could not be disaggregated. These data points were treated as outliers and the test repeated without them, the Shapiro-Wilk test then indicated a normal distribution.

The normal distribution permits allocation of the lower quartile as a low energy users and the upper quartile as a high energy users.
Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWhm2yr</td>
<td>.086</td>
<td>102</td>
<td>.062</td>
<td>.965</td>
<td>102</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

Figure 52 Histogram of all delivered energy (gas, electricity, coal, biomass and oil)
Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWhm²yr</td>
<td>.073</td>
<td>102</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWhm²yr</td>
<td>.975</td>
<td>102</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

* This is a lower bound of the true significance.

Figure 53 Test for Normality of delivered energy for heating, hot water and cooking
The test was repeated without data sets over 50 kWh/m²/yr

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWhm2yr</td>
<td>.156</td>
<td>102</td>
<td>.000</td>
<td>.853</td>
<td>102</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction
### Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWhm2yr</td>
<td>.089</td>
<td>89</td>
<td>.080</td>
<td>.968</td>
<td>89</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

Figure 54  Test for Normality of delivered electricity (non-heating) use
Figure 55 shows the results of gas use plotted against floor area, at first inspection this shows a linear correlation ($R^2=0.766$). There are two notable outlier data points, the same analysis was repeated without these data sets and shows a reduction in $R^2$ value to 0.685, this is still a good correlation.

The same analysis for electricity is at Figure 56 which shows a much weaker relation co-efficient, $R^2=0.462$ suggesting there are other important factors to consider for electricity use. Removal of one outlier reduced the $R^2$ result further to $R^2=0.349$. 
Figure 56  Delivered Electricity use v Floor area with and without 1 outlier
10.10 Energy Use

Figure 57 shows a comparison of total delivered energy consumption by typology and fuel type. This is regardless of how the energy is used within the dwelling.

![Figure 57: Total delivered energy use by fuel type by typology](image)

The results demonstrate a wide range of total energy use, ranging from 50 kWh/m²/yr to 438 kWh/m²/yr, with a mean of 197 kWh/m²/yr. Two properties used both gas and oil. In the terrace dwelling gas was used for cooking only. In the detached property the gas was used in a recent extension while oil was used in the existing property. The owner of the property was not prepared to replace a 28 year old oil boiler for a modern gas replacement as he didn’t believe it would be as reliable as his existing boiler.

The breakdown of delivered energy for cooking, heating and hot water is shown in Figure 58.
Given that dwelling form primarily governs heat loss through the fabric, the lower gas use for flats and some terrace dwellings is as expected. However, an unexpected finding is that heating and hot water energy consumption in a large number of mid terrace dwellings is close to, and in excess of, that for end terraced dwellings. Additionally, the difference in energy use observed between semi-detached and detached dwellings, was not as anticipated.

The majority of the sample population used gas for heating and hot water (8 properties used either oil, coal or biomass); this shows a factor of 7 difference within terrace and end of terrace typology. This is a noticeable difference, given that the properties surveyed have similar construction. The explanation lies with both the dwelling performance characteristics (insulation, windows, boiler efficiency and infiltration) and the occupant’s energy use behaviour.

**10.10.1 Test for Normality**

The previous section confirmed that the overall data set had a normal distribution. Figure 59-68 shows the histogram, Normal Q-Q plots, the Kolmogorov-Smirnov and Shapiro-Wilk tests for normality for each of the four typologies for both delivered gas and electricity energy use.
In three instances the Shapiro-Wilk test initially indicated a non-normal distribution. Where this occurred (in Flat, Terrace and Semi-Detached delivered electricity) the outlier data points were removed and the test repeated.

The high outlier results arise when electricity is used for heating, underfloor heating (in a conservatory) or cooking (7kW aga type stove on 24/7).

For Flats and Semi-Detached typologies repeating the Shapiro-Wilk test without outliers returned a significance that confirmed a normal distribution.

It was not possible to initially provide a test for normal distribution of Terrace typology electricity use. The Q-Q plot shows small deviations from the normal distribution and both upper and lower tails. The plot is close to a normal distribution but does not pass a significance test. It was evident, as when looking at all energy use in the previous section, that there were a number of high electricity energy users. The test was repeated without those data points in excess of 50 kWh/m² (5 data points). This returned a Normal distribution.
Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kolmogorov-Smirnov(^a)</td>
<td>.294</td>
<td>7</td>
</tr>
<tr>
<td>Shapiro-Wilk</td>
<td>.863</td>
<td>7</td>
</tr>
</tbody>
</table>

\(^a\) Lilliefors Significance Correction

Figure 59  Flat typology delivered gas energy
Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Electricity</td>
<td>.266</td>
<td>8</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction
Without outlier data point 52 kWh/m²

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Kolmogorov-Smirnov(^a)</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>Statistic</td>
<td>Sig.</td>
</tr>
<tr>
<td>Electricity</td>
<td>.214</td>
<td>7</td>
</tr>
</tbody>
</table>

\(^a\) Lilliefors Significance Correction

\(\ast\). This is a lower bound of the true significance.

Figure 60  Flat typology delivered electricity use
Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>.079</td>
<td>49</td>
<td>.200</td>
<td></td>
<td>.978</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.

Figure 61  Terrace typology delivered gas energy
Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic df Sig.</td>
<td>Statistic df Sig.</td>
</tr>
<tr>
<td>Electricity</td>
<td>.163 49 .002</td>
<td>.887 49 .000</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction
Without outlier data point 95 kWh/m²

Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Electricity</td>
<td>.140</td>
<td>48</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction

![Normal Q-Q Plot of Electricity](image)

Expected Normal vs. Observed Value
Without outlier data point > 50 kWh/m² (5 data points)

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Electricity</td>
<td>.103</td>
<td>43</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction
* This is a lower bound of the true significance.

Figure 62  Terrace typology delivered electricity (with and without outliers)
Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Statistic df Sig.</td>
<td>Statistic df Sig.</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction

<sup>*</sup> This is a lower bound of the true significance.

Figure 63  End of Terrace typology delivered gas energy
### Tests of Normality

<table>
<thead>
<tr>
<th>Tests of Normality</th>
<th>Kolmogorov-Smirnov(^a)</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
</tr>
<tr>
<td>Electricity</td>
<td>.182</td>
<td>9</td>
</tr>
</tbody>
</table>

\(^a\) Lilliefors Significance Correction

\(^*\) This is a lower bound of the true significance.

Figure 64 End of Terrace typology delivered electricity use
Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Kolmogorov-Smirnov</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>.108</td>
<td>.960</td>
</tr>
<tr>
<td></td>
<td>df 25</td>
<td>df 25</td>
</tr>
<tr>
<td></td>
<td>Sig. .200</td>
<td>Sig. .407</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

* This is a lower bound of the true significance.

Figure 65  Semi-Detached typology delivered gas energy
Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Electricity</td>
<td>.207</td>
<td>25</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction
Without 2 outliers 86 and 97 kWh/m²

Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>.159</td>
<td>23</td>
<td>.138</td>
<td>.962</td>
<td>23</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

Figure 66  Semi-Detached typology delivered electricity
Tests of Normality

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov(^a)</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
</tr>
<tr>
<td>Gas</td>
<td>.162</td>
<td>11</td>
</tr>
</tbody>
</table>

\(^a\) Lilliefors Significance Correction
\(^*\) This is a lower bound of the true significance.

Figure 67  Detached typology delivered gas energy
### Tests of Normality

<table>
<thead>
<tr>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
<th>Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</td>
<td>.115</td>
<td>11</td>
<td>.200*</td>
<td>.983</td>
<td>11</td>
</tr>
</tbody>
</table>

<sup>a</sup> Lilliefors Significance Correction

* This is a lower bound of the true significance.

Figure 68  Detached typology delivered electricity
The two lowest energy users in the flat typology were low income households, average occupancy 1.3. The lowest only used gas for cooking. Of the next three lowest properties, two only heated a minimal number of rooms to keep fuel bills low.

Closer examination of the lowest gas users in terrace dwellings revealed that they had energy efficiency retrofits within the last five years. The adaptations included good levels of roof insulation, double or secondary glazing, draught proofed windows and doors, condensing boilers, some internal wall insulation and good boiler controls. Occupant attitude may also be a factor as all these occupants were very concerned about their energy use and CO₂ emissions.

The lowest end of terrace had a gas use of 54 kWh/m²/yr. This property had good roof insulation, heating controls and new double glazed UPVC sash windows fitted in 2009. The property was occupied by a single retired person. Thermostatic radiator valves were used to heat only the main rooms to 21°C, the remainder was heated to 18°C unless there were additional occupants.

A similar explanation occurred in the semi-detached dwellings. The three lowest had 87, 102 and 108 kWh/m²/yr gas use. All of these properties also had energy efficiency adaptations fitted in the last 7 years.

Explanations for high energy use are more difficult to explain. Looking at semi-detached dwellings, in all cases above 250 kWh/m²/yr occupancy level was in excess of three and boilers were at least 10 years old, one was 20 years old. The lowest annual income per household in these high energy using properties was in excess of £50,000.

Breakdown of electrical use excluding heating is at Figure 69.
These data show a smaller variance between dwelling typologies, as expected, since electrical use is less affected by built form (very little heating in the UK is electricity driven), these variations may be a reflection of occupant behaviour with regard to electrical energy use.

Figure 69 also shows that there are some high electricity users. The three highest were 86/95/97 kWh/m²/year. This high electricity usage was attributable to either electric “Aga Stove” type cookers or underfloor heating in conservatories (it was not possible to determine this energy use). Ignoring these exceptional energy uses there was a factor of 4 difference for electricity use between dwellings of the same typology.

10.10.2 Mean Energy Use and Carbon Emissions

Table 8 shows a summary of mean energy use and carbon emissions for gas and electricity by typology.
Table 8  Energy Use and Carbon Emissions by Typology

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample Size</th>
<th>Mean energy use kWh/m²/yr</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gas</td>
<td>Std Dev</td>
<td>Electricity</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Flat</td>
<td>Gas=7 Elec =8</td>
<td>125</td>
<td>77.5</td>
<td>28</td>
<td>9.9</td>
</tr>
<tr>
<td>Terraced</td>
<td>49</td>
<td>157</td>
<td>64.9</td>
<td>30</td>
<td>16.7</td>
</tr>
<tr>
<td>End Terrace</td>
<td>9</td>
<td>159</td>
<td>90.5</td>
<td>23</td>
<td>10.8</td>
</tr>
<tr>
<td>Semi Detached</td>
<td>Gas=23 Elec =25</td>
<td>192</td>
<td>79.2</td>
<td>34</td>
<td>19.7</td>
</tr>
<tr>
<td>Detached</td>
<td>11</td>
<td>199</td>
<td>62.7</td>
<td>28</td>
<td>12.1</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>166</td>
<td>74.9</td>
<td>30</td>
<td>16.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample Size</th>
<th>Mean Carbon emissions kgCO₂/m²/yr</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gas</td>
<td>Electricity</td>
<td>All Energy</td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>Gas=7 Elec =8</td>
<td>24</td>
<td>15</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Terraced</td>
<td>47</td>
<td>30</td>
<td>16</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>End Terrace</td>
<td>9</td>
<td>30</td>
<td>13</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Semi Detached</td>
<td>Gas=23 Elec =25</td>
<td>37</td>
<td>18</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Detached</td>
<td>11</td>
<td>38</td>
<td>15</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>32</td>
<td>16</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

Carbon Factor  kg CO₂/kWh (SAP 2009)²¹

<table>
<thead>
<tr>
<th>Type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.198</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54</td>
</tr>
</tbody>
</table>


In Table 4 Carbon Factors from the Carbon Trust were used as they were applicable for the time the data was relevant for. SAP Carbon factors are slightly higher.

The values in Table 8 are actual energy use, and include energy used for heating/hot water/ cooking. This is in order to make a comparison to aggregated energy use data in Table 6. The population varies for flats and semi-detached typologies as some of the survey properties used no gas (oil and solid fuel are not included in this table as there was no aggregated energy use to compare to).

As expected, increased external surface or built form requires higher heating energy use (gas), however the expected difference between terraced and end terrace and semi-detached and detached dwellings was not observed.
More interestingly, Table 8 shows that the average energy use in historic dwellings is lower than the BANES average (245 kWh/m$^2$, Table 6). The gas use observed is 14%, and electricity use is 40% less than the BANES average. More importantly, it is considerably less than the indicated SAP value of 39 stated by the EHCS, which would result in an energy use of 321 kWh/m$^2$/yr. Only 7 out of 102 dwellings exceeded this level of energy use.

Carbon emissions show an average of 48 kg CO$_2$/m$^2$/yr for all dwellings. This is considerably lower than the figure of 65 kg CO$_2$/m$^2$/yr for the BANES average (Table 6).

### 10.11 Regression Model

The data collected included information on a number of variables that influence how energy is used in domestic dwellings. Having established energy use by typology a question that arises is can the level of energy use in any dwelling be explained by the information collated on the dwelling and occupants? Or are there any linear relationships between the energy use and the dwelling and its occupants. This is different to modelling energy use, the regression analysis considers a number of independent factors and their relationship with the dependant factor (normalised energy use)

This was an area where it may be possible to identify explanatory variables that can be influenced to reduce overall energy use (dependant variable). There are limitations to this approach; there is not enough information to assess accurately U values or detailed occupancy and heating patterns. On the other hand information was available to determine levels of insulation, heating plant efficiency, heating controls, household income and with a lesser degree of accuracy occupancy and levels of infiltration.

It was considered that there was adequate data on the dwelling and the occupants to warrant a regression analysis to attempt to expose key factors influencing energy use.

Stepwise regression was applied to determine the influence of the most significant parameters of energy use. Due to the different patterns of energy use a separate analysis was produced for gas and electricity use. This was necessary as the aim was to determine influencing factors on energy use.
There is a disadvantage to this approach, in that incidental gains from electricity use make a useful contribution to heating that is not included when gas and electricity are considered separately. With an average floor area of 159m² for all dwellings in the data set and an incidental gain of 2.1w/m² (from PHPP) gives a total contribution of 0.3 kW. Assuming this is available through the heating season with an occupancy factor of 30%, this amounts to approximately 2.3 kWh/m² in the heating season. This was felt to be a small figure compared to the average energy use of 166 kWh/m²/yr of gas use (less than 1.5%) so a separate analysis was for electricity and gas was selected.

Within each model normalised delivered energy for area use was considered.

### 10.11.1 Gas Use

To determine those parameters that most explained the variance in energy consumption a multiple linear regression model was developed using SPSS. Normalised gas use by floor area was considered as the dependant variable, independent variables were drawn from the survey data obtained (see Annex A). The range of independent variables were analysed individually and step wise to determine a model that delivered the highest correlation or $R^2$ value.

Before moving to the final regression analysis a number of possible relationships were explored. Firstly no relationship was found between the age of the buildings in the data base and their normalised gas energy use, see Figure 70.

![Histogram of normalised gas use against building age](image)

**Figure 70** Histogram of normalised gas use against building age
The possible relationship between typology (form) and energy use normalised for area is at Figure 71.

![Figure 71 Normalised gas energy use by Typology](image)

This shows the expected upward trend as increased surface area of the dwelling increases.

A weak correlation, $R^2 = 0.43$ was also observed between normalised gas energy use and the number of open flues in a property, see Figure 72.

![Figure 72 Normalised gas energy use by number of open flues](image)
There were a limited number of data points (n=17) with sufficient information to determine the property U value. These were correlated with gas kWh/m$^2$, see Figure 73. No relationship was found between the U value of external walls and normalised delivered gas energy use, this may be due to the small data set.

Figure 73 Normalised gas energy use with U value

The regression model for normalised gas use is at Table 9.

Table 9 Total Gas Use Regression Model

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>B</th>
<th>Std. Error (kWh/m$^2$)</th>
<th>β</th>
<th>t</th>
<th>P value (sig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>61.056</td>
<td>24.859</td>
<td>2.456</td>
<td>.017*</td>
<td></td>
</tr>
<tr>
<td>No of bathrooms</td>
<td>16.699</td>
<td>6.667</td>
<td>0.232</td>
<td>2.505</td>
<td>.015*</td>
</tr>
<tr>
<td>Draught proofing %</td>
<td>-0.435</td>
<td>.174</td>
<td>-0.221</td>
<td>-2.506</td>
<td>.015*</td>
</tr>
<tr>
<td>Boiler efficiency</td>
<td>2.858</td>
<td>1.118</td>
<td>0.224</td>
<td>-2.167</td>
<td>.001**</td>
</tr>
<tr>
<td>Porch</td>
<td>-32.898</td>
<td>15.179</td>
<td>-0.194</td>
<td>4.721</td>
<td>.000***</td>
</tr>
<tr>
<td>No open flues</td>
<td>20.891</td>
<td>4.425</td>
<td>0.431</td>
<td>2.556</td>
<td>.0013*</td>
</tr>
<tr>
<td>Typology</td>
<td>20.945</td>
<td>6.110</td>
<td>0.298</td>
<td>3.428</td>
<td>.034*</td>
</tr>
</tbody>
</table>

Significance

* < 0.05  ** < 0.01  *** < 0.001
The resulting regression model for normalised gas use by area was significant in predicting 52.6% of the variance in area normalised annual gas energy use, $R^2$ (adjusted) = 0.526. This showed that the variable group consisting of number of bathrooms ($\beta = 0.232, p < 0.05$), level of draught proofing ($\beta = -0.221, p < 0.05$), boiler efficiency ($\beta = 0.224, p < 0.05$), presence of a porch ($\beta = -0.194, p < 0.05$) and typology ($\beta = 0.298, p < 0.001$), were significant predictors. Other indicators that were found to be not significant were number of occupants, boiler age, boiler service intervals, thermostat, thermostatic radiator valves, heating programmer, income, age, number of occupants, and level of double glazing.

The number of open flues was significant with a high standardised regression weight. Draught proofing and the presence of an entrance porch had the correct sign in that they showed a reduction in energy use when present.

Without the inclusion of occupant heating patterns and the necessary details to determine the $U$ value of the external envelop, it is unlikely that a correlation greater than $R^2 = 0.7$ would be achieved (assuming approximately 30% of energy use is heat loss through the fabric).

A question raised here is: what would be an acceptable result for a regression model in the field of building energy use? Other research areas would accept nothing less than an $R^2 > 0.9$, medical research for example. In the literature review conducted in this thesis many papers were observed with $R^2$ values of $R^2 < 0.5$.

As $R^2$ is the proportion of variance in the dependent variable explained by independent variable(s), the question is really what we should accept as an adequate or perhaps minimum level of explanation, or, how strong should the linear relationship be between the independent and dependent variable before it is considered acceptable.

On the other hand the $R^2$ value is not the whole picture. There are other factors that should be considered in order to assess the degree to which the regression model explains variance, such as the Beta factor and standard error.

Further investigation is required to determine if a range of independent variables that could build a regression model in which $R^2$ is $> 0.7$, as this would indicate a satisfactory model to determine domestic energy use. This would require further information not available within this survey, in particular detailed information on external wall construction, a more accurate assessment of infiltration and detailed information on occupancy and demographics.
10.11.2 Electricity Use

As expected, no relationship was found between the age of the buildings in the data base and their electricity use, see Figure 74.

Figure 74  Normalised electricity use by dwelling age

Figure 75 shows, as would be expected, a weak correlation (R²=0.462) between floor area and total electrical use. The same result was run without one outlier data point, the R² decreased to 0.349.
Without outlier data point 21,420 kWh/yr

Figure 75  Electricity use normalised for floor area
The use of electricity by typology was also examined and is at Figure 76 and shows no correlation in this respect. This is as would be expected as electricity is generally not used for heating in the UK.

Figure 76 Normalised electricity use by typology

Table 10 shows the normalised regression analysis for total electricity use.

Table 10 Electricity Regression Model

<table>
<thead>
<tr>
<th>Dependant Variable</th>
<th>r=0.725</th>
<th>Adjusted R²= 0.503</th>
<th>Electricity total kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unstandardised Coefficients</td>
<td>Standardised Coefficients</td>
</tr>
<tr>
<td>Independent Variables</td>
<td>B</td>
<td>Std. error</td>
<td>β</td>
</tr>
<tr>
<td>---------------------</td>
<td>---</td>
<td>---------</td>
<td>---</td>
</tr>
<tr>
<td>Constant</td>
<td>18.241</td>
<td>4.606</td>
<td>3.960</td>
</tr>
<tr>
<td>Number Occupants</td>
<td>3.078</td>
<td>1.772</td>
<td>.187</td>
</tr>
<tr>
<td>Electric range</td>
<td>37.424</td>
<td>5.675</td>
<td>.710</td>
</tr>
<tr>
<td>Significance</td>
<td>* &lt; 0.05</td>
<td>** &lt; 0.01</td>
<td>*** &lt; 0.001</td>
</tr>
</tbody>
</table>

The overall model fit of $R^2$ (adjusted) = 0.503 was significant in predicting 50.3% of the variance in area normalised annual electricity energy use. This showed that the variable group consisting of number of occupants ($\beta = 0.187, p< 0.01$) and the use of an electric range ($\beta = 0.710, p<0.001$), were significant predictors. Other indicators that were found to be not significant were income, age, number of rooms and low energy lighting.
In both regression models for normalised gas and electricity use there is a lot of variability that is not explained from the data collected. This is considered in discussion at Chapter 13.

### 10.12 Benchmark

From the normal distribution found it is possible to fit a performance benchmark by using the lower quartile as energy efficient or better than average performance and the upper quartile as not energy efficient or worse than average performance (Mortimer et al, 1999).

A proposed benchmark for gas use in historic dwellings by typology is at Figure 77.

![Benchmark Gas Energy Use](image)

**Figure 77** Benchmark Gas Energy Use

The benchmark for electricity use is at Figure 78.
This benchmark is based on surveyed current performance; therefore it does not reflect the large reduction in energy use and associated CO$_2$ emissions that are required to meet proposed emissions reductions targets.

**10.13 Discussion and Conclusion**

This chapter analyses normalised energy use data from 102 pre 1919 dwellings in the City of Bath and establishes average gas and electrical energy use and CO$_2$ emissions. The benchmark of energy use in historic dwellings established from the survey data allows the results to be viewed in the wider context of reducing CO$_2$ emissions from the housing stock in general. The findings suggest that energy use in historic dwellings in Bath is lower than the national and regional average. This does not indicate that historic buildings are energy efficient, building science tells us otherwise as demonstrated by some high energy users.

The use of dwelling typologies to produce an aggregated benchmark figure may be rudimentary, but in the absence of previous data it provides a base line that can, with future research, be refined to reflect a dwellings level of efficiency and thermal performance. In the absence of previous findings for UK energy use in historic buildings, comparison can only be made to average regional and national energy use and the energy use predicted by their SAP rating.
It is generally expected that the historic building stock has a higher energy use normalised by area than more modern stock. This is based on the implicit assumption that such stock will have standard heating patterns and occupancy, inadequate levels of insulation, single glazing, excessive infiltration and inefficient heating systems, etc. The lower levels of energy use from energy efficiency retrofitted historic dwellings have been demonstrated. When grouped together the results show the historic buildings sampled are not using as much energy on average, particularly for heating, as current aggregated data suggests.

This may suggest that the aggregated data or modelling systems upon which we rely is wrong. This could be down to sampling errors or errors in assumptions (e.g. heating patterns) made while calculating the SAP rating, or using data that is not up to date. On the other hand, if the aggregated data average energy use and model predictions are correct, and the buildings we expect to use more energy are not as we anticipate, then the energy must be being used by buildings we expect to perform better. We know this is not due to fabric parameters and may therefore be associated with behavioural aspects regarding energy use, suggesting further investigation is required.

These results provide evidence that historic dwellings in Bath also have average energy use lower than expected given their average SAP rating. Given that historic dwellings account for 30% of the BANES stock, the implication for Bath is that parts of the remaining stock must be using higher than average amounts of energy.

This approach highlights visibly (within the results), in a way aggregated data cannot, dwellings using high levels of energy when compared with similar properties. This information may prove valuable when deciding the priority for action to improve the performance of historic buildings at the local level. Within each typology a wide range of energy use is reported. This is important when assessing the benefit of retrofit adaptations as there is a danger if the assessed savings are based on national average energy use figures, as monetary or carbon savings from retrofit measures may be seriously over estimated. The data provides a statistically representative baseline that can be used to assess district scale retrofits designed to reduce energy consumption and carbon emissions. Additionally, the benchmark allows a base line from which to monitor future performance and to gauge the direct benefits of retrofit adaptations in the surveyed dwellings.
A relationship was shown between energy use and the dwelling variables but this does not indicate causality. The independent variables recorded are not definitive and only partially explain possible reasons for variation in energy use. The linear regression models explored the effect of variables on delivered normalised energy use, accounting for 52.6% of the variance in gas energy use and 50.3% in electricity energy use. A better model fit (higher $R^2$) would be desirable. This analysis made use of secondary data collected in the survey designed to establish a benchmark of energy use and sought to offer an explanation for variations in energy use. The model considered actual energy use, and although not measured, occupant behaviour is an independent variable that is likely to be a key parameter in explaining a portion of the variance in energy use. There are also other factors to consider: examples are the contribution of the level of fabric energy efficiency adaptations and detailed information on occupancy in terms of hours of comfort/service demand. These provide a direction for future work.

The expected difference arising from built form was not observed. This may be a number of explanations for this. It may simply due to the size of the sample or could be a reflection of occupant behaviour/attitudes. This would require further work to confirm that expected findings from energy use predictions are reflected in observed data.

Within each typology there is a wide range of energy use. The study also found that both gas and electricity consumption varied considerably for similar dwelling types, by as much as a factor of 7 for gas and a factor of 4 for electricity. This will impact directly on the benefit of energy efficiency retrofit proposals in terms of the net reduction in both energy use and CO$_2$ emissions.

A point to consider is that only normalising for floor area ignores the important factor of occupancy, both actual numbers of individuals as well as hours in occupation. To this could be added the issue of demographics. This is a difficult issue to satisfactorily measure through the use of a questionnaire. There are good reasons for this. Firstly, current analysis parameters do not follow this approach, which would mean there would be no comparable benchmark. Secondly, the definition of the term “occupancy” is difficult. It cannot simply be the number of people who live at an address; it would need to reflect their hours of occupation and level of service demand. This data is not available from this survey. Also, there are issues that arise from demographics; young children and older people have additional energy requirements, e.g. additional hot water use and higher internal heating set temperatures.
The high survey response rate of 25% was much higher than suggested by previous fieldwork. This may reflect the attitude of the respondents, in that they are all conscious of their energy use for reasons that may include comfort, cost and a desire to tackle climate change. Further work will be required to verify that this sample is not self-selecting with regard to low energy use. This could be straightforward to resolve given that energy use data for every dwelling is held by utility companies and floor areas can easily be determined through GIS mapping. There is therefore potential, should this data protected information be made available, to make a national benchmark of data use for every dwelling.

The benchmark produced facilitates assessment of the performance of historic dwellings in Bath, permitting categorising dwellings into high, average or low energy users. English Heritage (2009) acknowledges the lack of reliable data available to policy makers regarding the energy performance of historic buildings and considers a key problem to be that most assessments are made using models that include assumptions without supporting evidence field studies.
Chapter 11 Photo Voltaic in Historic Buildings

Following the selection of Photo Voltaic (PV) for inclusion as a retrofit adaptation in Chapter 8 this chapter focuses on PV and its potential to reduce carbon emissions in historic buildings. A good deal of the discussion is equally applicable to the general building stock. The emphasis here is to provide empirical data to permit reasoned decision making by stakeholders and professionals when considering this technology using data obtained from historic buildings.

This chapter was included to avoid the criticism that the model findings in Chapter 12 using PV to reduce carbon emissions were not applicable as there was no data on the performance of PV in historic buildings. Therefore, it was necessary to conduct a separate review of the performance PV in historic buildings as there was no academic work specifically looking at his area.

11.1 Domestic Energy Use

Although electricity use in dwellings is typically 15% of total energy use (DECC, 2011), it contributes to 37% of the total carbon emissions, as electricity currently has 2.4 times the carbon factor of gas, see Figure 23.

This is significant, because, unlike heating and hot water, the options to reduce CO₂ emissions arising from electricity use are both limited and distinctly different. One possibility is to reduce the carbon factor of delivered electricity; this is beyond the control of householders and is more a function of Government energy policy (Chapter 13 returns to this point). Other options are to reduce demand within the dwelling or adopt LZC technology.

Demand reduction options include reducing lighting power through increased use of low energy CFLs and LED light fittings. This will arise as tungsten filament lamps are in the process of being phased out. Another is the introduction of energy monitors. The potential impact of monthly feedback on energy use patterns is usually estimated to be 5–10% (Darby, 2006), but the initial savings cannot be sustained in the medium-to long-term (Van Dam et al., 2010), suggesting these may not be a long term solution. Another opportunity arises when replacing appliances as energy efficiency choices are available. In the case of fridge freezers the most efficient A++ rating has limited availability and are generally an expensive alternative to an A rated appliance. Furthermore, only 16% of homes were aware of the energy rating of their new appliances when making replacement purchases (Yohanis, 2011), thus illustrating the problem of uptake even if more efficient appliances are on the market.
Within the home there are also suggested elements of occupant behaviour that can deliver energy savings. Examples are avoiding the use of standby mode for audio and television units, as well as avoiding leaving various charging units on while not charging. This action alone will have only a very small effect on overall electricity consumption but is required nonetheless.

Another approach to reducing CO\textsubscript{2} emissions is to adopt PV systems to provide low carbon electricity. This is in line with the current government renewable energy strategy that seeks to increase decentralised micro renewable generation to meet future CO\textsubscript{2} emissions reduction targets. The recent introduction of Feed in Tariffs for micro electricity generation in the UK and the prospect of the same for renewable heat, will lead to increased take up of domestic micro renewable energy generation systems; these are just as beneficial to historic buildings as the rest of the housing stock.

There is a view that micro generation is not the best use of resources in that efficiency of scale would benefit larger regional or community installations. This may well be true but this research focuses on current options and seeks to explore the current policy options to the benefit of carbon emissions reduction in historic buildings.

A key issue that is uncovered in this thesis is that current orthodoxy considers PV as a last option once all other energy efficiency measures have been implemented. Whilst this approach may be prudent with regard to provision of heating and hot water, where improved fabric energy efficiency generally leads to reduced plant size and therefore lower capital costs. The same cannot be said of PV, which, as it affects only emissions from electricity consumption, can in fact be sequenced quite separately from adaptations to reduce heat loss from the fabric.

11.2 Fit (Feed in Tariff)

Since the introduction of the FiT in April 2010, as of December 2013, the installed capacity of LZC has increased from 10MW to 1.45 GW (DECC, 2012), see Figure 79. At the end of 2012 there were a total of 383,908 registered FiT installations, PV accounted for 97% of these.
This research does not consider the economics of PV. This is primarily because the level of subsidy available to PV is currently under review in the UK and other studies have considered this in detail (Campoccia et al., 2009; Bergman et al., 2011; Caird et al., 2008; Platchkov et al., 2011). However, regardless of the precise nature of any future financial incentive, the 372,391 installations installed between April 2010 and September 2012 demonstrates that PV installations can be made financially attractive.

From Figure 24 it can be seen that PV has the potential to provide low carbon electricity for certain areas of demand. Given that PV output only occurs during the day, the match between supply and demand is likely to be weak for occupants working away from home, for lighting and cooking and zero for night demand. Whereas there is strong potential to match supply and demand for day time activities including cold, wet and elements of Consumer Electronics and base load electricity use. This demand match is further enhanced where the home is occupied during the day (e.g. retired occupants, students, unemployed or home workers).
11.3 Future Climate Change and Cooling Loads

There is currently no Government data for UK domestic cooling load use. Figure 24 does not show the demand for summer domestic cooling as this is currently very small compared with overall energy consumption. This will change in coming decades. Peacock et al. (2010) state that if the behavioural response of UK householders to a warming climate is akin to that of relationships found in the US, the expected domestic cooling season created as a consequence of climate change will see 18% of homes in the South of England having installed domestic air conditioning systems by 2030. Given the trend in CDD’s in Figure 7 there is likely to be increased demand in the South West (Bath).

This is likely to adversely affect domestic carbon emissions as cooling will require electricity that currently has a carbon factor 2.4 times greater than gas (although predictions are for this to decrease over coming decades). One study predicts that an increase in energy consumption due to the growth in active cooling systems in London by 2030 (550,000 homes with air conditioning equipment (Day et al., 2009)) may lead to a doubling of CO₂ emissions by 2030 (Li et al., 2012). This does not take into account savings as a result of a reduced heating load which may be as high as 40% for terraced dwellings (Gupta et al., 2012). Regardless of the overall net demand impact, there is consensus that changing climate will see an increase in domestic cooling demand. In this respect PV output is well aligned to cooling demand (PV peak out is in the summer months) and can provide low carbon electricity to service this requirement.

11.4 Methodology

This chapter sets out to evaluate the carbon reduction potential of PV technology in the scenario of historic buildings. The methodology presented will evaluate the benefit of PV generated electricity by establishing and comparing the pattern of PV generation and domestic electricity demand.
The main considered elements were:

- Establish typical dwelling daily energy usage pattern.
- Assess PV installation output.
- Correlate PV output with daily electricity demand pattern.
- Determine how much of PV electricity generated can be used.
- Ascertain CO₂ emissions reduction in the dwelling.

11.5 Case Studies

Five historic dwellings in and around Bath with a PV system installed were monitored, see Figure 80.
Figure 80 Case Study PV Installations
A key task was to establish a typical pattern of daily electrical consumption. Apart from aggregated and averaged national statistics, demand profiles are available (Richardson et al. 2010). It was not certain that these would be representative of the case studies (do historic buildings have the same pattern of electrical energy use as the remainder of the built stock?). It was therefore decided to measure actual electricity demand to establish an accurate demand profile.

Daily electricity use was measured in two dwellings at 30 second intervals using an Elcomponent energy data logger (Elcomponent, 2012) over a 6 month period from April–September 2011.

Annual PV generation was recorded in 5 dwellings, 4 of these provided monthly generation readings. One PV system output was recorded at 1 minute intervals using a Sunny Webbox (Sunny, 2012).

The case studies had a mix of Monocrystalline and Polycrystalline silicon photovoltaic panels with a rated efficiency of between 13.5-14.1%, see Table 11.

To determine the carbon emission reduction a grid carbon factor of 0.517 kg CO₂/kWh was used (BRE, 2009). A carbon factor of 0.095 kg CO₂/kWh was used for PV generated electricity (House of Parliament, 2012). From the data presented this is mid range for domestic PV mono-crystalline in the UK (0.075-0.116 kg CO₂/kWh). There is little research data currently available on carbon factors for domestic generated PV electricity in the UK, suggesting a key area for future research. Even at upper limits from recent research, domestic PV has a carbon factor considerably less than current delivered grid electricity.
Table 11  Case Study Data

<table>
<thead>
<tr>
<th>Case Study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age(yrs)</td>
<td>215</td>
<td>261</td>
<td>205</td>
<td>218</td>
<td>260</td>
</tr>
<tr>
<td>Typology</td>
<td>Semi-Det</td>
<td>Detached</td>
<td>Terrace</td>
<td>Terrace</td>
<td>Terrace</td>
</tr>
<tr>
<td>m²</td>
<td>168</td>
<td>177</td>
<td>160</td>
<td>175</td>
<td>250</td>
</tr>
<tr>
<td>Annual kWhe used</td>
<td>3462</td>
<td>4323</td>
<td>4526</td>
<td>3807</td>
<td>4388</td>
</tr>
<tr>
<td>Annual CO₂ kg</td>
<td>1869</td>
<td>2334</td>
<td>2444</td>
<td>2056</td>
<td>2370</td>
</tr>
<tr>
<td>Electricity kWh/m²</td>
<td>20.6</td>
<td>24.4</td>
<td>28.3</td>
<td>21.8</td>
<td>17.6</td>
</tr>
<tr>
<td>Installed kWp</td>
<td>1.85</td>
<td>2.6</td>
<td>2.0</td>
<td>3.3</td>
<td>1.85</td>
</tr>
<tr>
<td>PV Rated efficiency</td>
<td>13.9%</td>
<td>13.5%</td>
<td>13.7%</td>
<td>14.1%</td>
<td>12.9%</td>
</tr>
<tr>
<td>Generated kWh/yr</td>
<td>1640</td>
<td>1977</td>
<td>1715</td>
<td>3019</td>
<td>1173</td>
</tr>
<tr>
<td>kWh/kWp</td>
<td>886</td>
<td>760</td>
<td>858</td>
<td>915</td>
<td>634</td>
</tr>
<tr>
<td>Used PV kWh</td>
<td>736</td>
<td>996</td>
<td>1150</td>
<td>705</td>
<td>725</td>
</tr>
<tr>
<td>% PV generated kWh used</td>
<td>45%</td>
<td>50%</td>
<td>67%</td>
<td>23%</td>
<td>62%</td>
</tr>
<tr>
<td>Exported kWh</td>
<td>904</td>
<td>981</td>
<td>565</td>
<td>2314</td>
<td>448</td>
</tr>
<tr>
<td>Offset CO₂ kg/yr from used PV electricity</td>
<td>361</td>
<td>488</td>
<td>515</td>
<td>345</td>
<td>355</td>
</tr>
<tr>
<td>% total CO₂ saved</td>
<td>19%</td>
<td>21%</td>
<td>21%</td>
<td>17%</td>
<td>15%</td>
</tr>
</tbody>
</table>

11.6 PV Generation

An important indicator of a PV installations performance is the kWh generated per kW peak installed (kWp), this gives an indication of the real performance taking into account location, installation, system losses, shading and insolation. Figure 81 shows that in the case studies this varies from 634 - 915 kWh/kWp.
The difference is explained by variations in orientation, shading (from trees, buildings and chimneys) and system losses. The average performance was 811 kWh/kWp. This provides a useful planning benchmark when considering the retrofit benefits of PV systems (for this location), which would be independent of dwelling age.

Table 11 shows that there is considerable variation in the amount of PV generated electricity used within each dwelling, ranging from 23-67%. This factor is important when evaluating the net reduction in CO$_2$ emissions for each dwelling, as it has a corresponding effect on CO$_2$ emissions reduction by reducing imported electricity. Ignoring the lowest figure (Case Study 4), which was due to the property having a large 3.3 kWp system (on an out building), the average was 56% of PV generated electricity used within the home, which is slightly higher than the 50% assumed in FiT calculations. This raises the question of how much further use could be made of PV generated electricity to reduce a dwelling’s emissions rather than simply exporting excess to the grid. This would have two advantages; firstly it would increase the economic viability under the current FiT scheme as using a kWh of PV generated electricity is worth 4 times more than the received tariff for exported electricity. Also, using PV generated electricity produces almost 1/5$^\text{th}$ of grid generated electricity carbon emissions.
11.7 Daily Electrical Demand

Richardson et al. (2010) recognise that the pattern of electricity use in an individual domestic dwelling is highly dependent upon the activities of the occupants and their associated use of electrical appliances. For this reason energy use patterns were measured for Case Study 1 and 5.

Figure 82 shows a typical daily pattern of electricity use from data collected from case study 1; this is for occupancy of 2 adults working away from the home. The data was collected using an Elcomponent SPC mini data logger that recorded electricity use at 30 second intervals. The occupants were requested to keep a diary of the use of electrical devices for one week to identify the electrical footprint of domestic appliances.

In this graph the electric immersion heater was switched on, although normally the gas boiler was used to provide hot water. This was initiated in order to explore scenarios to match electricity demand with PV output; this is a viable area for future research.

Figure 82 Electric immersion heater was switched on, although normally the gas boiler was used to provide hot water. This was initiated in order to explore scenarios to match electricity demand with PV output; this is a viable area for future research.

Figure 82 shows the demand signature of various types of domestic electrical demand. In particular it shows a daily total base load of 2.3 kWh (this comprises the telephone base set, smoke alarms, clock radio, microwave display, components on stand-by, charging units and a boiler timer switch. The load fluctuates between 50-350W with the modulating demand of the fridge freezer. This figure is broadly in line with the Domestic Energy Demand Model produced by Richardson et al., (see Figure 83),
although the modulating load for refrigeration is larger and the peak loads observed are higher than in the Richardson model.

Figure 83  Load Profile CREST Domestic Energy demand Model

11.8 PV System Output

PV output from PV Case Study 1 was measured from January 2012 to December 2012. The PV system output for 2012 is at Figure 84.
In order to analyse the match between domestic electricity demand and PV output a histogram of daily PV generated electricity was generated, see Figure 85. This shows an average generation of 4.49 kWh/day for the year 2012.

![Histogram of daily PV generated electricity](image)

**Figure 85** Daily PV generation

As the contribution PV generation makes to the dwelling CO\textsubscript{2} emissions is dependent on the amount of insolation, the data collected was used to establish three typical PV days using the mean and upper and lower quartiles:

- Lower quartile PV day of 1.5 kWh/day.
- Mean output PV day of 4.5 kWh/day.
- High output PV day of 7.5 kWh/day.
These PV outputs were then compared to daily patterns of electricity demand (no hot water). This showed that for weekday occupancy, regardless of the PV output above the daily base load of 2.3 kWh, there is little variation in the amount of PV generated electricity used within the dwelling, see Figure 86. Where the PV output line goes above the energy demand line is where electricity is exported, or in other terms, this is a missed opportunity to reduce a dwelling’s carbon emission.

Figure 86  Domestic electrical demand and PV generation
The use of a washing machine was analysed to explore increasing the use of PV generated electricity as its kW rating is closer to the PV systems output on average and high output days, see Figure 87.

Figure 87  PV output v washing machine electricity demand
11.9 CO₂ Emissions

Annual CO₂ emissions from electricity use was established using the data at Table 11, see Figure 88. The range of 9.4–15.3 kg CO₂/m²/annum is slightly lower than the Bath historic building average of 16 kg CO₂/m²/annum (Moran, 2012).

![CO₂ Emissions from electricity use (no PV)](image)

Figure 88  CO₂ emissions from electricity use (no PV)

The effect of savings from the generated PV electricity on annual electricity use is shown at Figure 89. This shows a reduction in CO₂ emissions of between 15 – 23% (average 19%).

![CO₂ emissions from electricity use](image)

Figure 89  CO₂ emissions from electricity use
11.10 Used PV generated electricity

The potential to reduce CO$_2$ emissions is dependent on the portion of PV generated electricity used. Figure 90 shows the amount of PV electricity used which varied from 23-67%.

![Figure 90 Amount and Percentage of PV generated electricity used](image)

The variation in PV generated electricity used is attributable to occupant attitude and behaviour, patterns of occupancy and the size of the PV system. A post survey interview with case study 3 and 5 revealed that the occupants were particularly keen to reduce their CO$_2$ emissions and made a conscious effort to use appliances on good PV (sunny) days. Actions included deliberately timing the use of appliances, particularly washing machines, dishwashers and vacuum cleaners, with high PV output, to avoid importing electricity at a higher cost.

An interesting comment was made by Case study 5 who said that they would have increased the amount of PV used if there was an automatic means to activate devices to suit PV output, “rather than waiting for the sun to shine before switching on the washing machine”.

The problem here is that the average of 268 kWh/annum consumption (UKERC, 2007) for washing machines is not sufficient demand to make use of surplus PV generated electricity (448-2314 kWh/annum from Table 11). Whilst there are some controllers available on the market they are expensive and there is no data on the performance in further reducing carbon emissions. This is an important area for future research.
The reality is that in average occupancy (working away from home) there is little demand that aligns to PV output. The possibility of increased use of cooling will create a load. One other possibility is to divert surplus output to provide hot water.

A basic calculation of the carbon benefit of this approach using data from the Energy Saving Trust (2008) is at Table 12. This is a simple analysis to demonstrate potential. It would be dependent on matching the immersion element in the hot water cylinder to the PV array output. The minimum readily available “off the shelf” immersion element size is 1.5kW. In order to avoid importing electricity an element in the range of 0.5-0.8 kW would be more suitable depending on the PV array size (made to order this would cost £175.00).

**Table 12  PV v Gas for hot water**

<table>
<thead>
<tr>
<th>Daily hot water demand</th>
<th>122</th>
<th>litres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily energy consumption</td>
<td>4.7</td>
<td>kWh</td>
</tr>
<tr>
<td>Annual energy consumption</td>
<td>1703</td>
<td>kWh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>20% by PV (300-350 kWh available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Carbon Factor</td>
</tr>
<tr>
<td>PV energy</td>
</tr>
<tr>
<td>PV CO&lt;sub&gt;2&lt;/sub&gt; emissions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas Boiler efficiency</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Carbon Factor</td>
<td>0.198&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Gas boiler energy</td>
<td>378</td>
</tr>
<tr>
<td>Gas CO&lt;sub&gt;2&lt;/sub&gt; emissions</td>
<td>71.8</td>
</tr>
</tbody>
</table>

| Saving of hot water carbon | 55% |

**Notes**

2. BRE SAP 2009

This shows for boilers of 90% efficiency there is a dwelling carbon saving to use PV to heat water rather than export surplus electricity as PV generated electricity has approximately half the carbon factor of gas. As the rate for exported is electricity is approximately the same as gas (3.5p kWh) there is little or financial advantage.
11.11 Historic Buildings and PV

Case Study 5 was limited to the size of the PV array it could install because of its listed status. Although case study 5 used 61% of generated PV electricity it reduced its CO$_2$ emissions by the lowest amount, 15%. This is reflection of a lower kW/KWp output because of installation limitations (shading by a chimney and orientation). Case Study 5 is a Grade II Listed building with a double pitched roof construction with a central valley. Planning Permission was only granted for a PV installation in the central valley, see Figure 91.

Figure 91  Cross Section, Case Study 5

Although there was potential for a 3.7 kW system by using both south facing roof elevations, only a 1.85kW system received planning permission. If a 3.7 kW system had been installed, increased PV generated electricity would result in increased CO$_2$ emissions reduction, moving from 15% to at least 21%.

This can be supported by Case Study 3 which had a similar roof construction but although in a conservation area, was not a Listed Building; consequently it utilised both south facing roof facades for LZC technologies, achieving a 21% reduction in electricity CO$_2$ emissions.
11.12 Discussion and Conclusion

Is PV just a new aesthetic? Historic buildings have already changed with the times; examples are the use of gas for lighting followed by electrification, the introduction of bathrooms and central heating, conversion to smaller units and the use of previous below ground storage areas for accommodation. This suggests further change to reduce emissions may, with time, become just as accepted.

Historically the driving force for altering our historic buildings was more one of convenience and comfort. The difference today is that we now need to reduce the CO\textsubscript{2} emitted from our homes; this is a new approach and is to some extent out of line with cultural norms with regard to our built heritage. Today’s new low carbon paradigm means that we have to retrofit our existing housing stock, including historic buildings.

As a result it may be that we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to environmental imperatives. Perhaps we should consider that “we may have to be prepared for visually intrusive measures on much loved buildings” (House of Commons, 2008). This view may gather momentum because the options to improve energy efficiency in historic buildings are limited, even more so when dealing with electricity derived CO\textsubscript{2} emissions.

As historic buildings have withstood many changes in the past, is the introduction of renewable energy technologies really such a problem? They are after all, fully demountable. One argument against them is that these interventions are simply a question of glamour because the really effective measures (insulation, improved energy efficiency and draught proofing) are unattractive, and from observation, often ignored. Whilst this may well be the case, none of these measures would have a noticeable effect on emissions arising from electricity use.

The current orthodoxy for improving energy efficiency in historic buildings centres on reducing the heating load, and only when this is achieved does it turn to dealing with the approximate 35\% contribution electricity use makes to CO\textsubscript{2} emissions. The introduction of PV, though recommended as one of the last retrofit measures, is applicable to dwellings of all ages. This is an important point and raises the question “does PV have particular merit for historic buildings?”

The broad research in this thesis suggests that for historic buildings, the standard energy hierarchy has to be reconsidered. Particularly as PV, though recommended as one of the last retrofit measures can lead to significant reductions in CO\textsubscript{2} emissions through using less delivered electricity. When primary energy production losses are considered the benefits increase.
In essence, where for non-historic buildings, fabric efficiency must come first, for historic buildings other solutions could take precedence. Therefore, though the net reduction in carbon emissions is also likely applicable to more recent dwellings, it could be argued that given the scale of contributions possible with PV in historic dwellings, this aspect should be considered in tandem with other improvements. This is especially true when options for thermal improvements are limited either by planning (e.g. Listed buildings) or by uncertain impact of the quality of fabric post improvement.

It has been shown that in ordinary energy use patterns, without technical intervention, an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing CO₂ emissions by an average of 19%. Within the overarching aim to tackle climate change this is a substantial reduction. Furthermore, this reduction can be improved upon with demand management; the 67% of PV generated electricity used with in the dwelling reported chapter was achieved without any installed automatic/programmable demand management measures suggesting this figure could be increased. This shows that where occupant energy use patterns are arranged to synchronise with PV electricity generation and where the installation of PV systems is permitted to make use of available roof space, regardless of it heritage value, reductions of at least 23% can be made in CO₂ emissions arising from electricity use.

This chapter raises several questions:

- Is there a correlation between occupiers of historic buildings and electric use patterns?

- Can occupants be better informed at the time of PV installation (or when purchasing a dwelling with PV installed) to make optimal use of PV generated electricity. This will require occupation behaviour adjustments.

- How can the demand of domestic appliances be automatically controlled to make use of PV generated electricity. This is effectively the application of “load matching” or “demand shifting” within the home.

- Are there sufficient demand sinks to make use of daily PV generation or should energy storage be considered.
• Is it viable to use/store surplus PV electricity production to provide hot water or water pre heating? This requires further research as there are a number of factors to consider such as the efficiency of the boiler providing hot water, the immersion heater element power rating, the time of day the water is heated/pre heated, what other loads are present, controls for initiating immersion element to match PV output and what level of PV output makes this viable.

• Does it matter if PV generated electricity is exported when not required and imported via the grid at a later point? It could be argued that this simply offsets electricity imported at times when PV generation does not meet demand. But when counting carbon and establishing annual domestic emissions, imported electricity will have a carbon factor some 6 times greater than PV generated electricity. Further data is required on the exact carbon factor of domestic PV generated electricity in order to predict accurately full life cycle carbon reduction benefits.

• What is the area available for PV on the roofs of historic buildings? How does it compare to available roof area on more modern dwellings?

The study looked at only 5 case studies over a 12 month period. Further continued observations are required to explore the potential of domestic PV generation to reduce domestic CO₂ emissions. The life time of PV panels is at least 20 years; even with degradation at 1% year, their future performance can be reasonably predicted. What is less clear is the likely future carbon factor of grid electricity and the bearing this will have on domestic PV to offset emissions.

The demanding target of 80% reduction in CO₂ emission levels by 2050 suggests that this cannot be achieved without involving historic dwellings. This is a challenge, not only because of the high number of dwellings involved but also because of aesthetic/fabric constraints. Consequently, and in response to the overarching need to tackle climate change, all low carbon options should be exploited, particularly as the adoption of PV in historic buildings shows the potential to reduce significantly dwelling electricity CO₂ emissions. The challenge now is how to bring together the conservation of heritage and conservation of energy to reduce CO₂ emissions.
Chapter 12 Modelling Energy Use

It was not possible, due to time constraints, to model all building typologies. It was decided to focus on terrace dwellings as they have the highest incidence in Bath. This has limitations as the selected building typology may not be representative of other historic buildings in Bath due to differences in fabric, previous energy use alterations/improvements and the behaviour and attitude of the occupants. On the other hand, they will have the same basic initial construction, i.e. solid walls, large windows, high infiltration and uninsulated solid floors. Despite this limitation, the case studies remain relevant as their performance will be representative in demonstrating the benefits of retrofit adaptations, e.g. demonstrating the effect of solid wall insulation or the use of PV solar panels.

This chapter contains the case study analysis and considers one end terrace and two terrace dwellings using their actual measured energy use from the benchmark survey. Two aspects of the benefits of using models were considered. The first was to assess the model accuracy in predicting a dwelling’s energy use by comparing the model result with actual energy use. The second was to model a series of retrofit adaptations and their effect on reducing carbon emissions. The PHPP (selected in Chapter 7) is used to assess the dwelling performance.

12.1 Terrace Case Study Dwellings

The dwellings are Georgian buildings located in Bath, UK, constructed in 1826, see Figure 92. The range of and Low Zero Carbon (LZC) technologies and retrofit adaptations, established in Chapter 8 and 9 respectively, are examined to reduce CO₂ emissions.
Figure 92  Case Study Dwellings, front and rear elevations.

The buildings are Grade II listed, Case Study 1 and 2 are mid terrace and Case Study 3 is end terrace, they consist of two stories with solid dressed limestone walls. The roof is double pitched with a central valley and parapet wall. The front elevation faces south south east. Windows are a mixture of timber single glazed sash windows and double glazed casement units. The ground floors are a mixture of suspended timber floors, stone paving and concrete slab, as built details are at Table 13. Case study 2 underwent refurbishment in 2004 and incorporates energy efficient improvements. The delivered gas and electricity use is derived from the benchmark energy survey.
Table 13 Summary Details

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year of construction</strong></td>
<td>1826</td>
<td>1826</td>
<td>1826</td>
</tr>
<tr>
<td><strong>Typology</strong></td>
<td>Mid Terrace</td>
<td>Mid Terrace</td>
<td>End of Terrace</td>
</tr>
<tr>
<td><strong>Floor Area m² (excluding stairs)</strong></td>
<td>88</td>
<td>75</td>
<td>88</td>
</tr>
<tr>
<td><strong>Floor/ceiling height</strong></td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Number of bedrooms</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Delivered Gas kWh/m²</strong></td>
<td>127</td>
<td>41</td>
<td>171</td>
</tr>
<tr>
<td><strong>Delivered Electricity kWh/m²</strong></td>
<td>84</td>
<td>19</td>
<td>25</td>
</tr>
</tbody>
</table>

**U-value** W/m²K

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front walls</strong></td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Rear walls</strong></td>
<td>3.1/0.3</td>
<td>0.3</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Floor (timber /concrete/stone)</strong></td>
<td>1.9</td>
<td>0.3/2.7</td>
<td>1.9/2.7</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td>0.4/2.6</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Windows</strong></td>
<td>4.4</td>
<td>2.8/4.4</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>External doors</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Boiler type</strong></td>
<td>Non condensing</td>
<td>Condensing Combination</td>
<td>Non condensing Combination</td>
</tr>
<tr>
<td><strong>Boiler efficiency</strong></td>
<td>65%</td>
<td>89%</td>
<td>68%</td>
</tr>
<tr>
<td><strong>Boiler age (years)</strong></td>
<td>15</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td><strong>TRV’s</strong></td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Draught proofing %</strong></td>
<td>10%</td>
<td>60%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Assumed start q50</strong></td>
<td>12.5</td>
<td>9.8</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>Low energy lighting %</strong></td>
<td>10%</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Conservatory</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Conservatory Heated</strong></td>
<td>Yes</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**Appliances**

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fridge Freezer</strong></td>
<td>C 550 kWh a⁻¹</td>
<td>A 408 kWh a⁻¹</td>
<td>C 550 kWh a⁻¹</td>
</tr>
<tr>
<td><strong>Hob</strong></td>
<td>Electric 7.5 kW Range type in operation 24/7</td>
<td>Gas</td>
<td>Gas</td>
</tr>
<tr>
<td><strong>Oven</strong></td>
<td>Electric</td>
<td>Gas</td>
<td>Electric</td>
</tr>
<tr>
<td><strong>Microwave</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Washing Machine</strong></td>
<td>B 1.12 kWh cycle⁻¹</td>
<td>A 0.94 kWh cycle⁻¹</td>
<td>B 1.12 kWh cycle⁻¹</td>
</tr>
<tr>
<td><strong>Clothes Dryer</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Dishwasher</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* U Value Calculated using PHPP

Typical floor plans and sections are at Figure 93.
Figure 93  Case Study Plans and Section
The roof space available in the valley, which would conceal the installations form view at ground level, permits as a minimum one 4m² SHW panel and ten 185 Watt PV panels giving a 1.85 kWp system. These were considered as feasible as Listed Building Planning Permission has already been granted in Bath for similar proposals, see Figure 94.

Figure 94  1.8 kW PV system, 19 Devonshire Buildings, Bath, before and after installation

12.2 Retrofit Adaptations

The emphasis here is on energy by end use; this includes heating (active cooling not currently required in UK/Northern Europe climate zone), hot water, cooking, auxiliary electricity, appliances and plug-in consumer electronics. The benefits of this approach are measured by modelled delivered energy use before and after retrofit. The potential retrofit adaptations are summarised in Table 14 Retrofit Package Adaptations (methodology established in Chapter 9).

---

22 19 Devonshire Buildings, 2011, 1.8kW PV system.
<table>
<thead>
<tr>
<th>Serial</th>
<th>Adaptation</th>
<th>Specification</th>
<th>Target</th>
<th>EnerPHit Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Retrofit Package 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Increase roof insulation</td>
<td>Minimum 270mm fibre glass</td>
<td>U(^{1}) = 0.14 W/m(^2)K</td>
<td>0.12 W/m(^2)K</td>
</tr>
<tr>
<td>2</td>
<td>Install insulation to timber suspended floor</td>
<td>100mm foil backed polyisocyanurate board with breathable vapour membrane above insulation</td>
<td>U = 0.27 W/m(^2)K reduced infiltration</td>
<td>0.15 W/m(^2)K</td>
</tr>
<tr>
<td>3</td>
<td>Draught proof</td>
<td>Seal uncontrolled air ingress routes</td>
<td>q50 9.6 ach @50pa (see section on infiltration)</td>
<td>&lt;1.0 ach @50pa</td>
</tr>
<tr>
<td>4</td>
<td>Window thermal performance</td>
<td>Either replaces single glazed sash windows with double glazed units or overhaul window and fit secondary glazing (dependant on the condition/heritage value of the window). No works to existing double glazing was considered, allocated U = 3.0 W/m(^2)K</td>
<td>Double glazed sash window U= 2.23 W/m(^2)K Secondary glazed unit U=2.30 W/m(^2)K</td>
<td>0.85 W/m(^2)K</td>
</tr>
<tr>
<td>5</td>
<td>Central heating boiler</td>
<td>Upgrade to efficient condensing boiler designed to take advantage arising from low return temperatures. Include thermostatic radiator valves</td>
<td>Seasonal COP 90%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Central heating pump</td>
<td>Low power high efficiency pump</td>
<td>Auxiliary electricity power reduced from 100W to 25W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Insulate all service pipe runs and eliminate dead legs(^{23})</td>
<td>40mm foam insulation, no runs in cold spaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Washing machine</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fridge freezer</td>
<td>Upgrade</td>
<td>A++ energy rating</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Dish Washer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Clothes Dryer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Lights</td>
<td>CFL or LED</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td><strong>Retrofit Package 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Internal wall insulation</td>
<td>Timber stud frame, 100mm sheep’s wool or Hemp batts insulation with 40mm wood fibre boards, finished with 18mm lime plaster.</td>
<td>U= 0.24 W/m(^2)K</td>
<td>0.3 W/m(^2)K</td>
</tr>
<tr>
<td><strong>Retrofit Package 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Solar Hot water (SHW)</td>
<td>Evacuated tube system</td>
<td>60% hot water demand</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Photo Voltaic (PV)</td>
<td>2.05 kWp</td>
<td>850 kWh/KWp/pa 40-90% used within dwelling</td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\) U value calculated using PHPP work sheet

\(^{23}\) A dead leg is a length of pipe between the hot water store and the draw off point; this should be kept as short as possible to minimise the quantity of heated water that cools to room temperature.
12.3 Model Assumptions

12.31 Primary or Delivered Energy

In order to provide ready comparison with other model results and databases of domestic energy use (consumer energy use, government energy use data and the English House Condition Survey) all energy use reported is delivered energy. This is also appropriate as it reflects the energy performance of the dwelling rather than the inefficiencies of national energy generation systems. This approach is discussed further in conclusions/discussion.

Primary energy cannot be ignored entirely, therefore final primary energy use is calculated to make comparison with the Passivhaus Standard towards the end of this chapter.

The model assumed an internal set temperature of 20°C, see section 12.37 for further explanation.

The IES model used electrical use data established in the PHPP, see Table 15 for Case Study 2 example.

Table 15 Electric Demand
12.32 Carbon Factors

The carbon factors are taken from SAP (2009) as it includes a recent significant revision to assumed CO\textsubscript{2} emissions per kWh of fuel used; these are at Table 14. It also includes a figure for displaced grid electricity from PV.

Table 16 Carbon Factors

<table>
<thead>
<tr>
<th>Delivered energy Carbon Factor</th>
<th>kg CO\textsubscript{2}/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.198</td>
</tr>
<tr>
<td>Grid Electricity</td>
<td>0.517</td>
</tr>
<tr>
<td>PV generated electricity</td>
<td>0.095\textsuperscript{24}</td>
</tr>
</tbody>
</table>


12.33 Infiltration

CIBSE (2000) describes air leakage as the adventitious infiltration and exfiltration of air through a building envelope or component due to imperfections in its construction. It is given the term air permeability\textsuperscript{25} and is denoted as q50. It is reported as air changes per hour (ach) per m\textsuperscript{2} building envelope area at a forced pressure of 50 Pa (m\textsuperscript{3} h\textsuperscript{-1} m\textsuperscript{-2}). The advantage of this unit is that applying Kronvall’s rule of thumb (1978), dividing by 20, gives (at normal pressure and exposure conditions) a widely used approximation of the air infiltration rate in ach at normal pressure conditions.

There are maximum infiltration requirements a building must satisfy depending on its use and size. Approved Document L1A of the Building Regulations (England and Wales) (CLGC, 2006) currently sets a limit for airtightness of 10 m\textsuperscript{3}/h.m\textsuperscript{2} at 50 Pa (q50) for new buildings and alterations to existing buildings.

\textsuperscript{24} See Chapter 11.5 for explanation.

\textsuperscript{25} A method for pressure testing of dwellings is outlined in CIBSE technical memorandum TM23 (CIBSE, 2000). The recommended good practice air permeability for naturally ventilated dwellings is given as 10 m\textsuperscript{3}h\textsuperscript{-1}m\textsuperscript{-2} @ 50Pa, and 5 m\textsuperscript{3}h\textsuperscript{-1}m\textsuperscript{-2} @ 50Pa for dwellings with balanced whole house mechanical ventilation.
What is an acceptable infiltration rate to adopt for the historic case study dwellings? CIBSE Guide to building services for historic buildings (2002) makes the point that there is often too much infiltration in historic buildings which causes both discomfort and wastes energy. The mean measured for historic buildings by Johnston et al. (2004) was a q50 of 12.5 ach. This finding was in line with Stephen (1998) (Figure 30, page 64). Given that there is no research to suggest average q50 results lower than 10, this study will begin assume a start infiltration rate in the case study dwellings of 12.5 ach @ 50pa.

The infiltration can be improved, but by how much before indoor air quality becomes unacceptable? ESRU (University of Strathclyde, 2009) considered a q50 of 7.0 as readily achievable without leading to concerns over deterioration in indoor air quality and condensation risks. In the analysis in this chapter the energy savings in moving to this lower q50 will be calculated.

12.34 Ventilation in Historic Buildings

CIBSE Guide to building services for historic buildings (2002), recognising the absence of an impermeable damp proof course/membrane, suggests a “rule of thumb” to determine ventilation rates.

This rule suggests 8 l/s/occupant or 0.4 ach for occupants and an additional 0.4 ach for the dwelling, to reflect the different way historic buildings work with regards to movement of moisture in and out of the fabric. For this study, as it is slightly greater than the CIBSE recommendation, ventilation will be provided in line with The PHPP worksheet which allocates 8.3l/s per person on the ventilation worksheet (cell G14).

The lack of consensus and a reliance on a “rule of thumb” for historic buildings suggests that urgent further work is required in this area to establish minimum ventilation rates that avoid both unhealthy internal conditions and increased risk of fabric decay. There is now a pressing need to improve our overall understanding in this area. The roll-out of the Green Deal and the view that reducing heat loss through external walls through the application of insulation is a key component in meeting 80% carbon emissions reduction targets, only increases this urgency.
12.35 Thermal Bridging

The analysis of thermal bridges aims to make losses through thermal bridges negligible. The two main effects of thermal bridges are (Abel and Elmroth, 2006):

- Decreased interior surface temperatures which in the worst cases can result in high humidity in parts of the construction.
- Significantly increased heat losses.

In historic buildings this is particularly challenging as thermal bridges can occur in several places in the building envelope, see Figure 95.

![Diagram of a Georgian Townhouse showing potential thermal bridges](figure95.png)

**Figure 95 Potential Thermal Bridges Georgian Townhouse**

Building cross section without annotation sourced at: (BANES 2012)

Besides heat loss, thermal bridges cause low internal surface temperatures, which in turn heighten the risk of mould growth. This occurs in particular where a solid brick wall has not been thermally improved and where the thickness of the brick wall and insulation thickness are reduced i.e. around the windows (Rasmussen, 2011).
This analysis considered repeating and non-repeating thermal bridges, further work is required to investigate the effect and extent of random thermal bridges in historic buildings.

For this analysis thermal bridging of 0.04 W/mK was assumed throughout – based on earlier studies of another project using similar detailing (Bothwell et al., 2011). Thermal bridges were measured as linear length and included lintels, window/door jambs, cills, floor junctions to external and party walls and the roof eaves junction. In the PHPP exterior dimensions of the building envelop were used (this in effect over estimates heat losses using this calculation method). In the PHPP geometrical thermal bridges are accounted for in the calculated conduction losses.

**12.36 Mechanical Ventilation Heat Recovery (MVHR)**

Heat recovery (MVHR) systems were not modelled. The EST report (2010) suggested that only where air infiltration has been reduced to less than 5m$^3$/m$^2$/h @ 50Pa are significant energy efficiency improvements possible with balanced mechanical ventilation systems incorporating heat recovery (MVHR). Clearly this will be challenging to achieve in most historic buildings energy retrofit projects. Having said that, it is quite possible that as retrofit techniques are improved, MVHR products are developed to suit historic buildings, and once minimum ventilation rates are established this adaptation will increase in frequency as it makes good energy sense.

There may be instances where the use of extensive internal wall insulation in conjunction with replacement glazing leads to low infiltration rates necessitating MVHR. This was not modelled.

There is also the possibility of point source MVHR for rooms such as kitchens and bathrooms. This was not modelled.

There may be a case to promote MVHR in historic buildings. This is an important area for future work.
12.37 Mean Internal Temperature

This was a parameter that proved difficult to define conclusively. There were two key reasons.

Firstly, when considering the adopted model, a temperature input was required to reflect comfort levels in the main living area. With the SAP model, a lower temperature is calculated using algorithms for other areas of the dwelling (approximately 2-3°C lower if a temperature of 21°C inputted for living area). This is not the case with the PHPP model, which assumes a whole house temperature of 20°C, this can be changed by the model user. IES can be modelled to reflect either approach.

The second challenge was how to define the internal temperature. The questionnaire data simply asked for a thermostat setting, the histogram of the returned data is at Figure 96. The mean set point was 20.5°C.

![Figure 96 Histogram of thermostat set temperatures](image)

For Case Study 1-3 the thermostat set point was 19, 19 and 20 °C respectively.

There was no detailed data collated on the duration of and variation of the set temperature during the heating season. A review of recent research on mean internal temperature is at Table 17.
Table 17  Internal Set Temperatures

<table>
<thead>
<tr>
<th>Source</th>
<th>Average winter internal temperature</th>
<th>Average mean living room temperature</th>
<th>Rest of home</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHO 2003</td>
<td>21.0°C</td>
<td></td>
<td>18°C</td>
</tr>
<tr>
<td>Domestic energy fact file 2012</td>
<td>17.9°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lomas et al. 2010</td>
<td>19.9°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oreszczyn et al. (2006)</td>
<td></td>
<td>19.1/20.1°C</td>
<td></td>
</tr>
<tr>
<td>Low Carbon Domestic Retrofit (2012)</td>
<td></td>
<td>20°C</td>
<td></td>
</tr>
</tbody>
</table>

However a mean temperature does not reflect the duration and extent of heating and is affected by mean external temperatures.

SAP assumes an internal temperature of 20°C for the living area and calculates a lower temperature for other areas. PHPP assumes a whole house temperature of 20°C, which for a well-insulated and low infiltration dwelling is acceptable, but can the same be applied to a historic building? How many historic buildings are heated to 20°C throughout? This is unknown, although 21°C for main areas of occupation is likely, but how to determine a representative average whole house temperature?

Considering all these elements, in particular the mean set point established from the survey data, a mean internal temperature of 20°C was selected, this is also in line with PHPP methodology. However, as internal temperature will significantly affect energy use, mean temperatures of 17, 18, 19, 21, 22 and 23°C were also modelled for comparison, (section 12.47).

---

26 Average year 2000-2010
### 12.38 Model Parameters

Table 18 shows the model parameter inputs. These vary between models depending on the available inputs available to the user.

**Table 18  Model Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAP</th>
<th>IES</th>
<th>PHPP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treated floor area</strong></td>
<td>Internal measurements including stairways and cupboards</td>
<td>As PHPP</td>
<td>No stairs, unoccupied spaces</td>
</tr>
<tr>
<td><strong>Mean internal temperature</strong></td>
<td>20°C living area 18°C elsewhere</td>
<td>20°C</td>
<td>20°C</td>
</tr>
<tr>
<td><strong>Climate data</strong></td>
<td>Monthly</td>
<td>Hourly</td>
<td>Monthly</td>
</tr>
<tr>
<td><strong>Space heating</strong></td>
<td>Monthly</td>
<td>Monthly</td>
<td>Monthly</td>
</tr>
<tr>
<td><strong>Hot water</strong></td>
<td>Monthly</td>
<td>Monthly</td>
<td>Monthly</td>
</tr>
<tr>
<td><strong>Thermal mass</strong></td>
<td>User determined Option 3=High</td>
<td>User input</td>
<td>User input Summer work sheet c6</td>
</tr>
<tr>
<td><strong>Weather data</strong></td>
<td>Weather regions available</td>
<td>Local region imported</td>
<td>Local region imported</td>
</tr>
<tr>
<td><strong>Occupancy</strong></td>
<td>Algorithm based on floor area</td>
<td>User input 2</td>
<td>User input 2</td>
</tr>
<tr>
<td><strong>Heating duration options</strong></td>
<td>Choice of 3 regimes</td>
<td>User input</td>
<td>Only through reduction factor on annual heat demand worksheet, M41</td>
</tr>
<tr>
<td><strong>Thermal bridging</strong></td>
<td>Overall figure for Ψ x exposed surface area</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
<td>Calculated</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>q50</strong></td>
<td>Default or user input</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>Openings U-values</strong></td>
<td>Default</td>
<td>Calculated using PHPP</td>
<td>Calculated in U value worksheet</td>
</tr>
<tr>
<td><strong>Party wall U value</strong></td>
<td>Default</td>
<td>Calculated using PHPP</td>
<td>Calculated in U value worksheet</td>
</tr>
<tr>
<td><strong>Windows/doors</strong></td>
<td>Measured and user input</td>
<td>Measured and user input</td>
<td>Measured and user input</td>
</tr>
<tr>
<td><strong>Boiler efficiency</strong></td>
<td>SEDBUK(2009)plus correction factor</td>
<td>Calculated</td>
<td>Calculated</td>
</tr>
<tr>
<td>** Stored hot water systems**</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Gains from central heating pumps</strong></td>
<td>Need to add manually</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Primary pipe work losses and secondary (distribution) losses</strong></td>
<td>Default</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Solar gain</strong></td>
<td>Monthly, based on latitude 53.4°N (Manchester)</td>
<td>Yes, based on location</td>
<td>Yes, based on location</td>
</tr>
<tr>
<td><strong>Lighting</strong></td>
<td>Algorithm calculation</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>Low-energy lamps</strong></td>
<td>Correction factor</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>Equipment and electrical appliances</strong></td>
<td>Not included</td>
<td>User input</td>
<td>User input</td>
</tr>
<tr>
<td><strong>Internal heat gains</strong></td>
<td>5.9 W/m²</td>
<td>User input</td>
<td>2.1 W/m²</td>
</tr>
<tr>
<td><strong>Window reveals</strong></td>
<td>Not considered</td>
<td>Measured and user input</td>
<td>Measured and user input</td>
</tr>
<tr>
<td><strong>Window Frame factor</strong></td>
<td>Default setting according to window type calculated</td>
<td>calculated</td>
<td>calculated</td>
</tr>
<tr>
<td><strong>Shading</strong></td>
<td>User selected over shading factor</td>
<td>Measured and user input</td>
<td>Measured and user input</td>
</tr>
</tbody>
</table>
The three case study dwellings were surveyed. All dimensions were measured. All windows were surveyed and the widow details entered into the PHPP. A typical window detail is at Figure 97.

Figure 97  Typical window
12.4 Results

12.4.1 PHPP, SAP and IES Actual Energy Use

The case study dwellings actual energy consumption was analysed over an 18 month period from June 2010. The first 6 months data were discounted to eliminate the Hawthorne effect. Energy use for heating was normalised using 20 year degree data (Seven Valley region; CIBSE TM41, 2006).

The results of predicted delivered energy use against actual delivered energy use for all three case studies using PHPP, IES and SAP software is at Figure 98.

![Model Results](image)

Figure 98 Comparison of Model Results for All Energy Use

This shows that all the models overestimate energy use compared to actual energy use. A key explanation for this is that the case studies have individual intermittent heating patterns and varying levels of occupancy that are not reflected in standard model analysis.

Before considering the effect of intermittent heating a statistical test was completed to consider the validity of these results.
12.42 Statistical Analysis

A test for normality of gas use was conducted, see Table 19.

Table 19 Test for Normality for gas use

<table>
<thead>
<tr>
<th>Method</th>
<th>Kolmogorov-Smirnov²</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>PredictedGas SAP</td>
<td>.185</td>
<td>3</td>
</tr>
<tr>
<td>IES</td>
<td>.215</td>
<td>3</td>
</tr>
<tr>
<td>PHPP</td>
<td>.250</td>
<td>3</td>
</tr>
</tbody>
</table>

a. Lilliefors Significance Correction

As the sample group is small the Shapiro-Wilk test is used, as P>0.5 the data is not significantly different from a normal distribution.

ANOVA was used to evaluate the three models of predicting energy use for predicted delivered gas energy use, see Table 20.

Table 20 ANOVA test predicted gas energy use

<table>
<thead>
<tr>
<th>PredictedGas</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>56001.556</td>
<td>2</td>
<td>28000.778</td>
<td>7.695</td>
<td>.022</td>
</tr>
<tr>
<td>Within Groups</td>
<td>21834.187</td>
<td>6</td>
<td>3639.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>77835.742</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This test shows there is a significant difference (p< 0.05) among the three methods of modelling energy use. It is therefore appropriate to proceed to a posthoc (a posteriori) test to find out where the difference is.

A Tukey test was conducted, see Table 21. From these results we can conclude that IES and PHPP are the most effective method of predicting gas energy use.
Table 21  Tukey Test results

**Multiple Comparisons**

<table>
<thead>
<tr>
<th>PredictedGas</th>
<th>Tukey HSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) Method</td>
<td>(J) Method</td>
</tr>
<tr>
<td>SAP</td>
<td>IES</td>
</tr>
<tr>
<td></td>
<td>PHPP</td>
</tr>
<tr>
<td>IES</td>
<td>SAP</td>
</tr>
<tr>
<td></td>
<td>PHPP</td>
</tr>
<tr>
<td>PHPP</td>
<td>SAP</td>
</tr>
<tr>
<td></td>
<td>IES</td>
</tr>
</tbody>
</table>

*. The mean difference is significant at the 0.05 level.

As the sample group was small, the test was repeated the Kruskal-Wallis one-way non-parametric ANOVA. See Table 22. This test is less powerful but still significant.

Table 22  Kruskal Wallis test

<table>
<thead>
<tr>
<th>Test Statistics*a,b</th>
</tr>
</thead>
<tbody>
<tr>
<td>PredictedGas</td>
</tr>
<tr>
<td>Chi-square</td>
</tr>
<tr>
<td>df</td>
</tr>
<tr>
<td>Asymp. Sig.</td>
</tr>
</tbody>
</table>

a. Kruskal Wallis Test
b. Grouping Variable: Method

12.43 Intermittent Heating

Data collected from the case studies indicated an average 8 hour heating every day. The models were then re-run to reflect this intermittent heating (IH) pattern. This was not possible with the SAP model as there is no user input to adjust this parameter. The IES model was repeated using 8 hours heating a day (Oct–Apr inclusive). In the PHPP model, a reduction factor, although primarily aimed at commercial/industrial buildings that are only in use Monday–Friday, was adopted to represent 8 hours domestic intermittent heating in a 24 hour period (i.e. 8/24 = 33%). The results are at Figure 99.
This shows that when intermittent heating is factored in to the model analysis the results are closer to actual energy use. The PHPP returns results within 10% of actual energy use for Case Study 1 and 3. The SAP results are unchanged as there is no alteration to the heating pattern.

Figure 100 makes a comparison on a percentage difference basis for both gas and electricity use, it shows both the default and the intermittent heating pattern results for both IES and PHPP. With the use of intermittent heating PHPP provides the closest representation of actual gas energy use.
Figure 100  Comparison of Predicted Delivered Energy Use to Actual Delivered Energy Use

The results for electricity use have been presented and are shown for completeness. This shows that the SAP model under estimates electricity use, particularly so in Case Study 1 as there is no option to reflect the use of an electric range or to input actual electrical demand. The PHPP electrical use is based on an inventory of electrical loads within the dwellings (Table 13), the IES model used the PHPP inputs so has the same result. They both provide an accurate result for Case Study 1 (+4%) but over predict energy use in Case Study 2 and 3 (+52% and +19% respectively).
12.44 Retrofit Adaptations All Models

Having selected three models to assess actual energy use, the analysis was continued to make a comparison of the retrofit adaptations modelled by SAP, IES and PHPP. The results for each of the Case Studies are at Figure 101.
Following RP 1 and 2 the results of each software model are closer for gas energy use although variations remain.
In Case Study 1 and 3 the PHPP shows higher predicted gas use in the base case dwelling. This is difficult to account for. Case Study 2 already has a number of energy saving adaptations and is not comparable. In Case Study 1 part of the explanation may lie with the incidental heat gains from the Aga stove, as these are accounted for in the IES model. In Case Study 3, its end of terrace typology may lead to a higher prediction of gas energy use.

The overall reduction in each model for each Case Study is at Figure 102.

![Delivered Gas Energy Use](image)

**Figure 102** Modelled gas energy use for all models

Although cluttered, Figure 102 shows a broad convergence following all retrofit adaptations returning delivered gas energy use below 100 kWh/m² in all cases bar one. The exception is SAP Case Study 2; this is probably due to the way this model cannot fully reflect previously installed energy efficiency retrofit adaptations.
12.45 Retrofit Adaptations PHPP Model

Figure 103 shows PHPP predicted delivered energy consumption (based on surveyed construction details) with no reduction for intermittent heating compared to actual recorded delivered energy use.

![Figure 103 PHPP predicted energy v actual energy use](image)

This shows that for gas (heating and hot water) use PHPP estimates a considerably higher demand than actual. For electricity use it is much closer to demand. The reason for the remaining difference may be that occupants do not heat the whole house to the same temperature. This presents a challenge in how to define a realistic heating pattern that accurately reflects occupant behaviour, particularly when faced with draughty dwellings with poor thermal performance.

Within the case studies there is also a noticeable variation in energy use. Case study 1 has significantly higher electricity use. This is due to occupancy by a semi-retired person with high occupancy and the presence of an electric range and an electrically under floor heated conservatory. End of terrace typology in Case Study 3 may make a contribution to the higher gas use.
12.46 PHPP Model Analysis

This section now looks specifically at the use of the PHPP and the results of modelling without any allowance for intermittent heating is presented. This methodology was adopted for two reasons. Firstly, the aim of this research was to establish the merit of using the PHPP as a planning tool for retrofit adaptations, the introduction of a reduction factor requires further research to establish a reliable means to establish both magnitude and a selection methodology for this factor. Secondly, although there appeared to be merit in adopting a reduction factor to reflect occupancy patterns there was not enough data to fully validate this approach.

Case Study 1

The summary of the modelled retrofit adaptations for delivered energy use and CO₂ emissions is shown in Figure 104. In this dwelling the use of an electric range (7.5 Kw) for cooking distorts the results in that it makes a useful contribution to heating that cannot be discerned in the model. Total delivered energy use following all retrofit adaptations was reduced by 74% from the modelled base case energy use of 473 to 125 kWh/m², CO₂ emissions were reduced by 64% from 121 to 43 kg CO₂ /m².
Figure 104 Retrofit adaptations on Case Study 1 delivered energy and CO₂ emissions
Case Study 2

The summary of the retrofit adaptations are shown in Figure 105. Total delivered energy use following all retrofit adaptations was reduced by 54% from the modelled base case energy use of 197 to 91 kWh/m$^2$. CO$_2$ emissions were reduced by 55% from 48 to 22 kg CO$_2$/m$^2$.

Figure 105 Retrofit adaptations on Case Study 2 delivered energy and CO$_2$ emissions.
Case Study 3

The summary of the retrofit adaptations are shown in Figure 106. Total delivered energy use following all retrofit adaptations was reduced by 85% from the modelled base case energy use of 499 to 84 kWh/m². CO₂ emissions were reduced by 82% from 109 to 20 kg CO₂/m².

Figure 106  Retrofit adaptations on Case Study 3 delivered energy and CO₂ emissions.
Comparison of results of the retrofit package on total delivered energy use and CO\textsubscript{2} emissions are shown in Figure 107.

![Energy use and CO\textsubscript{2} emissions following retrofit measures](image)

Figure 107  Energy use and CO\textsubscript{2} emissions following retrofit measures

Figure 107 indicates that basic measures in RP 1 make modest progress to creating low energy historic buildings. The benefit of RP 1 is less in Case Study 2 as it already had many energy saving adaptations. Likewise RP 2 delivers a smaller saving in Case Study 2 as it had some internal wall insulation fitted previously.
The final reduction of emissions from the base case was between 54-85%, but only with the contribution from improvement to the thermal performance of external walls. Without internal wall insulation improvements would range from 20-48%.

12.47 Effect of Internal Set Temperature and “Take Back”

In section 12.37 there was discussion on the appropriate internal temperature for the case studies. Figure 108 shows the effect of different internal temperatures ranging from 17-23°C for each of the case studies on delivered gas energy use using the PHPP.

This shows that for predicted energy consumption the internal set temperature has considerable effect on the overall delivered energy use. The difference on average is approximately 10% per °C change (or approximately 30 kWh/m²/yr/°C).

What is more interesting is that following all retrofit adaptations the difference in gas energy use per °C change in temperature is still 10% but as overall energy use is greatly reduced, it equates to approximately 8 kWh/m² per °C change in internal temperature.
However, when all 3 retrofit packages are completed, the difference between a possible expected set
temperature of 18°C and a possible future temperature of 21°C (to reflect the “take back” effect) is
22% additional gas energy use. This may sound high, but amounts to approximately 23 kWh/m²/yr
additional delivered gas energy use. Compared to the predicted base case delivered gas energy use for
Case Study 1 and 3 in excess of 450 kWh/m²/yr, this seems modest.

Figure 108  Retrofit adaptations delivered gas energy with different internal temperatures
12.48 Infiltration

Following RP 1 the effect of further reduction in the infiltration rate from a q50 of 9.6 to 5.0 was modelled (q50 of 5.0 is considered the point beyond which MVHR is beneficial in energy saved (Thorpe, 2011)). This resulted in a further reduction of the heating load of between 16-21 kWh/m²/a or approximately 9-11% of the heating load, see Figure 109.

![Figure 109 Benefit of reducing infiltration in RP 1](image)

12.49 Low and Zero Carbon Technology

RP 3 included both SHW and PV (LZC technologies selected from the review in Chapter 8).

SHW contributed 60% to the domestic hot water demand. This resulted in an average of 10% reduction in carbon emissions. These savings are reflected in the PHPP methodology so no additional work is required to adjust for carbon savings that arise.
The same cannot be said of PV where no benefit is attributed from generating PV electricity. In this study, contrary to Passivhaus methodology, PV generated electricity (within RP 3) was allocated according to demand. This was analysed to explore options for carbon emissions reduction that are independent of a “fabric first” approach. For Case Study 1, 90% of electricity was allocated due to the constant demand of the electric range and full time occupation. As weekday occupancy was minimal in Case Study 2 and 3, 40% of PV generated electricity was allocated as used on site (in line with the findings in Chapter 11).

Total Carbon emissions from electricity use varied between the case studies and are shown in Figure 110. Case Study 1 has higher emissions due to a 7.5 kW electric range cooker in operation 24/7. It was not possible to change this for a gas type model as there was no feasible option to provide the necessary flue arrangements and the occupant considered it an important life style choice. In Figure 110 the use of PV reduced carbon emissions by 20% and by approximately 40% in Case Study 2 and 3.

![Figure 110 CO₂ emissions due to electricity use](image)

Figure 110 CO₂ emissions due to electricity use
There is a small reduction in CO₂ emissions for all the case studies following retrofit package 2 (internal wall insulation) attributable to reduced electricity use for boiler and auxiliary electricity (e.g. central heating pump).

Unused PV generated electricity was exported to the grid and not considered to reduce the dwellings carbon emissions in Figure 110. This is a point that requires further discussion as this low carbon electricity could be considered as offsetting carbon emissions. Figure 111 shows the effect of allocating all PV generated electricity. For case study 1 there is little difference as most PV electricity has already been allocated (90%). For case study 2 and 3 allocating all PV generated electricity would reduce CO₂ emissions from electricity to zero, just placing them into carbon negative overall electricity use.

![Figure 111 Projection for CO₂ emissions using all PV generation (3.9 kWp Array)](insert_diagram)

There are limited options to further reduce CO₂ emissions from the current demand. One would be to install additional PV capacity, using the front elevation of the double pitch roof (or garden space). This would be visible at a distance (properties located on a hillside) on the main elevation but would permit an additional 2.4 kW system (larger system possible as no space required for the SHW system), producing an additional 2040 kWh of electricity annually (based on an output of 850 kWh /kWp/yr).
If this electricity was also used to offset all electricity it would make little difference to Case Study 2 and 3 emissions as PV generation is already greater than consumption, though this would mean they were carbon positive dwellings for electricity in that they would generate considerably more electricity than they consumed. For case study 1 this would reduce final CO₂ emissions to 13 kg CO₂/kWh, a reduction of 72%, see Figure 112.

![Figure 112 Projection for CO₂ emissions using all PV generation with an additional 2.4kWp Array](image)

**Figure 112 Projection for CO₂ emissions using all PV generation with an additional 2.4kWp Array**

**12.410 Primary Energy**

When making comparison with the Passivhaus standard primary energy must be considered. The primary energy demand includes all energy for heating, cooling, hot water, auxiliary electricity, lighting and all other electricity uses. This limiting value in the EnerPHit standard is 120 kWh/m²/a. This formula applies to residential buildings, offices and schools.

The primary energy used by the case studies following RP 1-3, but not including PV generated electricity as used within the dwelling, is at Figure 113, for comparison the EnerPHit standard is also shown.

---

This shows that total primary energy use in Case Study 3, although exceeding the maximum heat demand of 25 kWh/m²/a, just meets the total primary energy for Passivhaus EnerPHit standard.

The primary energy is reduced if PV generated electricity (2.05 kWp) is taken into account, see Figure 114.
This shows that Case Study 2 and 3 use approximately 8% and 16% less total primary energy respectively than a Passivhaus (EnerPHit) compliant solution, although they could not obtain PH compliance as they exceed the maximum heat demand of 25 kWh/m²/a.

12.5 Error Checking Analysis

All spreadsheets have errors, ranges vary, but an error rate of 4% would not be unusual (Panko, 2008). This rises to general errors of 5.6% for researchers working alone (Panko et al., 1997).

With enough time and resources (additional researchers for example) it may be possible to eliminate almost all errors. As a sole researcher I decided rather to look at the key areas of data entry that would have the greatest effect on the results, mainly focusing on the structural design and calculation formulas. In addition, areas where there were concentrations of calculations were also given attention.

One PHPP book was used for each case study and the results copied and pasted to a results spreadsheet. As the results spreadsheet was developed comments were inserted throughout, these were essential when it came to rechecking the sheet several months later.

To check the initial results the PHPP were re-worked from a blank PHPP workbook. There were small variations in the results. On examination these were tracked down to data entry errors or failure to change the input parameters for each of the retrofit packages. Some of these small errors took a considerable amount of time to track down.

On the results sheet cross checks were used for sum totals, and subtraction was used to determine that the difference between both the total and the checked column were zero, this made it easier to spot errors on the spreadsheet. The sheets were also checked in” Formulae view”; this was particularly useful to ensure correct treatment of the data according to energy and model type.

To avoid “order of operation” errors in calculation, parentheses were used to ensure the correct calculation.

None of the above will guarantee that there are no errors but they help ensure that the possibility is minimised.
12.6 Discussion and Conclusion

The use of PHPP has presented challenges when attempting to predict delivered heating energy use. The failure of the model to accurately predict delivered gas energy use arises from applying the default assumption of a set internal temperature of 20°C throughout the heating season in a highly insulated and very airtight building and applying it to a dwelling that is less thermally efficient, has much higher infiltration rates and is not maintained at a constant temperature during the heating season.

By considering intermittent occupancy to vary heating demand through the use of a reduction factor to reflect occupancy (annual heat demand worksheet), predicted gas energy was returned much closer to actual energy use. This approach requires further empirical validation to demonstrate confidence that the model can predict extant energy use in buildings other than those that meet the Passivhaus philosophy.

There are other approaches to reflect occupancy patterns and intermittent heating. Although departing from the principle of simplicity and user friendliness, dwellings could be subdivided into separate heating zones to reflect different set temperatures. Additionally the contribution of the boiler to full season heating could be adjusted to reflect occupancy. This would require further detailed analysis to develop confidence in an approach to reflect actual occupancy and demand.

However, there should be no departing from the intention to evaluate/develop a straight forward, user friendly and cost effective suitable software package for wide scale adoption at the district level. The results showed that the adoption of a reduction factor to reflect intermittent heating provided results close to the actual energy use. Reliability in this approach could increase with additional empirical data leading to greater overall accuracy using a simple to use coefficient. This would be the next step in developing confidence in the use of PHPP to model energy use in historic building.

How could this be achieved? One approach could be to collate empirical data on actual occupancy patterns through logging central heating, hot water and electrical load patterns of use for different social and demographic groups. It would be interesting to make a comparison between what occupants think their energy use pattern is and actual recorded data of energy use. What would be more interesting would be a detailed study of energy use patterns before and after retrofit adaptations.
There may be merit in modelling a series of occupancy patterns and producing the results for all types, allowing selection of the appropriate result to reflect the established pattern of occupancy.

This work could then be aligned with the database established in Chapter 10 where the survey questionnaire could be amended to seek adequate information to better establish occupancy and link this to energy use.

The present work emphasises that establishing a realistic heating pattern is key to developing accurate energy and CO\textsubscript{2} emissions savings; this applies to all dwelling types. The reality is that occupants have varying lifestyles and comfort levels. For modelling purposes a standard is defined to enable comparison. But there is a danger if the standard overestimates energy used for heating, as monetary or carbon savings from retrofit measures may be seriously overvalued. This suggests the need for additional research to align the model to reflect the occupancy effect on energy demand.

This is closely linked with the take back effect. The modelled heating regimes are based on observation. It may arise that following deep retrofit adaptations occupants may adopt increased levels of heating (in line with model predictions) as it would involve no additional cost. Little is known about the rebound effect in domestic dwellings following increased thermal performance. More research is required to consider this aspect.

The limited work on the effect of internal temperatures showed that 1°C of take back post retrofit in the form of increased comfort, equated to approximately 8 kWh/m\textsuperscript{2}. Given the high energy use before retrofit the end result is still a dwelling with considerably lower energy use and carbon emissions.

As an example, moving from a pre retrofit temperature of 18°C and a post retrofit internal temperature of 21°C, this would amount to an approximate additional 24 kWh/m\textsuperscript{2}/yr of delivered gas energy use. Given the predicted start energy use ranging from 200 to plus 400 kWh/m\textsuperscript{2}/yr, take back in the form of increased comfort still results in a considerably lower energy use.

The case studies have shown that energy efficiency is not only solely dependent on the performance of the building, occupants play a vital role. One way to mitigate this effect is to collect empirical data on actual energy use to improve the accuracy of energy use software prediction. PHPP was developed over time analysing the results of as built performance against predicted results. Clearly more case study analysis will develop similar accuracy for retrofit in historic buildings.
The potential of existing materials and components were utilised and exploited to improve thermal performance. The model has potential to consider adaptation options to optimise performance. This now requires validation of effectiveness, reliability and durability in real retrofitted case studies.

This analysis has considered three distinct retrofit options as stand-alone packages. To some extent the solution is not that simple. The point is not to implement a suite of separate unconnected retrofit adaptations but to consider the impact of combined adaptations. For example, the use of hygroscopic materials for internal wall insulation may be able to cope with lower rates of natural ventilation; whereas the effect of internal wall insulation with a vapour barrier on ventilation rates is unsure, particularly as the previous buffer effect of walls will have been dislocated. This may require additional ventilation if moisture within the dwelling previously moved in and out of external walls in a seasonal rhythm.

There is more to take back than just energy use. There is the impact of improved internal heating duration and set temperature, as this will also affect the previous equilibrium of moisture movement subsequent to any retrofit adaptations. This is an ongoing complicated area of research, and with regard to the long term fabric performance of historic buildings, is particularly important.

Intervention to improve energy use will have its risks. On the one hand they can improve energy use by improving the fabric performance and mechanical plant of the building, but on the other hand, intervention can affect the performance of the fabric that may lead to unseen decay as well as affecting the aesthetic value of the building. The debate on internal wall insulation continues. Many retrofits have been completed in recent years; as yet there is little documented evidence of these or previous internal wall installations leading to fabric decay.

Internal insulation was selected as the prospect of external wall insulation on a Georgian terrace would have an unacceptable effect on aesthetics. An advantage of internal wall insulation is that it increases the rate of the dwelling’s thermal response, an advantage with intermittent heating.

This paper highlights the uncertainty in what is an acceptable infiltration rate for historic buildings to prevent fabric decay and maintain occupant comfort. In the case of existing dwellings there are numerous sources for good practice, yet there is no empirical evidence for what is a minimum acceptable standard for historic buildings. A q50 of 9.6 may be capable of further reduction without increased risk to occupant comfort or fabric performance. To make future use of any model it is necessary to define accurately this parameter as reducing infiltration from a q50 of 9.6 to 5.0 reduces CO₂ emissions by approximately 10%.
CO₂ emissions savings of 55-83% are possible but only when the thermal fabric is significantly improved and the use of PV is included. This confirms to some extent what we know, in that without improvement to thermal performance overall potential for CO₂ reduction is reduced considerably (less than 50%). Given the large numbers of historic buildings, current emissions reduction targets are unlikely to be met without significantly reducing the CO₂ emissions resulting from heating. In the absence of a low carbon heat source suitable for use at the urban scale, improvements to external wall thermal performance will be required if emission reduction targets are to be approached by the historic buildings stock as a whole.

A reduction in CO₂ emissions of 83%, although positive, was only achieved in Case Study 3. Case Study 1 and 2 achieved 55% and 64% respectively. This may be viewed as disappointing given national energy reduction targets. This highlights how we may be looking at the problem from the wrong angle. What may be of more interest is final emission levels; this was 41, 19, and 21 kg CO₂/m²/yr respectively for Case studies 1-3. From Table 4 the BANES average was 65 kg CO₂/m²/yr, applying an 80% reduction would give a target of 13 kg CO₂/m². This was not achieved by any of the case studies. It is noted that this figure is based on energy use in 2009 and not 1990, which is the base year for the 80% reduction in CO₂ emissions target.

It is unclear how to make further improvements to achieve an 80% reduction in all dwellings. Options are to achieve lower infiltration rates, consider MVHR and the use of heat pumps. These are all areas for further work.

The methodology adopted a simplified approach regarding thermal bridges, the effect of which increases in significance as fabric heat loss decreases. The calculation of thermal bridges is complicated and requires specialist software (such as THERM). In the case of historic buildings there remain challenges in defining material properties in unknown construction which vary greatly depending on the moisture level in the fabric.

The benefit of allocating PV generated electricity was demonstrated. Additional PV capacity would reduce Case Study 1 emissions by almost 80%. For case studies 2 and 3 they would become carbon negative dwellings. This raises several issues, some of which were highlighted in Chapter 11. Firstly, should exported electricity be considered for offsetting domestic CO₂ emissions? Also, as the case studies are listed buildings, under current planning constraints they would be unlikely to gain planning permission for PV installation on the front façade. This restricts the potential for these dwellings to achieving optimum CO₂ emissions reductions. Given the challenge in meeting the UK’s 80% CO₂ emissions reduction target, the increased carbon saving from additional PV on the front elevation roof may be worth the toll on aesthetics.
PV generated electricity will have a carbon factor based on a full Life Cycle Analysis. The actual factor requires research to establish an accurate figures for the UK based on the type and size of the installed PV system and lifetime annual output.

The reality is that all measures are required as no one solution can bring about the required reduction individually.

Energy use was reported as delivered energy, this is effectively the fuel or electricity used within the dwelling. This allows direct comparison to both national and international energy end use. However, for true comparison, and to reflect the inefficiencies of centrally generated electricity, primary energy should also include the effect of on-site generation. In this study this approach demonstrated that historic buildings can achieve lower overall energy use than the current Passivhaus EnerPHit standard (although exceeding the 25 kWh/m² heating limit), this is further improved by including on-site generated electricity.

PHPP has shown that as a model it can provide both predictions of energy use and assessments of the benefits of retrofit adaptations in historic buildings. But more importantly and with regard to aligning the conservation of energy to the conservation of heritage, it can provide empirical data to evaluate the benefit of decisions that affect fabric and/or aesthetics.

At the beginning of the thesis was an aspiration to find a model that stakeholders would accept to weigh up energy efficiency retrofit adaptations against loss of fabric and aesthetics. It is the detail that is within PHPP (that leads to accurate results) that is more likely to lead to its acceptance; this gives a great advantage over the current standard approach of using SAP/RdSAP.

It is the level of detail that is required that may hold back its wide spread uptake, mainly because of the initial training required to ensure accurate completion of the worksheet. From experience, this is no more onerous than most dynamic modelling systems

How likely is it that a model designed for superinsulated dwellings will be accepted by stakeholders, architects and other professionals in the retrofit for energy efficiency process of historic buildings? This is a difficult question to answer. With further work and verification, it seems feasible from this study that PHPP could be shown to be accurate and acceptable to stakeholders when considering adaptations to historic buildings.
The possible benefits of retrofit adaptations have been discussed. What is less clear is how these buildings will perform in the long term. Concerns have been highlighted in the course of this thesis and within this chapter, they are:

- Indoor air quality.
- Movement of moisture through the fabric and the risk of interstitial condensation.
- The effect of non-repeating cold bridges and the risk of condensation.
- Effect on the likelihood risk of summer overheating.
- Effect of future climate scenarios.
- Occupant take-back or the rebound effect.
- What future carbon factors to plan for?

What can we reasonably expect from historic buildings in terms of reducing CO₂ emissions? Deep retrofit case studies in Chapter 4 report savings in the region of 80%. This case study analysis shows an average of 67% savings.
Chapter 13 Conclusions and Discussion

13.1 Conclusions

A data base of energy use in historic buildings in Bath has been established. This shows that the energy use of Bath’s historic buildings is less than UK, Regional and BANES averages and less than the prediction of their SAP based EPC (Energy Performance Certificate).

The benchmark categorised dwellings into high, average or low energy users. The lower levels of energy use from energy efficiency retrofitted historic dwellings have been confirmed. This demonstrates that carbon emissions in historic buildings can be significantly reduced.

This approach adopted highlighted (within the results), in a way aggregated data cannot, dwellings using high levels of energy when compared with similar properties. The benchmark data also demonstrated that energy efficiency adaptations return lower annual energy use.

From the benchmark data three case studies were used to model predicted energy use against actual energy use. SAP, IES and PHPP were used. With a reduction factor to reflect actual occupancy the PHPP model provided results closest to observed energy use. It was not possible to adopt the reduction factor without more work to determine its reliability to reflect real time energy demand. Without a parameter to reflect occupancy all models vastly over predict heating energy use.

The PHPP modelled predicted energy use and retrofit adaptations. Without an allowance for actual occupancy pattern actual energy use was over estimated. The use of a reduction factor to reflect occupancy returned a figure much closer to actual energy use.

When analysing retrofit adaptations the model showed that energy use in historic buildings can be reduced significantly. This will reduce CO₂ emissions and improve comfort conditions. Achieving these reductions from the historic building sector is likely to require a mixture of existing materials, technologies, SHW, PV and behavioural changes by occupants.

The maximum overall carbon emissions reduction was 82%. This was only achieved in one case study using a comprehensive list of retrofit adaptations, the other case studies returned emissions savings of 55% and 64%, below the current UK 80% target.
Retrofit Package 1 (RP1) is straightforward and likely to be relatively low cost. Reductions in energy use in the region of 8-51% were found, depending on whether any previous energy efficiency improvements had been made. Coupled with the addition of the internal wall insulation (RP2) this reduced the heating load by approximately 70%.

Analysis of the performance of PV systems in 5 historic buildings showed that in ordinary energy use patterns, without technical intervention, an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing delivered electricity CO₂ emissions by an average of 19%. With demand management this can rise to 67% of PV generated electricity used within the dwelling.

SHW and PV were selected as suitable LZC technologies and modelled in the Case Studies. SHW contributing 60% of hot water demand reduced gas carbon emissions by 10%. PV contributed at least 40% of electricity demand and reduced electricity carbon emissions by a minimum of 20%.

The question of what is a realistic internal temperature when modelled was discussed. Before retrofit each degree reduction equated to approximately 10% reduction in annual energy use for heating. The effect of internal set temperature was also presented after all three retrofit packages were completed. This shows that post retrofit the issue on internal temperature is of less importance as any increase in the internal temperature as a result of “take back” or the “rebound effect” still results in a dwelling with considerably lower overall energy use and carbon emissions.

13.2 Discussion

The database established leads to two observations. Firstly, if these buildings are using less than average, then other buildings must be using more than average. These dwellings should be identified as priority for energy efficiency improvements as the application of energy efficiency will bring about larger net carbon savings. Secondly, dwellings with lower energy use will achieve smaller carbon and financial savings. This may present challenges for the current Green Deal and the forthcoming Domestic RHI.

Extending the database would assist targeting dwellings on a priority basis to reduce district scale emissions at the fastest possible rate.
Current confidence in the PHPP to model low energy buildings derives from its evolution in response to a process of improvement and review with feedback to deliver a reliable model that delivers accurate prediction of energy use. But how reliable will it be for historic buildings? The initial results are encouraging, particularly when a reduction factor to reflect occupancy is applied. This will require a validation process following retrofit on historic buildings to establish stakeholder confidence in the model results and predictions.

At the outset an aspiration was set out to confirm a tool/model that could be accepted as trustworthy by stakeholders whilst at the same time, is adoptable by architects and retrofit specialists, who will be at the forefront of implementing retrofit at a national scale. The PHPP has potential in this regard. Its analysis is comprehensive, considering all aspects of the dwellings design and construction to deliver realistic energy use results. It is this thoroughness that is likely to develop confidence in its adoption.

The application of an ambitious U-value for external walls will level criticism from some quarters. There is genuine concern for the long term fabric and occupancy health conditions if this approach were to be adopted without detailed dynamic moisture performance analysis. This problem is not new; the BRE is mid-way through an 11 year evaluation of various external walls insulation solutions in Wales. However, though the findings will be welcome they may not reflect accurately likely outcomes of less harsh weather conditions in other parts of the UK.

Thermal performance is not just a matter of insulation. The performance of glazing and infiltration levels is also of significance. This work has shown the benefits of addressing these issues. The model assumptions were conservative with regard to infiltration. It highlighted the need to explore what is a minimal level of infiltration for a historic building. There is scope to make additional energy use savings in this respect. MVHR was not explored. There is no reason why retrofit package (RP) 1 could not go straight to minimal infiltration rates as advocated by the Passivhaus approach and utilise the MVHR to regulate humidity levels. There is little work in this area to date, but it is one where a new approach may emerge. One key advantage here is that current high infiltration rates for historic buildings could be replaced with controlled ventilation if they are needed for fabric equilibrium while heat energy is recovered and reused. There is no research to show if this would achieve long term energy and carbon savings.
A range of adaptation options have been considered. None of these are new. The innovation presented here is how far they can reduce emissions when applied collectively and how energy savings can be balanced against loss of fabric and changes to aesthetics. It is clear that heat demand cannot be reduced to near zero, but it can be significantly reduced, by as much as 84%. This leads on to the next stage in the evolution of low energy historic buildings, sharing collective knowledge on the careful implementation of retrofit adaptations to satisfy conservation needs.

This work contributes to making decisions on sustainable energy use in historic buildings by increasing knowledge of the expected response of historic buildings to the retrofit process by the application of validated modelling prediction techniques for energy use and CO₂ emissions.

The analysis of PV in historic buildings showed that in one case, 67% of PV generated electricity was used within the dwelling. This was achieved without computer or automated controls, suggesting that this figure could be increased with better controls. Increasing the amount of PV generated electricity use increased delivered electricity carbon emissions reduction to 23%.

These results make a valid case for the inclusion of PV in historic buildings. There are few options to reduce emissions from domestic electricity use. The results can now be evaluated against the perceived negative effect on aesthetics.

PV too can play an increasing role. Research is required to make effective use of unused PV generated electricity that is currently exported to the grid. This energy can be used to reduce domestic demand and emissions. Examples are operating appliances to align with PV production, converting unused electricity to thermal storage in a buffer tank to contribute to both central heating and hot water production. The development of hybrid systems that combine more than one LZC technology, though adding a level of complexity, is also a further area for research.

The current orthodoxy for improving energy efficiency in buildings centres on reducing the heating load, and only when this is achieved does it turn to dealing with the approximate 35% contribution electricity use makes to CO₂ emissions. Historic buildings may require a different approach. The introduction of PV in this building typology, though currently recommended as one of the last retrofit measures, can lead to reductions in CO₂ emissions through using considerably less delivered electricity. When primary energy production losses are considered the benefits increase.
An area not considered, that the literature review has shown will soon be of increased importance, is what to prepare for regarding the National Grid carbon factor. If carbon factors decrease slowly or remain stagnant then the role for micro CHP increases. If they decline significantly then the potential benefits of heat pumps increases. It is unclear if this will mean that historic buildings should use ASHP without improvements to external wall thermal performance and still achieve lower carbon emissions. This requires a close study to evaluate future scenarios.

The methodology that evolved has established extant energy use in historic buildings and demonstrated credible incremental carbon savings. The interventions selected allow for progressive decision-making and implementation of intervention measures through attributing expected CO₂ emissions savings against more intrinsic issues such as fabric alteration and changes to aesthetics. This should be attractive to professionals and stakeholders, but wide scale adoption is unlikely without further fieldwork and model validation.

The literature review and the limitations identified in the methodology, highlight that the applications of intervention measures have a combination of aesthetic, fabric, technical and occupational challenges. This suggests that it is of paramount importance to assess empirically the entire process of reducing energy use in historic buildings.

Reducing energy use and emissions is not just the appropriate combination of materials and plant; it is also about occupants and their perception of comfort. This is an unquantified challenge; occupants vary greatly in their definition of comfort and how to retrofit dwellings that serve the widest range of anticipated comfort is yet to be resolved. The answer probably lies in the KISS principle (Keep It Simple, Stupid). This means that we need to avoid reinventing the wheel with every retrofit project, we need simple controls and systems that need minimal maintenance and we need retrofit options that do “what they say on the box”. This is likely to counter the adoption of complex hybrid energy storage systems.

Retrofit adaptations will inevitably be ‘tailored’ for each historic building, which implies a validation process based on the specific, real application conditions. This work has provided a model-based assessment of the real potential for current materials, components and plant options to reduce energy use and carbon emissions in historic buildings. Validation can be assessed by post occupancy evaluation of retrofit projects and incorporating the findings to future modelling. The time scale for this will at least 10 years, as it may take several years for some potential issues identified to manifest themselves, particularly those associated with internal wall insulation.
13.3 Research Impact

In establishing a data base of the performance of historic buildings future improvements in both energy use and CO₂ emissions in these buildings can be compared back to a base line. The database also allows comparison of energy use from similar dwellings; this is of use to professionals, stakeholders and occupants on a dwellings use of energy and how it compares to good or bad practice.

Knowing actual energy use and carbon emissions allows assessment of retrofit measures based on actual performance. This reality may make some measures less attractive, particular when calculating cost savings and payback periods.

It is not sufficient to simply predict how to save energy, the overriding aim must be to apply findings and monitor and reassess retrofit techniques. It is hoped that these finding can be used in future retrofit projects that permit feedback to refine the methodology for selecting future retrofit options.

Quantifying the contribution historic dwellings make to the domestic emissions of Bath brings into focus the role of these buildings in the overall domestic emissions. But more importantly, it shows that other dwellings types may be emitting more CO₂ emissions than previously thought.

The findings can aid in meeting 2050 targets. There are some 15,000 dwellings in Bath constructed prior to 1945, there are also 15,000 dwellings constructed from 1945 to 1980. If 2050 was a deadline for an 80% reduction in carbon emissions (in line with stated Government targets) and if work commences in earnest in 2015 (giving 12 months to draw up district wide retrofit options) that would leave 35 years to improve the energy efficiency of the existing domestic stock in Bath. On the basis of visiting every dwelling only once, it would mean that 2.4 dwellings would need to be completed every single day of the year. We now need to draw up effective and durable solutions to significantly reduce carbon in these dwellings that will stand the test of time. The benchmark established has to be driven down through retrofit and occupant behaviour.
The impact of this proposal is serious. The current orthodoxy points to upgrading every historic building. The solutions available will mean actual loss of fabric and alteration to aesthetics if alterations/improvements include upgrading/replacement of windows/doors, providing access to currently inaccessible roof areas to install insulation, lifting floor boards to install insulation, alterations through fitting internal/external wall insulation and placing LZC plant on roofs/walls. Further loss of fabric would arise from, if future research confirms their suitability, the installation of heat pumps and MVHR. There will also be a loss of visible fabric, in other words some historic features will no longer be visible, e.g. wall mouldings/dados/cornices when they are concealed behind internal wall insulation for example. Weighed against all of this are the benefits of reduced energy use, financial savings, reduced fuel poverty, increased comfort, reduced winter morbidity and reduced CO₂ emissions.

13.4 Future Work

The reason for the higher percentage of domestic emissions in BANES compared with national domestic emissions from aggregated data sources was unexplained. This requires further research to establish possible causes, particularly as the database of energy use in historic buildings was lower than the Bath average.

The prospect of grid parity of electricity with gas suggests that in the near future, decisions of plant choice to provide heating will be influenced by changes to the carbon factor of the fuel it uses during its lifetime. This is an area that is suitable for further detailed research, in particular how changes in carbon factor affect a dwelling’s carbon emissions. Current models will need to adapt to reflect plant lifetime emissions with varying carbon factor scenarios.

Additional research is required to compare steady state PHPP simulations in historic buildings with actual energy use and energy performance following retrofit adaptations. This should be done at scale and is required to develop confidence in the model for use in this building category. Additional modelling of different typical dwellings in Bath, for example pre Georgian dwellings, a Georgian town house, Victorian and Edwardian dwellings would add breadth to this study. This would facilitate assessing the potential for CO₂ emissions reduction across the entire stock of historic buildings.
Additional research is required to compare PHPP simulations in historic buildings to post occupancy energy use and energy performance following retrofit adaptations. This should be applied on a large scale to align design performance intent with delivered energy performance. This is required to develop confidence in the model for use in this building category.

It is of prime importance to establish a methodology to define a realistic and effective minimum infiltration rate for historic buildings undergoing energy efficiency retrofit adaptations. Without optimising this parameter energy saving opportunities will be missed, and, if set too low, may lead to fabric decay. This can be achieved by providing empirical data measuring current infiltration rates to establish extant levels of ventilation. In addition, the effect of draught proofing, window/door upgrades, additional insulation, upgrading heat plant and the installation of LZC systems on infiltration rates is required. There is no guarantee that they will significantly reduce infiltration or how long they will remain effective. The retrofit options involve additional fabric penetration for services and cable runs. Unless close attention is paid to workmanship there is a risk that infiltration rates could actually increase.

We need to know/understand what works and what does not. Therefore a critical analysis of recent retrofit projects across Europe focusing on monitoring, measurement and evaluation of achieved carbon emission reductions to exploit previous successes and either ignore, or reappraise, disappointing findings is required. To some extent this should be a central responsibility for the EU as CO₂ does not respect international boundaries and we all want to avoid re-inventing the wheel.

Internal wall insulation is an area of study in itself. There are several issues highlighted in this report. Firstly there is the long term performance of the fabric and the possible risk of interstitial condensation and frost damage. The behaviour of penetrating rain water following internal wall insulation will vary depending on the exposure and porosity of the wall. Some work has explored the application of emulsions to reduce water penetration, though there is no peer reviewed work on the findings.

There is also the risk of overheating following the installation of internal wall insulation arising from dislocating a portion of the buildings thermal mass. The effect of the remaining thermal mass on preventing over heating or its ability to make use of solar gains is unsure. Additional work is required to explore future climate scenarios to ensure dislocating the thermal mass does not lead to a cooling load that may negate any CO₂ emissions savings arising from heating demand reduction. When using PHPP this is particularly important as it assesses overheating on a whole house basis and not room by room.
Cold bridging is difficult to measure when modelling and presents a risk in practice. The effect of thermal bridging was not explored in this study. The adoption of internal wall insulation will increase the risk of fabric decay if this aspect is not dealt with; an example is joist penetrations in external walls and solid lintels over openings. Part of the problem is that actual construction details can be challenging to establish accurately. Thermal imaging may assist in identifying areas of concern. This is an area where once projects have been undertaken, following detailed software analysis, on-site knowhow will begin to accumulate.

Heat recovery was not explored in this study. The potential for MVHR is clear; it would be useful to analyse a case study where this has been undertaken in an historic building. MVHR is relatively new to the UK and there is little post occupancy review research so far. There are concerns about the long term benefits, particularly as the filter systems they rely on require regular maintenance.

There may be a case to promote the use of MVHR in historic buildings. If high ventilation rates are required to facilitate the movement of water vapour in and out of historic fabrics to prevent decay then recovering heat that would otherwise be wasted seems a logical approach.

Although the installation of a complete MVHR installation may not be ideally suited to historic buildings, because of fabric alterations as well as the challenge of reducing the q50 to 5.0 ach to meet the threshold where it becomes viable, or n50 of 0.6 ach (as in PHPP) to ensure its most efficient operation, there may be opportunities to explore heat recovery in high energy extract areas, such as kitchens and bathrooms for example.

In order to estimate the predicted potential for CO₂ emissions reduction an understanding of how occupants affect energy use and emissions from the home is required as technical measures have been shown not be enough in themselves. How can we positively influence long term occupant attitude to reducing CO₂ emissions in dwellings? All of the proposals discussed need post occupancy review feedback to refine the proposed methodology. This requires a multi-disciplinary research project to establish what works and to take successful outcomes to district wide replication.

The utilisation of the occupant/building interface has potential to positively influence energy use through information feedback and building management systems; in particular how to ensure initial savings can be sustained in the medium-to long-term. This is an emerging research field that may identify an effective interface between occupants and energy use.
The failure to match PV generated electricity to daytime demand results in a missed opportunity to reduce a dwelling’s electric use and CO\textsubscript{2} emissions. There is clearly a need here to programme or automatically operate domestic loads to align with available PV surplus generation before exporting to the grid. There is also the possibility to consider using electric PV electricity to heat water. If this was in conjunction with a heat pump 2-3 kWh of hot water could be generated from 1 kWh of electricity. This area is one that could benefit very quickly if research can bring to market affordable and suitable management systems to resolve this issue.

There is little research data currently available on carbon factors for domestic generated PV electricity in the UK. An accurate assessment of this is urgently required to ensure proper carbon accounting.

Analysis of life cycle CO\textsubscript{2} emissions is an area where future research is required to ensure there are no carbon consequences arising from retrofit adaptations.

During the literature review evidence was found to suggest that poor workmanship, inadequate detailing and inappropriate materials can return higher than expected energy use. This suggests that there should be a strong focus on post occupancy evaluation with a means to centrally share any lessons learnt.
13.5 Contribution to the field

This work makes the following contributions to the field of domestic energy use:

1. This work represents the first attempt to develop a database of a benchmark of delivered energy use and CO$_2$ emissions from domestic historic buildings. The benchmark produced can be used to evaluate the benefit of retrofit adaptations, both in monetary and carbon terms. This will enable energy and carbon benefits to be weighed against any possible fabric and aesthetic losses.

2. This work is one of the first to utilise PHPP to model the energy performance of historic buildings. The application of the PHPP has increased our theoretical understanding of the relationship between fabric insulation levels, infiltration rates and heating regimes in forecasting the benefits of retrofit adaptations.

3. The data gathered on the contribution PV can make to reducing CO$_2$ emissions has shown that there is merit in sequencing the application of the LZC technology quite separately from the current orthodoxy to tackle heat loss first.

4. In increasing our understanding of energy use in historic buildings this research can influence the future performance of this building type.
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Annex A Questionnaire

March 2010

Dear Resident,

Information for participants of research project:

The Energy Efficiency of Historic Buildings in Bath

This research aims to assist householders to reduce expenditure on energy in the home as well as reducing CO2 emissions. I am writing to ask you to take part in a survey of energy use in historic buildings in Bath.

As part of my PhD research I am collecting data through interviews and questionnaires and would be grateful for the opportunity to explore your own point of view regarding the use of energy in your home through the completion of the attached survey.

Information will be collected and processed solely for the purposes of my doctoral thesis. The information will not be used for commercial purposes, unless through express permission from the respondent. All the data and information collected will be treated with utmost confidentiality and stored securely.

If you have any concerns over the research or wish to withdraw from participation, you may contact me at the above address. If you prefer to communicate to somebody external to the project please contact Dr. Sukumar Natarajan, Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, United Kingdom, phone 01225 386358, email S.Natarajan@bath.ac.uk.

I would like to thank you in advance for your help and time, and hope that you will enjoy the experience of participating in this interesting research study.

Yours faithfully,

Francis Moran
Doctoral Candidate
Home Energy Use Questionnaire

This questionnaire is part of a research project on the energy efficiency of historic buildings in Bath.

Helpful hints for completing this questionnaire

- Thank you for taking the time to complete this questionnaire.
- The questionnaire can be completed by any resident aged 18 or over living at this address.
- Please read each question carefully and tick a box to indicate your answer.
- In most cases you will only have to tick one box but please read the questions carefully as sometimes you will need to tick more than one box or give a comment.
- The survey consists of 9 pages and should take no longer than 30 minutes to complete.
- If you have any queries about the questionnaire please do not hesitate to contact Francis Moran on 01225 386749.
- Once you have completed the questionnaire please return it in the pre-addressed envelope supplied by 15th September 2010. You do not need to add a stamp.

About You:

What is your name? Mr/Mrs/Ms First Name ........................................ Surname ....................................
What is your address? ...................................................................................................................................
................................................................................................................................................. Postcode: ...........................................................................
What is your email? ........................................................................................................................................

Data Protection:

Data Protection Act 1998: information or data that you provide will be maintained as confidential by the University of Bath.

All information gathered is confidential and will be used only for research. All personal information will not be revealed to anyone. Nobody will be able to identify you or use the information against you.

By completing this form you agree to taking part in this research project and give permission for the researcher Francis Moran to use the findings in subsequent papers and general publications.
### Section A: Your Home

**A1** Do you own or rent your home?
- [ ] Own / mortgaged
- [ ] Rented: Local authority (council)
- [ ] Other
- [ ] Rented: Housing association
- [ ] Rented: Private landlord

**A2** What type of property do you live in?

<table>
<thead>
<tr>
<th>House</th>
<th>Flat/Maisonette</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of terrace</td>
<td>In a purpose built block</td>
</tr>
<tr>
<td>Mid terrace</td>
<td>In a converted house</td>
</tr>
<tr>
<td>Semi detached</td>
<td>Over a shop/office</td>
</tr>
<tr>
<td>Detached</td>
<td>Lowest floor</td>
</tr>
<tr>
<td></td>
<td>Mid Floor</td>
</tr>
<tr>
<td></td>
<td>Top Floor</td>
</tr>
</tbody>
</table>

**A3** When was your home built?

- [ ] Pre 1700
- [ ] 1701-1750
- [ ] 1751-1800
- [ ] 1801-1850
- [ ] 1851-1900
- [ ] 1901-1920
- [ ] 1921-1950
- [ ] Post 1950
- [ ] Not Known

**A4** Is your building Listed/in a conservation area?
- [ ] Listed Grade I
- [ ] Listed Grade II
- [ ] Conservation Area
- [ ] Not sure

**A5** How many habitable floors (storeys) do you occupy (including lofts)?

*Enter a number in the box*

**A6** How many heated rooms does your home have?

(Excluding halls, WC's and bathrooms)

*Enter a number in the box*

**A7** Are any of these rooms in the loft?

- [ ] Yes
- [ ] No

**A8** How many bedrooms does your home have?

*Enter a number in the box*

**A9** How many bathrooms/shower rooms does your home have?

*Enter a number in the box*
## Section B: Structure

### B1 What is the main outside wall construction?
- [ ] Smooth/Dressed stone
- [ ] Rough/Undressed Stone
- [ ] Rendered
- [ ] Other

*If other please specify........................................

### B2 How many walls are there to the outside/interior of your house?
*Enter a number in the box*

### B3 Is the roof structure:
- [ ] Pitched
- [ ] Double pitched
- [ ] Flat
- [ ] Not Sure

### B4 What is the main roof covering?
- [ ] Slate
- [ ] Clay tiles
- [ ] Concrete tiles
- [ ] Not sure

### B5 What direction does the roof towards the street face?
- [ ] South
- [ ] South East or South West
- [ ] East or West
- [ ] North
- [ ] Not sure

### B6 How much roof insulation do you have?
- [ ] 50mm (2")
- [ ] 100mm (4 ")
- [ ] 150mm (6 ")
- [ ] 200mm (8 ")
- [ ] 250mm + (10 " +)

*What type is it?*
- [ ] Fibreglass
- [ ] Rigid foam
- [ ] Not Sure
- [ ] Other

*If other please specify........................................

### B7 Which best describes the windows of your house?
- [ ] Timber
- [ ] UPVC
- [ ] Metal
- [ ] Other

*Do you have do you have?:*

<table>
<thead>
<tr>
<th><strong>Double Glazing</strong></th>
<th><strong>Secondary Glazing</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Half</td>
<td>Half</td>
</tr>
<tr>
<td>Most</td>
<td>Most</td>
</tr>
<tr>
<td>All</td>
<td>All</td>
</tr>
</tbody>
</table>

### B8 Which of the following do your windows mainly have?
- [ ] Shutters
- [ ] Curtains
- [ ] Blinds
- [ ] None

### B9 Do you close shutters or curtains at night during winter?
- [ ] Never
- [ ] Sometimes
- [ ] Usually
- [ ] Always
- [ ] Not Applicable

### B10 How many doors are there to the exterior?
*Enter a number in the box*

*Is there a closed Porch?*
- [ ] Yes
- [ ] No
Section B: Structure (continued)

B11 Is there draught-proofing on your doors and windows?
- None
- Some
- Half
- Most
- All

B12 What is most of the ground (or lowest occupied) floor made of?
- Wood
- Concrete/solid
- Not sure

Is the floor insulated?
- Yes
- No

B13 What is the height of your main living room?
- Average 2.4m (8’0”)
- Low 2.0m (6’6”)
- Cottage
- High 3.0m (10’0”)
- Georgian/Victorian

B14 How many open fireplaces with chimneys does your home have?
- Enter a number in the box

B15 If known, please provide internal occupied floor area:
- Enter a number in the box
  - m²
  - ft²

B16 Does your home have a sunroom or conservatory?
- Yes
- No

If yes is it heated by
- Central Heating
- Separate fire
- Under-floor heating
- No heating
- Other....please specify

Section C: Heating

C1 What type of heating and fuel is used in winter?

Heating
- Central heating with radiators and Combi boiler
- Central heating with radiators and back boiler
- Central heating with radiators and standard boiler
- Warm air system
- Electric storage heaters (Peak Tariff)
- Electric storage heaters (Economy 7)
- Individual heaters
- Individual fires/wood burners

Fuel
- Gas
- Electricity
- Oil
- LPG
- Coal
- Wood

C2 How old in years, approximately, is your boiler?
- Enter a number in the box

Is it serviced at least every two years?
- Yes
- No
Section C: Heating (continued)

C3 How many hours a day is your central heating on in the winter?
During the week
Enter a number in the box
During the weekend
Enter a number in the box

C4 What heating controls does your main heating system have? (Tick all that apply)
- On/Off only
- Programmer/time clock
- Room thermostat
- Thermostatic radiator valves (TRV)

C5 If you have a thermostat what temperature (°C) do you set it to in winter?
Enter a number in the box

C6 Do you use any other form of heating in your home (tick all that apply)?
- Gas fire
- Electric heater
- Open solid fuel fire
- Wood burner
- None
- Underfloor Heating

C7 Do you have a hot water cylinder? Yes No
If YES is it from:
- The main heating system
- Immersion heater
- Off peak immersion heater
- Range
- Not sure
If NO is your hot water from:
- Combi Boiler
- Gas instantaneous
- Electric instantaneous
- Not sure

C8 If YES, does it have any insulation (lagging)?
- None
- Jacket
- Foam

C10 If lagged, how thick is it?
- 12mm (1/2”)
- 25mm (1”)
- 35mm (1 1/2”)
- 50mm (2”)
- Not Sure

C12 How do you set your heating at night?
- Switch off completely
- Leave on and turn thermostat down to less than 16°C
- Leave on with no change

C13 How do you set your heating when you leave the house for at least three hours to all day?
- Switch off completely
- Leave on and turn thermostat down to less than 16°C
- Leave on with no change

C14 How do you set your heating when you leave the house for more than one day?
- Switch off completely
- Leave on and turn thermostat down to less than 16°C
- Leave on with no change
Section D: Electricity

D1 How many low energy light bulbs do you have in your home?
- None
- Some
- Half
- Most
- All
- Not sure

D2 If you have a garden do you use electricity in the garden/ outside (tick all that apply)?
- Hedge cutter
- Grass cutter
- Lights
- Pond
- Greenhouse
- Other, please specify

D3 Is your oven
- Gas
- Electricity
- Other, please specify

D4 Is your hob
- Gas
- Electricity
- Other, please specify

Section E: Occupants

E1 How many people live in your house in total?
- Enter a number in the box

How many are under 16?
- Enter a number in the box

How many are over 60?

How many are over 80?

E2 How many people in your house work from home?
- Enter a number in the box
- If so, how many days per week

An important aspect I would like to consider is to what extent household income determines energy use in the home. Please remember that your answers are in complete confidence. If however you feel this question is intrusive then please skip it.

E3 What approximately, is the total combined gross (before tax) income of the household?
- Less than £10,000
- £10,001 - £15,000
- £15,001 - £20,000
- £20,001 - £25,000
- £25,001 - £30,000
- £30,001 - £40,000
- £40,001 - £50,000
- £50,001 - £60,000
- £60,001 - £70,000
- More than £70,000
- Rather not say
Section F: Comfort

F1 During winter how would you rate thermal comfort in your home?
- [ ] Cold
- [ ] Cool
- [ ] Slightly Cool
- [ ] Just right
- [ ] Slightly warm
- [ ] Warm
- [ ] Hot

F2 During summer how would you rate thermal comfort in your home?
- [ ] Cold
- [ ] Cool
- [ ] Slightly Cool
- [ ] Just right
- [ ] Slightly warm
- [ ] Warm
- [ ] Hot

Section G: Energy Use

This is perhaps the most difficult part of the questionnaire. If there is any difficulty in providing this information please feel free to contact me for assistance as it is of importance to this research, otherwise the inclusion of copies of previous years gas and electricity bills would be welcomed.

If you feel unable to provide this information then please skip this question.

Please enter energy use using the dates of actual meter readings or a fuel delivery, an example is shown:

<table>
<thead>
<tr>
<th>Date</th>
<th>Amount Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>30/4/09</td>
<td>30/4/10</td>
</tr>
<tr>
<td>Gas kWh</td>
<td>25700</td>
</tr>
<tr>
<td>Electricity kWh</td>
<td>3800</td>
</tr>
<tr>
<td>Oil Litres</td>
<td>1500</td>
</tr>
<tr>
<td>Coal Kg</td>
<td>100</td>
</tr>
<tr>
<td>Wood / biomass Kg</td>
<td>20</td>
</tr>
<tr>
<td>Other (please specify)</td>
<td></td>
</tr>
</tbody>
</table>
## Section H: Energy efficiency at home

### H1 Do you have or would you install (if there were no constraints such as Planning Permission), any of the following technologies in your home?  
*(Tick all that apply)*

<table>
<thead>
<tr>
<th>Energy Efficiency Technology</th>
<th>Already have</th>
<th>Like to install</th>
<th>Not Interested</th>
<th>Not Sure</th>
<th>Not Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary glazing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Loft/roof insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid wall insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Draught proof doors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Draught proof windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved efficiency boiler</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shutters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy lined curtains</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy saver light bulbs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A' Rated appliances</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermostatic controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central heating programmer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulate pipe in unheated spaces</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Renewable Energy Technology</th>
<th>Already have</th>
<th>Like to install</th>
<th>Not Interested</th>
<th>Not Sure</th>
<th>Not Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar electric panels (PV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar water heating panels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground/Air source heat pumps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood fired boiler system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood burner stoves</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other energy saving / source (please specify)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### H2 If you already have renewable energy installations on your property what is your opinion of them?  

__________________________________________________________________________

__________________________________________________________________________

(Please continue on a separate sheet if required)

### H3 What is your opinion of barriers preventing you from installing the above options on your home?  
*(Tick all that apply)*

<table>
<thead>
<tr>
<th>Planning regulations</th>
<th>Agree</th>
<th>Disagree</th>
<th>Not Sure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual appearance/unattractive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cost/expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>They would not produce enough energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>They are too complicated and/or too technical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative impact on the historic façade or property decoration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other, please specify:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### H4 If buying a home would you be more likely to buy one with renewable energy installations?  

- [ ] Yes  
- [ ] No  
- [ ] Not Sure


### Section H: Energy efficiency at home (continued)

**H5 What are your views on reducing carbon emissions on historic buildings?**

<table>
<thead>
<tr>
<th></th>
<th>Agree</th>
<th>Disagree</th>
<th>Unsure</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is just as important to save energy in historic buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable technologies should be hidden in historic buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable technologies should be incorporated in historic building restoration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy saving measures only make sense if payback is less than 10 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate change should be a priority in every town/city</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not enough information is provided to save energy in historic buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you very much for taking the time to complete this questionnaire. It is of invaluable help in my research.

If you would like feedback on your energy use please tick (ensure email address entered on front sheet)

Please return this questionnaire in the pre paid envelope to:

Francis Moran  
Department of Architecture and Civil Engineering  
Rm 3.14  6 East  
University of Bath  
Bath  
BA2 7AY

If you have any questions please contact me on:

01225 386749 (office)     0773 6678586 (mobile)

Or email: f.p.moran@bath.ac.uk
Annex B Benchmark Data
Benchmark Data 102 Case Studies
<table>
<thead>
<tr>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>2</td>
<td>130</td>
<td>153</td>
<td>170</td>
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<td>196</td>
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<td>1025</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
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<td>4</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
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<td>5</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>6</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
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<td>1025</td>
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<td>7</td>
<td>130</td>
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<td>170</td>
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<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>8</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>9</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>10</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
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<tr>
<td>11</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
</tr>
<tr>
<td>12</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
<td>196</td>
<td>202</td>
<td>1025</td>
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<tr>
<td>13</td>
<td>130</td>
<td>153</td>
<td>170</td>
<td>184</td>
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<td>184</td>
<td>196</td>
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<td>1025</td>
</tr>
</tbody>
</table>

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Annex C Published Papers

Paper 1


Developing a database of energy use for historic dwellings in Bath, UK.

Francis Moran a,*, Sukumar Natarajan a, Marialena Nikolopoulou b

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Abstract

Historic dwellings in the UK make up 20% of all homes. In the Georgian city of Bath this rises to 30%. These buildings are amongst the most poorly performing part of the English housing stock in energy use terms, with the lowest SAP rating and highest average annual CO$_2$ emissions.

The legal aim to reduce CO$_2$ emissions by 80% by 2050 will involve all existing dwellings, including historic buildings. The degree to which proposals to retrofit the UK housing stock can reduce emissions depends on how much energy they currently use, what it is used for and how much CO$_2$ they emit.

This paper establishes a benchmark of energy use and CO$_2$ emissions for historic dwellings in Bath. This permits comparison of their energy performance against other parts of the housing stock and will facilitate evaluation of potential retrofit adaptations.

Key Words: historic dwellings, energy use, CO2 emissions.

1.0 Introduction

We are entering a new low carbon paradigm [1], as a result Oreszczyn et al. [2] state the main thrust for research is how to decarbonise the built environment. The UK government recognise that the existing domestic sector could make a significant contribution to the overall reduction of national emissions [3]. But to achieve this, the scale of change needed in the built environment over the coming decades dwarfs anything achieved historically, and must be brought about over a timescale of 20–30 years [2].

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In the UK, dwellings account for 26% of CO$_2$ emissions [4] and are at the centre of the governments focus to reduce emissions, along with transport and industry. At the same time it is accepted that the majority of homes in England that will be standing in 2050 have already been built. However, the exact percentage can only ever be an estimate; consequently figures vary (85% Palmer et al. [5], 80% Sustainable Development Comission [6]. 70%, Lowe [7]). Regardless of the exact numbers, it will clearly be necessary to make existing buildings energy efficient rather than focusing primarily on new dwellings.

Within the group of domestic homes, historic dwellings are those built before 1919 (which is considered the date for the introduction of damp proof courses and the start of the use of cavity wall construction). Figure 1 shows that in England, 21.5% of all dwellings were built before 1919.

![Figure 1 Number (000s) and percentage of homes by age in 2007](Source: English House Condition Survey (EHCS) [8])

2.0 Performance of Historic buildings

Bath is one of only two complete cities with World Heritage status (the other being Venice), but this heritage status cannot avoid the emerging low-carbon paradigm that questions the energy use, and by proxy, CO$_2$ emissions of historic buildings.
Despite government statistics showing higher CO₂ emissions from the historic building stock [8] there are differences on how the energy efficiency of these buildings is viewed. English Heritage [9] views their energy efficiency as good whereas Boardman[10] considers their energy efficiency as poor.

A common measure of the energy performance of a dwelling is the rating derived from the Standard Assessment Procedure (SAP)\textsuperscript{28}, this is the National Calculation Method (NCM) for England as mandated by the EPBD. The English House Condition Survey [8] reveals a close correlation between the age of a building and its energy performance. Homes built before 1919 have an average SAP rating of 39 (Band E), the effect of this is demonstrated by their average 9 tonnes CO₂ emissions for heating and lighting, twice those of the post 1990 stock (Figure 2).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{SAP and CO₂ emissions by building Age}
\label{fig:figure2}
\end{figure}

To put this into perspective in energy use and emission terms, using Elmhurst 2009 software, a SAP rating of 39(E) equates to approximately 320 kWh/m²/yr and 81 kg CO₂ /m²/yr.

\textsuperscript{28} SAP rating is calculated from an estimate of annual heating, hot water and internal lighting costs per m² of a property. The SAP scale runs from 1 to 100, with 100 being the best [11].
Within these statistics it is recognised that there are differences in typical size between older and newer homes, which is why such data should be normalised by floor area to allow direct comparisons to be made, see Figure 3.

![Figure 3](image)

Figure 3  Floor area for building age
Source: English House Condition Survey, 2007 [8]

Despite having a higher distribution of larger dwellings it is unlikely to alter the fact that although pre 1919 buildings are a significant contributor to CO$_2$ emissions, the whole built environment will have a role to play in future emissions targets.

The use of SAP to effectively predict a dwellings energy use regarding space heating is questioned [12]. To make a comparison requires a data base of actual energy use, and although the UK has been producing benchmarks for several decades, these have focused mainly on new domestic dwellings and the commercial sector. The development of a benchmark for historic buildings can facilitate rating the performance of a dwelling through provision of a reference to which the dwellings performance can be compared [13]. Oreszczyn et al. [2], recognise that there is very little benchmark data on the energy consumption of the domestic stock. English Heritage [9] also recognises that there is a lack of reliable data for historic dwellings. In direct response to this situation, the aim of this paper
is to produce a normalised benchmark of the annual energy consumption and CO$_2$ emissions annually for historic buildings. This is essential to allow suitable analysis to effectively plan future decarbonisation of this portion of the domestic sector.

2.1 CO$_2$ emissions in Bath

The aggregated figures for the UK are not necessarily representative of Bath. Using Local Authority Carbon Dioxide data from DECC [14], the total CO$_2$ emissions for Bath and North East Somerset (BANES) in 2009 were 967,000 tonnes, of which the domestic stock is responsible for 39% of the total emissions, see Figure 4. The average for the domestic stock in the UK is 26%.

![Figure 4 CO$_2$ Emissions by Sector BANES 2009 Source: DECC 2009 [14]](image)

Figure 5 shows CO$_2$ emissions for 2005 to 2009. In this period emissions from the domestic sector in BANES has maintained at a similar proportion of overall emissions, but they have also reduced by approximately 9%.
The reason for the higher percentage of domestic emissions in BANES compared to national domestic emissions is unclear. One might be tempted to presuppose that this may be due to the higher proportion of historic dwellings (which are generally considered to have higher energy use than modern dwellings) in Bath compared to the national average. For example, Figure 6 shows that Bath has a higher than average concentration of pre 1919 dwellings, having 30% of all dwellings constructed before 1919 compared to a UK average of 22%.

Figure 6  Breakdown by Dwelling Type  
Indeed, an analysis of data from DECC [14] and the English Housing Survey\textsuperscript{29} [8] would suggest that pre 1919 dwellings accounted for 39% of all CO\textsubscript{2} emissions in the domestic sector for BANES in 2009. However, as we shall demonstrate in this paper, such an assumption could be misleading. Regardless of their exact energy use, the high proportion of historic stock suggests these buildings will have to play a significant role in meeting future emission reduction targets (Figure 7) in BANES, even with restrictions that arise from their heritage status.

\textbf{Figure 7}  BANES CO\textsubscript{2} Emissions by Volume, 2009

More importantly, failure to achieve 80\% reduction in any dwelling, historic or otherwise, means that another dwelling must exceed 80\% reduction by an equal amount if targets are to be met.

\textsuperscript{29} The EHCS is a cross sectional study of approximately 8000 dwellings and their occupants. Data was collected by face-to-face interview, house inspection and surveyor property inspection.
3.0 Methodology

The study comprised a survey collection of energy use data followed by a statistical analysis of factors affecting energy use. The Bath building stock consists of 37,600 dwellings [15], this analysis considered the 11,280 pre 1919 buildings. In order to ensure statistical relevance for energy use in historic dwellings in Bath the following had to be fulfilled before distributing the questionnaire:

- Ascertain typology distribution.
- Determine statistically relevant sample size.
- Randomly select target addresses.

Once these were fulfilled and the questionnaires distributed and collected, it was then possible to establish benchmark energy use in historic dwellings in Bath.

Within the survey additional secondary data was collected, this was then use through a multiple linear regression analysis to investigate significant factors that explain the variance in energy use in these historic buildings. Constraints of resource and time availability meant it was not possible to produce a detailed breakdown of energy consumed by end use within each dwelling.

3.1 Sample Size

The selection of strategy for sample size considered the population size, the variability of the parameters being considered and the desired level of confidence. The simplified formula by Yamane [16] which relies on a normal distribution was considered suitable to calculate sample sizes:
\[ n = \frac{N}{1 + N(e^2)} \]

Where
- \( N \) = Population
- \( n \) = sample size
- \( e \) = error (level of precision, not less than 90%)

With a total population (N) of 11,280 dwellings, 99 responses are the lowest number of returns required to achieve a 95% confidence level with a 10% error level, returns in excess of this increase the accuracy of the survey.

3.2 Survey
It was also necessary to consider the typology of the buildings; Figure 8 shows typology distribution in Bath.

Figure 8  Building Typology Bath
Source: BANES House Condition Survey [15]

The dwellings were randomly selected to reflect typology distribution from all pre 1919 dwellings within the City of Bath Conservation area, see Figure 9.
In total, 600 household energy use questionnaires were hand delivered from March-July 2010. Prepaid envelopes were provided for reply, a return rate of 25% was achieved. The questionnaire was kept short in order to mitigate against participant saturation and disturbance [18]. This meant compromising the total number of questions asked, resulting in a constraint on the amount of data that could be collected on disaggregated gas and electricity use within the dwelling.

The questionnaire presented an opportunity to collect information on a range of parameters that would help to analyse the energy consumption. These included: type and quantification of energy use, typology, construction material, orientation, building age, heritage protection classification, level of insulation, window type, level of draught proofing, number of open flues, number of floors, heated rooms and bathrooms, heated floor area, heating plant and age, heating pattern and set temperature, loft conversion, number and age of occupants, appliances and income.

It was not possible to collect adequate data to calculate SAP for the respondent dwellings, because apart from the information required proving difficult for respondents to provide.
accurately, it would also enlarge the survey to the point that would dissuade respondents from replying at all.

Interestingly, providing energy used was a complicated question for some respondents to answer due to difficulty in reading utility bills and lack of access to information through having either changed supplier or being unable to access paperless billing. Consequently, initially a total of 54% of respondents provided complete energy use data. In a number of cases assistance was given to derive this information, increasing the response rate for energy use to 68%. This resulted in 102 data complete sets of energy use comprising a twelve month period.

4.0 Analysis

For each case the energy use was normalised for internal heated floor area based on the data provided by respondents. There is room for error here, as the subsequent analysis relies on respondent input that cannot be verified. This was checked by a follow up of 12 replies (11.7%) to verify the data provided. The error margins in the replies were found to be less than 5% for floor area and 6% in the energy used data.

To allow direct comparison between individual dwellings all energy used discussed in this paper is delivered energy to the dwelling and is reported in kWh/m$^2$/year and CO$_2$ emissions as kg CO$_2$ /m$^2$/year.

4.1 Region Average

For comparison, average energy use per dwelling was established using DECC Sub-national Local Authority gas and electricity consumption statistics from 2009 [19, 20]. An average floor area for urban dwellings of 80m$^2$ was established from EHCS 2007 Summary Statistics [21]; the results are shown in Table 1.
Table 1 Dwelling 2009 average annual energy use

<table>
<thead>
<tr>
<th></th>
<th>GB</th>
<th>England &amp; Wales</th>
<th>England South West</th>
<th>South West</th>
<th>BANES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh</td>
<td>15838</td>
<td>15300</td>
<td>15306</td>
<td>13650</td>
<td>15295</td>
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<tr>
<td>kWh/m²</td>
<td>198</td>
<td>191</td>
<td>191</td>
<td>171</td>
<td>191</td>
</tr>
<tr>
<td>kg CO₂/m²/yr</td>
<td>38</td>
<td>36</td>
<td>36</td>
<td>32</td>
<td>36</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh</td>
<td>4152</td>
<td>4149</td>
<td>4136</td>
<td>4448</td>
<td>4343</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>kg CO₂/m²/yr</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td><strong>Gas &amp;</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kWh/m²</td>
<td>250</td>
<td>243</td>
<td>243</td>
<td>227</td>
<td>245</td>
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<tr>
<td>kg CO₂/m²/yr</td>
<td>66</td>
<td>64</td>
<td>64</td>
<td>62</td>
<td>65</td>
</tr>
</tbody>
</table>

Delivered energy Carbon Factor: kg CO₂/kWh

- Gas: 0.19
- Electricity: 0.54

From the available regional energy use data the average for domestic gas and electricity use combined for BANES in 2009 was 245 kWh/m²/yr. This is slightly higher than the South West average but in line with the England average.

4.2 Results

This paper compares energy use data collected from 102 pre 1919 Buildings in Bath during 2010/2011. Table 2 shows the principle details of the buildings surveyed. The dwellings were all pre 1919, solid wall, pitched roof homes. The flats were in converted houses.
<table>
<thead>
<tr>
<th>Dwelling Parameter</th>
<th>Value</th>
<th>Count</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typology</td>
<td>Flat</td>
<td>7</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>Terrace</td>
<td>47</td>
<td>46%</td>
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<tr>
<td></td>
<td>End Terrace</td>
<td>9</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>Semi-Detached</td>
<td>28</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>Detached</td>
<td>11</td>
<td>11%</td>
</tr>
<tr>
<td>No of Storeys</td>
<td>1</td>
<td>11</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>56</td>
<td>55%</td>
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<tr>
<td></td>
<td>3</td>
<td>17</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2</td>
<td>2%</td>
</tr>
<tr>
<td>Occupancy</td>
<td>1</td>
<td>18</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16</td>
<td>16%</td>
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<td></td>
<td>4</td>
<td>10</td>
<td>10%</td>
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<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>&gt;6</td>
<td>2</td>
<td>2%</td>
</tr>
<tr>
<td>Demographics</td>
<td>Children&lt;16</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(total occupants =251)</td>
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</tr>
<tr>
<td></td>
<td>17-60</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61-80</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;80</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Classification</td>
<td>Grade I</td>
<td>4</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Grade II</td>
<td>54</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>Not Listed</td>
<td>44</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>Conservation Area</td>
<td>102</td>
<td>100%</td>
</tr>
</tbody>
</table>

4 properties used electricity for heating and hot water; gas, oil and coal use were grouped together to derive heating and hot water use. As Cooking accounts for less than 3 % of energy use in domestic dwellings [4] this was only considered in the regression analysis. Where electricity was used for heating (4 dwellings), 82% was attributed to heating and hot water in accordance with energy consumption by end use [4]. Excel and SPSS software
were used for statistical analysis. Excel provided mean energy use and SPSS was used to provide a multiple linear regression model. to assess the independent variables that most explain the variance in energy performance of the historic dwellings data set.

Distribution histograms for all energy, gas and electricity showed a normal distribution in all cases (necessary to apply the Yamane formula).

Figure 10 shows the results of gas use plotted against floor area showing a strong linear correlation ($R^2=0.766$).

![Figure 10](image)

**Figure 10  Delivered Gas Use v Floor area**

The same analysis for electricity is at Figure 11 which shows a much weaker correlation, $R^2=0.462$, suggesting there are other important factors to consider for electricity use.
Figure 11  **Delivered Electricity Use v Floor area**

Figure 12 shows a comparison of total delivered energy consumption by typology and fuel type.

The results demonstrate a wide range of total energy use, ranging from 37 kWh/m²/yr to 437 kWh/m²/yr, with a mean of 195 kWh/m²/yr.
4.2.1 Gas Energy Use

Given that dwelling form primarily governs heat loss through the fabric, the lower gas use for flats and some terrace dwellings is as expected. However, an unexpected finding is that gas consumption in a large number of mid terrace dwellings is close to and in excess of that for end terraced dwellings. Additionally, the difference in energy use observed between semi-detached and detached dwellings, was not as anticipated.

The majority of the sample population used gas for heating and hot water; this shows a factor of 7 difference within terrace and end of terrace typology. This is a noticeable difference, given that the properties surveyed have similar construction, the explanation lies with both the dwelling performance characteristics (insulation, windows, boiler efficiency and infiltration) and the occupant's energy use behaviour.

The three lowest energy users in the Flat typology were all low-income households, average occupancy 1.3. The two lowest properties only heated a minimal number of rooms to keep fuel bills low.

Closer examination of the lowest gas users in Terrace dwellings revealed that they had energy efficiency retrofits within the last five years. The adaptations included good levels of roof insulation, double or secondary glazing, draught proofed windows and doors, condensing boilers, some internal wall insulation and good boiler controls. Occupant attitude may also be a factor as all these occupants were very concerned about their energy use and CO₂ emissions.

The lowest End of Terrace had a gas use of 54 kWh/m²/yr. This property had good roof insulation, heating controls and new double glazed UPVC sash windows fitted two years
ago. The property was occupied by a single retired person. Thermostatic radiator valves were used to heat only the main rooms, which were altered when there were additional occupants.

A similar explanation occurred in the Semi Detached dwellings. The four lowest had 99, 102, 105 and 109 kWh/m²/yr gas use. All of these properties had installed energy efficiency adaptations in the last 5 years.

Explanations for high energy use are more difficult to explain. Looking at Semi Detached dwellings, in all cases occupancy level was in excess of three, all boilers were at least 10 years old, one was 20 years old. The lowest annual income per household in these high energy using properties was in excess of £50,000.

4.2.2 Electricity Energy Use

These data show a smaller variance between dwelling typologies, as expected, since electrical use is less affected by built form (very little heating in the UK is electricity driven). These variations may be a reflection of occupant behaviour with regard to electrical energy use. Figure 12 also shows that there are some high electricity users. The two highest users in the Flat typology used electricity for a proportion of heating. The highest Semi-Detached user was 135 kWh/m²/year, this also provided heating. The other 3 dwellings using electricity in excess of 60 kWh/m²/yr were attributable to either electric “Aga Stove” type cookers or under floor heating in conservatories. Ignoring these exceptional energy uses there was a Factor of 4 difference for electricity use between dwellings of the same typology.

4.3 Mean Energy Use

Table 3 shows a summary of mean energy use by typology.
Table 3  Average Energy Use

<table>
<thead>
<tr>
<th>Style</th>
<th>Sample Size (n)</th>
<th>Mean energy use kWh/m²/yr</th>
<th>Mean CO₂ emissions kg CO₂/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas</td>
<td>Electricity</td>
<td>All Energy</td>
</tr>
<tr>
<td>Flat</td>
<td>7</td>
<td>93</td>
<td>34</td>
</tr>
<tr>
<td>Mid Terrace</td>
<td>47</td>
<td>157</td>
<td>30</td>
</tr>
<tr>
<td>End Terrace</td>
<td>9</td>
<td>159</td>
<td>23</td>
</tr>
<tr>
<td>Semi Detached</td>
<td>28</td>
<td>192</td>
<td>34</td>
</tr>
<tr>
<td>Detached</td>
<td>11</td>
<td>199</td>
<td>28</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>167</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon Factor</th>
<th>kg CO₂/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.19</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.54</td>
</tr>
</tbody>
</table>

As expected, increased external surface or built form requires higher heating energy use, although there is a less than expected difference between semi-detached and detached dwellings. More interestingly, Table 3 shows that the average energy use in historic dwellings is significantly lower than the BANES average (245 kWh/m², Table 1). The gas use observed is 12%, and electricity use is 44% less than the BANES average. More importantly, it is considerably less than the indicated SAP value of 39 stated by the EHCS, which would result in an energy use of 321 kWh/m²/yr. Only 7 out of 102 dwellings exceeded this level of energy use.

Carbon emissions show an average of 48 kg CO₂/m²/yr for all dwellings, this is considerably lower than the figure of 65 kg CO₂/m²/yr for the BANES average (Table 1).

4.4 Statistical Analysis

The benchmark data is based on 102 respondents’ energy use, Figure 13 and 14 show gas and electricity use against property age.
A correlation between age and energy use was not expected and is not observed, as the dwellings have similar construction, though there may be some dwellings with energy efficiency adaptations. To determine those parameters that most explained the variance in
energy consumption a multiple linear regression model was developed using SPSS. Normalised gas and electricity use (by floor area) were considered the dependant variables, independent variables were drawn from the survey data obtained. The range of independent variables were analysed individually and step wise to determine a model that delivered the highest $R^2$ value.

The regression model for normalised gas use is at Table 4.

**Table 4  Normalised Gas Use Regression Model**

<table>
<thead>
<tr>
<th>Dependant Variable</th>
<th>Unstandardised Coefficients</th>
<th>Standardised Coefficients</th>
<th>STD Error=52.90289</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r=0.755$</td>
<td>Adjusted $R^2=0.526$</td>
<td>Gas kWh/m²/yr</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>61.056</td>
<td>24.859</td>
<td>2.456</td>
</tr>
<tr>
<td>No of bathrooms</td>
<td>16.689</td>
<td>6.667</td>
<td>-0.221</td>
</tr>
<tr>
<td>Draught proofing %</td>
<td>-0.435</td>
<td>.174</td>
<td>-0.221</td>
</tr>
<tr>
<td>Boiler efficiency</td>
<td>2.858</td>
<td>1.118</td>
<td>-0.298</td>
</tr>
<tr>
<td>Porch</td>
<td>-32.888</td>
<td>15.179</td>
<td>-0.194</td>
</tr>
<tr>
<td>No open flues</td>
<td>20.891</td>
<td>4.425</td>
<td>.431</td>
</tr>
<tr>
<td>Typology</td>
<td>20.945</td>
<td>6.110</td>
<td>.298</td>
</tr>
</tbody>
</table>

The resulting regression model for normalised gas use by area was significant in predicting 52.6% of the variance in area normalised annual gas energy use, $R^2$ (adjusted) = 0.526. This showed that the variable group consisting of number of bathrooms ($\beta = 0.232, p<0.05$), level of draught proofing ($\beta = -0.221, p<0.05$), boiler efficiency ($\beta = 0.224, p<0.05$), presence of a porch ($\beta = -0.194, p<0.05$) and typology ($\beta = 0.298, p<0.001$), were significant predictors. Other indicators that were found to be not significant were number of occupants, boiler age, boiler service intervals, thermostat, thermostatic radiator valves, heating programmer, Income, age, number of occupants, and level of double glazing.
The number of open flues was significant with a high standardised regression weight. Draught proofing and the presence of an entrance porch had the correct sign in that they showed a reduction in energy use when present.

The regression model for area normalised electricity use is at Table 5.

Table 5  Normalised Electricity regression Model

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>B</th>
<th>Std. error</th>
<th>(\beta)</th>
<th>t</th>
<th>P value (sig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>18.24</td>
<td>4.606</td>
<td>3.960</td>
<td>.000***</td>
<td></td>
</tr>
<tr>
<td>Number Occupants</td>
<td>3.078</td>
<td>1.772</td>
<td>.187</td>
<td>1.737</td>
<td>.090*</td>
</tr>
<tr>
<td>Electric range</td>
<td>37.42</td>
<td>5.675</td>
<td>.710</td>
<td>6.594</td>
<td>.000***</td>
</tr>
</tbody>
</table>

Significance * < 0.05 ** < 0.01 *** < 0.001

The overall model fit of \(R^2\) (adjusted) = 0.503 was significant in predicting 50.3% of the variance in area normalised annual electricity energy use. This showed that the variable group consisting of number of occupants (\(\beta = 0.187, p< 0.01\)) and the use of an electric range (\(\beta = 0.710, p<0.001\)), were significant predictors. Other indicators that were found to be not significant were Income, age, number of rooms and low energy lighting.

In both regression models for normalised gas and electricity use there is a lot of variability that is not explained from the data collected, this is considered in the discussion.

5. Benchmark
Following work produced by Mortimer et al. [22], from the normal distribution found within the data collected, it is possible to fit a performance benchmark by using the lower quartile as energy efficient or better than average performance and the upper quartile as not energy efficient or worse than average performance. A proposed benchmark for gas and electricity use in historic dwellings by typology is at Figure 15 and 16.

![Figure 15 Benchmark Gas Use](image)

**Figure 15 Benchmark Gas Use**

The benchmark for electricity use is at Figure 14.
This benchmark is based on surveyed current performance; therefore it does not reflect the large reduction in energy use and associated CO\textsubscript{2} emissions that are required to meet proposed emissions reductions targets.

6. Discussion and Conclusions

This paper analyses normalised energy use data from 102 pre 1919 dwellings in the City of Bath and establishes average gas and electrical energy use and CO\textsubscript{2} emissions. The benchmark of energy use in historic dwellings established from the survey data allows the results to be viewed in the wider context of reducing CO\textsubscript{2} emissions from the housing stock in general. The findings suggest that energy use in historic dwellings in Bath is lower than the national and regional average, this does not indicate that historic buildings are energy efficient, building science tells us otherwise as demonstrated by some high energy users.
The use of all dwelling typologies to produce an aggregated benchmark figure may be rudimentary, but in the absence of previous data it provides a base line that can, with future research, be refined for different dwelling typologies. In the absence of previous findings for UK energy use in historic buildings, comparison can only be made to average regional and national energy use and the energy use predicted by their SAP rating.

It is generally expected that the historic building stock has a higher energy use per unit area than more modern stock. This is based on the implicit assumption that such stock will have standard heating patterns and occupancy, inadequate levels of insulation, single glazing, excessive infiltration and inefficient heating systems, etc. The lower levels of energy use from energy efficiency retrofitted historic dwellings has been demonstrated. The results also show that the historic buildings sampled are not using as much energy on average for both gas and electricity, as current aggregated data suggests.

This may mean that the aggregated data or modelling systems upon which we rely is wrong. This could be down to sampling errors or errors in assumptions (e.g. heating patterns) made while calculating the SAP rating, or using data that is not up to date. On the other hand, if the aggregated data average energy use and model predictions are correct, and the buildings we expect to use more energy are not as we anticipate, then the energy must be being used by buildings we expect to perform better. We know this is not due to fabric parameters and may therefore be associated with behavioural aspects regarding energy use, suggesting further investigation is required.

These results provide evidence that historic dwellings in Bath also have average energy use lower than expected given their average SAP rating. Given that historic dwellings account for 30% of the BANES stock, the implication for Bath is that parts of the remaining stock must be using higher than average amounts of energy.
Benchmarking energy use highlights visibly, in a way aggregated data cannot, dwellings using high levels of energy when compared to similar properties. This information may prove valuable when deciding the priority for action to improve the performance of historic buildings at the local level. Within each typology a wide range of energy use is reported. This is important when assessing the benefit of retrofit adaptations as there is a danger if the assessed savings are based on national average energy use figures, as monetary or carbon savings from retrofit measures may be seriously overestimated. Our data provides a statistically representative baseline that can be used to assess district scale retrofits designed to reduce energy consumption and carbon emissions. Additionally, the benchmark allows a base line from which to monitor future performance and to gauge the direct benefits of retrofit adaptations in the surveyed dwellings.

A relationship was shown between energy use and the dwelling variables but this does not indicate causality. The independent variables recorded are not definitive and only partially explain possible reasons for variation in energy use. The linear regression models explored the effect of variables on delivered normalised energy use, accounting for 52.6% of the variance in gas energy use and 50.3% in electricity energy use. A better model fit (higher $R^2$) would be desirable, this analysis made use of secondary data collected in the survey designed to establish a benchmark of energy use and sought to offer an explanation for variations in energy use. The model considered actual energy use, and although not measured, occupant behaviour is an independent variable that is likely to be a key parameter in explaining a portion of the variance in energy use. This was demonstrated by the variation in energy use in similar dwellings, by as much as a factor of 7 for gas and a factor of 4 for electricity. There are also other factors to consider, examples are the contribution of the level of fabric energy efficiency adaptations and detailed information on occupancy in terms of hours of comfort/service demand, these provide a direction for future work.
A point to consider is that only normalising for floor area ignores the important factor of occupancy, both actual numbers of individuals as well as hours in occupation. To this could be added the issue of demographics. This is a difficult issue to satisfactorily measure through the use of a questionnaire. There are good reasons for this. Firstly, current analysis parameters do not follow this approach, which would mean there would be no comparable benchmark. Secondly, the definition of the term “occupancy” is difficult. It cannot simply be the number of people who live at an address, it would need to reflect their hours of occupation and level of service demand, this data is not available from this survey. Also, there are issues that arise from demographics; young children and older people have additional energy requirement, e.g. additional hot water use and higher internal heating set temperatures.

The high survey response rate of 25% may reflect the attitude of the respondents, in that they are all conscious of their energy use for reasons that may include comfort, cost and a desire to tackle climate change. Further work will be required to verify that this sample is not self-selecting with regard to low energy use. This could be straightforward to resolve given that energy use data for every dwelling are held by utility companies and floor areas can easily be determined through GIS mapping, there is therefore potential, should this data protected information be made available, to make a national benchmark of data use for every dwelling.

The benchmark produced facilitates assessment of the performance of historic dwellings in Bath, permitting categorising dwellings into high, average or low energy users. English Heritage acknowledges the lack of reliable data available to policy makers regarding the energy performance of historic buildings and considers a key problem to be that most assessments are made using models that include assumptions without supporting evidence field studies. The next step in this research will be to model the SAP predicted energy performance of the dwellings surveyed and compare this to actual energy use.
Acknowledgements

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The co-author’s names appear alphabetically.

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Accessed 5/2/2012


Accessed 12/9/2011


Annex D Accepted Papers

Paper 2

PV in Historic Dwellings: the potential to reduce domestic CO₂ emissions

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Abstract:

In response to a new low carbon paradigm, government financial incentives and societal pressures, innovative solutions to reduce energy use and CO₂ emissions are gaining a foothold on the urban built heritage. The recent Feed in Tariff (FiT) has seen a sharp rise in the number of roof mounted Photo Voltaic systems in both urban and rural landscapes.

Historic heritage is as much the recipient of this new technology as other portions of our built stock. But in the case of traditional and historic buildings, the drive to use less energy and by proxy emit less CO₂, in buildings designed when fuel consumption or emissions reduction was not a priority, challenges long held principles of conservation.

In particular it raises the question of whether the price of altering the built historic environment is worth the contribution such measures could make to meet the overarching and serious challenge of climate change.

This paper considers the potential for roof mounted Photo Voltaic (PV) installations to reduce CO₂ emissions in historic dwellings. The research examines 5 case studies in and around Bath in the South West of the UK. The generation pattern of the PV systems is compared to electricity demand in the dwelling to assess the potential for maximising the use of PV electricity and minimising domestic CO₂ emissions.

Results indicate that in ordinary energy use patterns, without technical intervention, an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing CO₂ emissions by an average of 19%. Results also show that where energy use patterns are arranged to synchronise with PV electricity generation, reductions of 23% can be made in CO₂ emissions arising from delivered electricity use.

Keywords: Photovoltaic systems, historic dwellings, carbon emissions, occupant behaviour

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Tel: +44 0773 6678586
1.0 Introduction

Climate change is a key challenge of the 21st Century. Meeting this challenge requires reductions in Greenhouse Gas (GHG) emissions, particularly CO$_2$, from all sectors of society. The UK’s Climate Change Act mandates a reduction in GHG emissions of 80% by 2050. In addition, as part of its European commitments, the UK is bound to source 15% of its energy from renewable sources by 2020.

Buildings in the UK contribute almost 40% of all emissions [1]; this is higher than the overall contribution of buildings to global emissions at 34.2% (2000 data)\(^{30}\). Within the UK, domestic dwellings accounted for 26% of CO$_2$ emissions in 2010 [2] as a result of operational energy use. As between 70% - 80% of UK dwellings in 2050 have already been built [3], it is clearly necessary to improve the energy efficiency of the existing built stock if carbon reduction targets are to be met.

Figure 1 shows the distribution of dwelling stock by age in England for 2008 [4]. It is evident that a significant proportion of these (4.8 million or 21%) were built before 1919. For the purposes of this study, all pre-1919 dwellings are defined as ‘historic’ dwellings [5].

These historic buildings have significant cultural and heritage value and the overarching aim of reducing CO$_2$ emissions demands solutions that are specific, suitable and replicable at district scale to deliver enduring energy efficiency savings and emissions reduction while maintaining their heritage value.

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Further, taken together with dwellings built between 1919-1945 (which also have a heritage value), these buildings account for 37% of all dwellings. Whilst built form and age has little effect on electricity use (most heating is provided by gas/oil), the significance of the higher proportion of older dwellings is apparent if their contribution to our built heritage limits the take up of roof mounted PV on grounds of visual aesthetics. This is of importance as the options to reduce CO₂ emissions arising from electricity use in dwellings are limited.

The challenge of reducing CO₂ emissions in existing dwellings is demonstrated by Jenkins et al. [6] who modelled an extensive list of retrofit adaptations that could only achieve 52% reduction in CO₂ emissions, but with the inclusion of PV this increased to 75%. This highlights the difficulties in achieving sizeable CO₂ emissions reductions in existing buildings and the potential contribution the adoption of PV systems can make.

In historic buildings achieving such savings is likely to involve fabric and aesthetic alterations. This research aims to evaluate the CO₂ emissions reduction through the adoption of PV arrays in historic buildings under current planning regulations. There is no methodology to balance reduction in emissions against loss of heritage, although carbon emission reductions come at the price of loss of visual aesthetics, perceived or actual. The intention of this paper is to evaluate the benefit of carbon savings thereby quantifying the retrofit adaptation benefit of PV systems in historic buildings.

This approach challenges the long held conservation principles [7] of minimal intervention to use less energy, reduce emissions and maintain comfort in buildings by advocating the adoption of effective and durable adaptations.

1.1 Domestic Energy Use

Figure 2 shows that the majority of energy use in the home is for heating and hot water (63%). The options to reduce this demand in historic buildings are varied and on the whole well understood but are not fully implemented for many reasons, including conservation constraints, cost, planning restrictions and the possible risk of loss or decay of building fabric. Current orthodoxy focuses on reducing this demand through improvements to fabric and system efficiency before turning to low and zero carbon technologies (LZC). We argue here, however, that given the contribution of electricity use to overall carbon emissions, LZCs have a role to play, especially for historic building where options for fabric improvements may be somewhat limited.

Although electricity use in dwellings is typically 15% of total energy use [8] it contributes to 37% of the total domestic carbon emissions (UK electricity currently has 2.4 times the carbon factor of gas [9]).
This is significant, because unlike heating and hot water the options to reduce CO₂ emissions arising from electricity use are both limited and distinctly different. One possibility is to reduce the carbon factor of delivered electricity; this is beyond the control of householders and is more a function of government energy policy requiring long-term structural changes to supply. Other options are to demand reduction or the adoption of LZC technology.

1.2 Domestic Electrical Demand Reduction

The breakdown for domestic electrical use emissions is at Figure 3, this shows there are several areas to focus attention on within the home to reduce CO₂ emissions.
One is to reduce lighting demand through increased use of low energy CFL and LED light fittings. Recent regulations [11, 12] have significantly improved uptake but these remain expensive and occupants are not always satisfied by the type of light produced. Similarly, energy efficient choices are now widely available when replacing appliances. However, the most efficient A++ rating appliances currently have limited availability and are generally an expensive alternative to an A rated appliance. Furthermore, household awareness is an issue since only 16% were aware of the energy rating of their new appliance when making a replacement purchase [13], thus illustrating the problem of uptake even if more efficient appliances are on the market. Finally, another option is real-time occupant energy use feedback. The potential impact of monthly feedback on energy use patterns is usually estimated to be 5–10% [14], but it would appear that initial savings cannot be sustained in the medium to long-term [15]; this is an area of on-going research.

Within the home there are also elements of occupant behaviour that can deliver energy savings. Examples are switching off lights/appliances when not in use, avoiding the use of...
standby mode for audio and television units, as well as avoiding leaving various charging units on while not charging.

1.3 Future climate change and cooling loads

There is currently no Government data for UK domestic cooling load use. Figure 3 does not show the demand for summer domestic cooling as this is currently very small compared with overall energy consumption. This will change in coming decades. Peacock et al. [16] state that if the behavioural response of UK householders to a warming climate is akin to that of relationships found in the US, the expected domestic cooling season created as a consequence of climate change will see 18% of homes in the South of England having installed domestic air conditioning systems by 2030.

This is likely to adversely affect carbon emissions as cooling will require electricity that currently has a carbon factor 2.4 times greater than gas. One study predicts that an increase in energy consumption due to the growth in active cooling systems in London by 2030 (550,000 homes with air conditioning equipment [18]) may lead to a doubling of CO₂ emissions by 2030 [17]. This does not take into account savings as a result of a reduced heating load which may be as high as 40% for terraced dwellings [19]. Regardless of the overall net demand impact, there is consensus that changing climate will see an increase in domestic cooling demand. In this respect PV output is aligned to cooling demand and can provide low carbon electricity to service this requirement.

1.4 PV Generation

Another approach to reducing domestic CO₂ emissions is to adopt Photo Voltaic (PV) systems to provide low carbon electricity. This is in line with the current government renewable energy strategy that seeks to increase decentralised micro renewable generation. This approach is supported by Natarajan’s and Levermore’s [20] view that on-site renewable energy generation will be key to reducing or even balancing emissions through energy export.

This would suggest the onsite generation of electricity is essential to meet future CO₂ emissions reduction targets. For some time there has been growing acceptance that renewable energy technologies can achieve a significant reduction in CO₂ emissions beyond that from the standard energy-efficiency methods [21]. The recent introduction of Feed in Tariffs31 for micro electricity generation in the UK and the prospect of the same for renewable heat, is likely to increase take up of domestic micro renewable energy generation systems (this has already been observed in the PV market at the time of writing). These tariffs are likely to be at least as beneficial (if not more, as suggested in this paper) in historic buildings as the rest of the housing stock, though there is currently little evidence to measure this effect.

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31 A payment made to households or businesses for each kWh of electricity generated through the use of low and zero carbon technologies, including PV arrays. A further payment is available for each kWh of electricity exported to the National Grid.
A key issue is that current orthodoxy considers PV as a last option once all other energy efficiency measures have been implemented. Whilst this approach may be prudent with regard to provision of heating and hot water, where improved energy efficiency generally leads to reduced plant size and therefore lower capital costs. The same cannot be said of PV, which as it affects only emissions from electricity consumption can in fact be sequenced quite separately from adaptations to reduce heat loss from the fabric.

Since the introduction of the FiT in April 2010, as of September 2012 the installed capacity of PV has increased from 7MW to 1.45GW [22], see Figure 4.

![Figure 4 PV Installations in the UK](image)

Growth in this technology is expected to continue, DECC project delivery of 2.7GWp of PV by 2020 [23]. This paper does not consider the economics of PV. This is primarily because the level of subsidy available to PV is under continual review in the UK and other studies have considered this in detail [24, 25, and 26]. In addition, regardless of the precise nature of any future financial incentive, the 372,391 installations between April 2010 and September 2012 [22], demonstrate that PV installations can be made financially attractive.

From Figure 3 it can be seen that PV has the potential to provide low carbon electricity for wide areas of demand. Given that PV output only occurs during the day, the match between supply and demand is likely to be weak for occupants working away from home, for lighting and cooking and zero for night demand. Whereas there is strong potential to match supply and demand for day time activities including Cold, Wet and elements of Consumer Electronics and base load electricity use. This demand match is further enhanced where the home is occupied during the day (e.g. retired occupants, home workers, unemployed and students).
2.0 Methodology

This paper sets out to evaluate the carbon reduction potential of PV technology in the scenario of historic buildings. The methodology presented will evaluate the benefit of PV generated electricity by establishing and comparing the pattern of PV generation and domestic electricity demand.

The main considered elements were:

- Establish typical dwelling daily energy usage pattern
- Assess PV installation output
- Correlate PV output with daily electricity demand pattern
- Determine how much of PV electricity generated can be used
- Ascertain CO$_2$ emissions reduction in the dwelling

Five historic dwellings with a PV system installed were monitored. Daily electricity use was measured in two dwellings at 30 second intervals using an Elcomponent energy data logger [27] over a 6 month period from April–September 2011. Annual PV generation was recorded in 5 dwellings, 4 of these provided monthly generation readings. One PV system output was recorded at 1 minute intervals using a Sunny Webbox [27].

Establishing a pattern of daily electrical consumption was challenging. Apart from aggregated and averaged national statistics, demand profiles are available [29]. But there are questions as to how representative they would be of the case studies. It was therefore decided to measure actual electricity demand to establish a representative profile.

To arrive at the carbon emission reduction a grid carbon factor of 0.5246 kg CO$_2$/kWh was used [9]. A carbon factor of 0.095 kg CO$_2$/kWh was used for PV generated electricity [30], from the data presented this is mid range for domestic PV mono-crystalline in the UK (0.075-0.116 kg CO$_2$/kWh). There is little research data currently available on carbon factors for domestic generated PV electricity in the UK. Even at upper limits from recent research domestic PV has a carbon factor considerably less than delivered grid electricity.

3.0 Results

3.1 Case Studies

Five case studies in and around Bath in the South West of the UK were examined, see Figure 5 for installations. They were a mix of Monocrystalline and Polycrystalline silicon photovoltaic panels with a rated efficiency of between 13.5- 14.1%.
Case Study 1  1.85 KWp

Case Study 2  2.6 KWp

Case Study 3  2.0 KWp

Case Study 4  3.3 KWp
Rear, on Outbuildings

Case Study 5  1.85 KWp
Central Valley Only

PV System
Table 1 shows data from the five case study buildings located in and around Bath, UK.

### Table 1: Case study data

<table>
<thead>
<tr>
<th>Case Study</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age(yrs)</td>
<td>215</td>
<td>261</td>
<td>205</td>
<td>218</td>
<td>260</td>
</tr>
<tr>
<td>Typology</td>
<td>Semi-Detached</td>
<td>Detached</td>
<td>Terrace</td>
<td>Terrace</td>
<td>Terrace</td>
</tr>
<tr>
<td>Floor Area m²</td>
<td>168</td>
<td>177</td>
<td>160</td>
<td>175</td>
<td>250</td>
</tr>
<tr>
<td>Annual kWh used</td>
<td>3462</td>
<td>4323</td>
<td>4526</td>
<td>3807</td>
<td>4388</td>
</tr>
<tr>
<td>Annual CO₂ kg</td>
<td>1869</td>
<td>2334</td>
<td>2444</td>
<td>2056</td>
<td>2370</td>
</tr>
<tr>
<td>Electricity kWh/m²</td>
<td>20.6</td>
<td>24.4</td>
<td>28.3</td>
<td>21.8</td>
<td>17.6</td>
</tr>
<tr>
<td>Installed kWp</td>
<td>1.85</td>
<td>2.6</td>
<td>2.0</td>
<td>3.3</td>
<td>1.85</td>
</tr>
<tr>
<td>Rated efficiency</td>
<td>13.9 %</td>
<td>13.5 %</td>
<td>13.7 %</td>
<td>14.1 %</td>
<td>13.7 %</td>
</tr>
<tr>
<td>Generated kWh/yr</td>
<td>1640</td>
<td>1977</td>
<td>1715</td>
<td>3019</td>
<td>1173</td>
</tr>
<tr>
<td>kWh/kWp</td>
<td>886</td>
<td>760</td>
<td>858</td>
<td>915</td>
<td>634</td>
</tr>
<tr>
<td>Used PV kWh</td>
<td>736</td>
<td>996</td>
<td>1150</td>
<td>705</td>
<td>725</td>
</tr>
<tr>
<td>% PV gen kWh used</td>
<td>45%</td>
<td>50%</td>
<td>67%</td>
<td>23%</td>
<td>62%</td>
</tr>
<tr>
<td>Exported kWh</td>
<td>904</td>
<td>981</td>
<td>565</td>
<td>2314</td>
<td>448</td>
</tr>
<tr>
<td>Offset CO₂ kg/yr from used PV electricity</td>
<td>361</td>
<td>488</td>
<td>515</td>
<td>345</td>
<td>355</td>
</tr>
<tr>
<td>% total CO₂ saved</td>
<td>19%</td>
<td>21%</td>
<td>21%</td>
<td>17%</td>
<td>15%</td>
</tr>
</tbody>
</table>
An important indicator of a PV installations performance is the kWh generated per kW peak installed (kWp); this gives an indication of the real performance taking into account location, installation, shading and insolation. Figure 6 shows that in the case studies this varies from 634 – 915 kWh/kWp. Interestingly, all but the lowest output were in line with installers’ estimates. The lowest system output was attributable to shading from a large tree and a high ridge line in close proximity.

![Figure 6 kWh/kWp output](image)

The difference is explained by variations in orientation, shading (from trees, buildings and chimneys) and system losses. The average performance was 811 kWh/kWp, this provides a useful benchmark when considering the retrofit benefits of PV systems (for this location), which would be independent of dwelling age.

Table 1 shows that there is considerable variation in the amount of PV generated electricity used within each dwelling, ranging from 23-67%. This factor is important when evaluating the net reduction in CO₂ emissions for each dwelling, as it has a corresponding effect on CO₂ emissions reduction by reducing grid-imported electricity. Ignoring the lowest figure (case study 4), which was due to the property having a large 3.3 kWp system (on an out building), the average was 56% of PV generated electricity used within the home, which is slightly higher than the 50% assumed in FIT calculations. This raises the question of how much further use could be made of PV generated electricity to reduce a dwelling’s emissions rather than simply exporting excess to the grid. This will be explored further in the discussion section.

3.2 Daily electricity demand

Richardson et al. [29] recognise that the pattern of electricity use in an individual domestic dwelling is highly dependent upon the activities of the occupants and their associated use of
electrical appliances. For this reason energy use patterns were measured for Case Study 1 and 5.

Figure 7 shows a typical daily pattern of electricity use from data collected from Case Study 1, this is for occupancy of 2 adults working away from home. In this graph the electric immersion heater was switched on, although normally the gas boiler was used to provide hot water, this was initiated in order to explore matching electricity demand to PV output.

![Electricity energy demand pattern, Case Study 1](image)

In particular, it shows a peak base load at approximately 350W, this comprises a fridge/freezer, telephone base set, smoke alarms, clock radios, microwave display, toothbrush charger, boiler controls and a timer switch and satellite box standby. This compares favourably to the Domestic Energy Demand Model produced by Richardson et al. [24], although this model produces a slightly lower peak base load of 200 watts.
3.3 PV System output

PV output from case study 1 was measured from January 2012 to December 2012; the PV system output is at Figure 8.

![Figure 8 Case study 1, PV output 2012]

In order to analyse the match between domestic electricity demand and PV output a histogram of daily PV generated electricity was generated (Figure 9). This shows an average generation of 4.49 kWh/day for the year 2012.
As the contribution PV generation makes to the dwelling CO₂ emissions is dependent on the amount of insolation, the data collected was used to establish three typical PV days using the mean and upper and lower quartiles:

- Lower quartile PV day of 1.5 kWh/day
- Mean output PV day of 4.5 kWh/day
- Upper quartile PV day of 7.5 kWh/day

These PV outputs were then compared to daily patterns of electricity demand (no hot water). This showed that for weekday occupancy, regardless of the PV output above the baseload of 2.3 kWh, there is little variation in the amount of PV generated electricity used within the dwelling (Figure 10). Note that electricity is exported when the PV output line goes above the energy demand line. This could be viewed as a missed opportunity to reduce dwelling carbon emissions.
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PV Output = 7.5kWh
2.5 kWh used

PV Output = 1.5 kWh
1.3 kWh used

PV Output = 4.5 kWh
2.1 kWh used
Figure 10  Domestic Electrical Demand and PV Generation

The use of a washing machine increases the use of PV generated electricity as its power rating is closer to the PV systems output on average and high output days, see Figure 11.
4.5 kWh Day

PV Output = 4.5 kWh
3.5 kWh used

Washing Machine Load

7.5 kWh Day

PV Output = 7 kWh
4.6 kWh used

Washing Machine Load

Figure 11  PV output v washing machine electricity demand
3.4 CO$_2$ Emissions

Annual CO$_2$ emissions from delivered electricity use were established from utility bills, normalised to internal floor area (Figure 12).

![Graph showing CO$_2$ emissions from delivered electricity use](image)

**Figure 12** CO$_2$ emissions from delivered electricity use (no PV)

The effect of savings from the generated PV electricity on annual electricity use is shown at Figure 13, this shows a reduction in CO$_2$ emissions of between 15 – 23% (average 18%).
Figure 13  CO₂ emissions from delivered electricity use with and without PV. Percentages show reductions obtained with PV compared to the no PV case.

The potential to reduce CO₂ emissions is dependent on the portion of PV generated electricity used. This also has an impact on repayment costs as a displaced unit of imported electricity is currently worth 4 times more than an exported unit. Figure 14 shows the amount of PV electricity used which varied form 23-67%.

Figure 14 -------------------------------------------------
The variation in PV generated electricity used is attributable to occupant attitude and behaviour, patterns of occupancy and the size of the PV system. A post survey interview revealed that the occupants in case studies 3 and 5 were particularly keen to reduce their CO$_2$ emissions and made a conscious effort to use appliances on good PV (sunny) days. Actions included deliberately timing the use of appliances, particularly washing machines, dishwashers and vacuum cleaners, with high PV output, to avoid importing electricity at a higher cost.

An interesting comment was made by Case study 5 who said that they would have increased the amount of PV used if there was an automatic means to activate devices to suit PV output, “rather than waiting for the sun to shine before switching on the washing machine”.

Although case study 5 used 61% of generated PV electricity it reduced its CO$_2$ emissions by the lowest amount, 15%. This is due to: (i) reduced output (kWh/KWp) as planning permission was only granted for a PV installation in the central valley of the roof and (ii) limitations in the size of the PV system due to its Grade II listed status, see Figure 15.
Figure 15 Cross Section, Case Study 5

So although there was potential for a 3.7 kW system by using both south facing roof elevations, only a 1.85kW system received planning permission. If a 3.7 kW system had been installed, increased PV generated electricity would result in increased CO₂ emissions reduction, moving from 15% to at least 21%.

This can be supported by Case Study 3 which had a similar roof construction but although in a nearby conservation area was not a Listed Building; consequently it installed a 2.0 kW PV system utilising both south facing roof sections, achieving a 21% reduction in electricity CO₂ emissions.

4.0 Discussion

Is PV just a new aesthetic? Historic buildings have already changed much over time; examples are the use of gas for lighting followed by electrification, the introduction of bathrooms and central heating, conversion to smaller units and the use of previous below ground storage and roof areas for accommodation. This suggests further change to reduce emissions may, with time, become just as accepted.

Historically the driving force for altering our historic buildings was more one of convenience and comfort. The difference today is that we now need to reduce the CO₂ emitted from our homes; this is a new approach and is to some extent out of line with cultural norms with regard to our built heritage. Today’s new low carbon paradigm means that we have to retrofit our existing housing stock, including historic buildings.

The current orthodoxy for improving energy efficiency in buildings centres on reducing the heating load, and only when this is achieved does it turn to dealing with the approximately 35% contribution electricity use makes to CO₂ emissions. Historic buildings may require a different approach. The introduction of PV in this building typology, though currently recommended as one of the last retrofit measures, can lead to reductions in CO₂ emissions through using considerably less delivered electricity. When primary energy production losses are considered the benefits increase.

As a result it may be that we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to environmental imperatives. Perhaps we should consider that “we may have to be prepared for visually intrusive measures on much loved buildings” [30]. This view may gather momentum because the options to improve energy efficiency in historic buildings are limited, even more so when dealing with electricity derived CO₂ emissions.

As historic buildings have withstood many changes in the past, is the introduction of renewable energy technologies really such a problem? They are after all, fully demountable and leave the fabric intact. One argument against them is that these interventions are simply a question of glamour because the really effective measures (insulation, improved energy efficiency and draught proofing) are unattractive, and from observation, often ignored. Whilst this may well be the case, none of these measures would have a noticeable effect on emissions arising from electricity use.

It has been shown that in ordinary energy use patterns, without technical intervention an average of 56% of electricity generated from a roof mounted PV system is used within the dwelling, reducing CO₂ emissions by an average of 18%. In the overarching aim to tackle climate change this is a sizeable reduction. Furthermore, this reduction can be improved
upon with demand management; the 67% use of generated PV electricity reported in this paper was achieved without any installed demand management measures, suggesting this figure could be increased. This shows that where energy use patterns are arranged to synchronise with PV electricity generation and where the installation of PV systems are permitted to make use of available roof space, regardless of its heritage value, reductions of at least 23% can be made in CO₂ emissions arising from electricity use.

These findings may be just as applicable to more modern dwellings, but unlike historic buildings they can implement a fabric first approach to reduce carbon emissions. Further work is required to assess the potential contribution Historic buildings can make, are the roofs of such buildings more suitable, through either total available surface area or orientation. Is there a correlation between the occupants of historic buildings and their pattern of electricity use that aligns with PV output.

This research also raises the following questions and issues about the introduction of the PV regardless of building typology:

1. Can occupants be better informed at the time of PV installation (or when purchasing a dwelling with PV installed) to make optimal use of PV generated electricity?
2. How can the demand of domestic appliances be automatically controlled to make use of PV generated electricity; this is effectively the application of “load matching” or “demand shifting” within the home.
3. Is it feasible to use/store surplus PV electricity production to provide hot water or water pre heating? This requires further research as there are a number of factors to consider such as the efficiency of the boiler providing hot water, the immersion heater element power rating, the time of day the water is heated/pre heated, what other loads are present, controls for initiating immersion element to match PV output and what level of PV output makes this viable.
4. Does it matter if PV generated electricity is exported when not required and imported via the grid at a later point? It could be argued that this simply offsets electricity imported at times when PV generation does not meet demand. But when counting carbon and establishing annual domestic emissions, imported electricity will have a carbon factor some 10 times greater than PV generated electricity. Further data is required on the exact carbon factor of domestic PV generated electricity in order to predict accurately full life cycle carbon reduction benefits.

5.0 Conclusions

The study looked at only 5 case studies over a 12 month period. Further continued observations are required to explore the potential of domestic PV generation to reduce domestic CO₂ emissions. The life time of PV panels is at least 20 years; even with degradation at 1% year, their future performance can be reasonably predicted. What is less clear is the likely future carbon factor of grid electricity and the bearing this will have on domestic PV to offset emissions.

The demanding target of 80% reduction in CO₂ emission levels by 2050 suggests that this cannot be achieved without involving historic dwellings. This is a challenge, not only because of the high number of dwellings involved, but also because of aesthetic/fabric constraints. Consequently, and in response to the overarching need to tackle climate change, all low carbon options should be exploited, particularly as the adoption of PV in historic buildings shows the potential to significantly reduce dwelling electricity CO₂ emissions. The challenge now is how to bring together the conservation of heritage and conservation of energy to reduce CO₂ emissions.
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Paper 3

The use of Passive House Planning Package to reduce energy use and CO₂ emissions in historic dwellings

Francis Moran, Tom Blight, Sukumar Natarajan, Andy Shea

Abstract

Since historic buildings constitute 25% of the European built environment they have a role to play in delivering CO₂ emissions reduction targets along with the rest of the domestic stock. However, historic buildings have significant cultural value and were built with technologies and materials that promote fabric breathability. This demands solutions that will deliver enduring and radical energy efficiency savings and emissions reduction, which while maintaining their heritage value, are also capable of district wide replication.

Before embarking on wide scale retrofit adaptations, affordable and accurate procedures to assess the potential for such measures to reduce CO₂ emissions are of primary importance. Some measures will have an impact on both fabric and aesthetics. It is therefore necessary to ensure that the reductions in CO₂ emissions from a set of proposed alterations are significantly higher than any actual or perceived reduction in loss of built heritage.

This paper demonstrates the use of the Passive House Planning Package (PHPP) modelling tool to assess the potential for retrofit adaptation measures in three terrace dwellings in Bath, England. It compares modelled against delivered energy use and then models energy and emission reduction following the introduction of a suite of retrofit adaptations.

Results indicate that PHPP can assess total electrical energy consumption but requires the use of a reduction factor to reflect accurately intermittent occupancy/heating patterns. The modelled results suggest retrofit adaptations in historic buildings could deliver energy savings and CO₂ emissions savings between 55-83% but only when the thermal fabric is significantly improved and the use of PV is included.

PHPP provided assessments of the benefits of retrofit adaptations in historic buildings that can facilitate decision making on retrofit methodology in historic buildings that affect fabric and/or aesthetics.

Key words: energy use, historic buildings, CO₂ emissions, PHPP, EnerPHit, PV.

Impact:
Combines empirical field data with modelled results.
Assesses potential for retrofit adaptations to provide CO₂ emissions reduction.
Demonstrates that PV can make a significant contribution towards reducing domestic CO₂ emissions.
Introduction

In Europe, historic buildings [1] account for over 25% of all buildings [2]. The scale of the problem is large, every building in Europe will have to cut its carbon emissions by 20% by 2020 [3]. The UK government has set more challenging targets with a reduction in emissions of 34% by 2020 and 80% by 2050 [4]. This is despite the UK having the oldest building stock in Europe, with almost 40% of the existing residential buildings built before 1946.

This means that for every one of 25 million existing dwellings in the UK that fails to reduce its emissions by 80% another one must increase its emissions reductions by a commensurate amount. Natarajan and Levermore [5] have previously shown how difficult achieving even a 60% stock-wide reduction would be. Historic dwellings, at 21% of existing stock, cannot side step this issue and therefore must play an equal part in the effort to reduce emissions. Since most retrofit measures affect fabric, this brings the conservation of energy (and hence the reduction of emissions) into conflict with the conservation of built heritage.

Research indicates that a suite of adaptations can have effects varying from 40-80% [6, 7, 8, 9, 10 and 11]. It is also evident that occupant behaviour will have a significant effect on energy use [12].

What is less clear is a suitable methodology to produce and implement radical CO$_2$ emissions reduction solutions that are not only effective, but prove to be both durable and non-deleterious to the buildings fabric. There is a need for a model/tool to provide in a straightforward manner, at reasonable cost, accurate and reliable assessments of the benefits of retrofit adaptations in historic buildings. If this is accepted and trusted by stakeholders it will facilitate decision making based on empirical data.

The English House Condition Survey (EHS) [13] suggests a close correlation between the age of a building and its energy performance. Homes built before 1919 have average CO$_2$ emissions of 86 kg CO$_2$/m$^2$. However, this can be misleading as previous work by Moran [1] has shown that the EHS can overestimate energy use in historic buildings by 12% for gas and 44% for electricity. In either case, from an overall stock point of view, it is clear that historic buildings will have a strong role to play in attaining emissions targets.

The current heritage landscape has developed over time, so too has the approach regarding the preservation of our built heritage. Loulanski [14] set out the evolution of the protection of historical assets in the UK, showing a move from preservation to a broader concept of Conservation and Heritage. More recently, a new challenge to this orthodoxy has emerged: how do we align the conservation of energy with the conservation of heritage to the benefit of both historic buildings and occupants? This is of importance as at least 75% dwellings that will be standing in 2050 have already been built and historic dwellings will account for at least 1/3 of these [1]. This suggests that solutions to reduce CO$_2$ emissions in the UK domestic sector (as well as a large portion of the EU stock) will have to involve historic buildings.

In this paper, we consider this new era of low carbon and energy efficient buildings as the alignment of the conservation of heritage with the conservation of energy. Failure to deliver low carbon historic buildings will fail both occupants and the buildings and may see historic buildings becoming redundant; the price of which may be environmental obsolescence or demolition [15].

Cassar [15] also suggests aligning the principles and practice of conservation in the 21$^{st}$ century more fully with sustainability principles. This will involve weighing up the perceived benefits of energy savings and CO$_2$ emissions reduction against loss of fabric. Loss of fabric includes actual alteration to/or removal of amounts of the original building. They vary in scale and nature and can include cutting service chases and taking down ceilings to reach inaccessible roof voids. It also includes loss of visual fabric. This can occur where a part of the original building is covered from permanent view.
but remains intact, an example is internal wall insulation in front of a plastered wall with stucco features.

This paper will concentrate on historic buildings in the UK using case studies from the City of Bath in the SW of England. It is anticipated that the findings will also be applicable to the historic European stock.

Methodology

The aim is to evaluate the potential contribution retrofit adaptations can make to reducing energy use and CO$_2$ emissions in three case study historic dwellings in Bath, UK with the following identified objectives:

- Collect delivered energy use data for minimum of 12 months
- Evaluate available modelling options and select for a balance between ease of use, cost and detail of outputs.
- Model predicted gas and electricity energy use using localised weather data
- Estimate the energy and carbon savings for retrofit measures
- Evaluate the potential contribution of LZC (Low and Zero Carbon) technology (solar hot water and 2.0 kWp Photovoltaic array in this study)

Model Selection

Three different modelling methods were evaluated for this work: Integrated Environmental Solutions (IES) software, Standard Assessment Procedure (SAP) (2009) and Passive House Planning package (PHPP) see Table 1. SAP was adopted as it is the NCM (National calculation Method) for the UK. IES is widely used as a dynamic modelling tool. PHPP was considered as it has recently begun to be adopted more widely.
### Table 1 Model Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>IES VE</th>
<th>SAP 2009</th>
<th>PHPP Version 7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic calculation method</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Steady State calculation method</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Dynamic simulation</td>
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<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Monthly heat load</td>
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<td>Y</td>
<td>Y</td>
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<td>Number heating zones</td>
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<td>1</td>
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<td>NCM compliant</td>
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<td>Y</td>
<td>N</td>
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<tr>
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<td>Y</td>
<td>N</td>
<td>Y</td>
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<td>££</td>
<td>£</td>
</tr>
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<td>Window orientation</td>
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<td>Y</td>
<td>Y</td>
</tr>
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<td>Ease of Use</td>
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<td>Easy</td>
<td>Medium</td>
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<td>Transparency</td>
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<td>Medium</td>
<td>High</td>
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<tr>
<td>Suitable for historic buildings</td>
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<td>N&lt;sup&gt;2&lt;/sup&gt;</td>
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<tr>
<td>Appliances incidental heat gain</td>
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<tr>
<td>Evaluates solar hot water</td>
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<tr>
<td>Evaluates PV array to CO&lt;sub&gt;2&lt;/sub&gt; emissions reduction</td>
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<td>Y</td>
<td>Y&lt;sup&gt;3&lt;/sup&gt;</td>
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<td>N&lt;sup&gt;4&lt;/sup&gt;</td>
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<td>2.1 W/m²&lt;sup&gt;5&lt;/sup&gt;</td>
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<td>Energy Use Reporting</td>
<td>Primary and delivered</td>
<td>Primary and delivered</td>
<td>Primary</td>
</tr>
</tbody>
</table>

Notes: 1 revision in progress  
2 includes incidental heat gain only  
3 although not included in energy use and CO<sub>2</sub> emissions results  
4 uses data for Sheffield, UK  
5 can be input manually from IHG sheet to Annual Heat Demand Sheet

While dynamic simulation software such as IES is most likely to deliver more accurate results they are more expensive, time intensive, have complex data inputs, require a period of user training and are not specifically designed for small scale domestic use. For these reasons SAP has generally been used, and more recently the PHPP has begun to emerge as an option.

Of the remaining two packages, PHPP was selected because of its transparency regarding how results are determined, relative ease of use, inclusion of appliance energy consumption and its affordability. The perceived disadvantage of not having been readily applied to historic buildings, although a
retrofit standard exists, was viewed as an opportunity to explore its suitability for this sector of existing dwellings.

For completeness both SAP and IES models were chosen to make a comparison of the base case energy use. The SAP analysis was conducted as it has historically been the default option for considering energy use in dwellings. In addition the IES simulation was run alongside the PHPP analysis in order to determine the extent of energy use detail lost through adopting a steady state analysis only.

It should be noted that it is not the intention of this paper to compare the merits of these three energy modelling packages, but rather to assess the possible merits of using the PHPP for historic buildings undergoing retrofit adaptions.

Passive House Planning Package

PHPP is a spreadsheet design and compliance tool produced by the Passivhaus Institute to model the performance of a proposed Passivhaus building. It is considered an accurate tool in the Passivhaus community because it was systematically developed by comparing dynamic simulations to validated measurements in completed Passivhaus projects. Though not specifically designed to model energy use in historic buildings it is used for the retrofit of existing buildings (EnerPHit\(^{32}\)) and has targets for heating and non-heating energy use.

The Passivhaus Standard has a high degree of flexibility in that energy use targets can be met using a variety of design strategies, construction methods and technologies. Monthly average local weather data can be also inserted or imported; this study used the Severn Valley data set from the BRE\(^{33}\). It also allows occupancy to be prescribed, as well as starting conditions for the performance of the dwelling (including internal temperature, infiltration level, appliances and electrical goods).

Passivhaus methodology is primarily energy driven and focuses on minimal fabric and ventilation losses, maximum passive internal heat gains and solar gain in winter (requires attention to avoid summer overheating), the use of energy efficient MVHR (mechanical ventilation heat recovery) plant (requires a very low heat load) and incorporates LZC technologies to meet the remaining energy demand.

For this study the intention was not necessarily to meet the EnerPHit standard, but to assess the potential reductions arising from retrofit adaptation for the case study buildings. There are limitations to using the PHPP either as a result of the way the software operates or from the methodology proposed in this study, these can be outlined as:

- It is not a dynamic modelling package, so suffers from limitations of quasi steady state approaches.
- Thermal bridges present little opportunity for amendment in historic buildings; they are also difficult to measure, though this could be done through thermal imaging. In this study, default settings were accepted which may underestimate the effect of thermal bridges.
- What airtightness to start from and what to reduce to (this is discussed further in the section on infiltration).
- MVHR may be impractical in existing historic buildings though it may be possible to consider the point use of MVHR for bathrooms and kitchens (this requires further analysis).

\(^{32}\) PHI has developed the “EnerPHit – Quality-Approved Energy Retrofit with Passive Haus Components” Certificate for the refurbishment of old buildings. Max heat 25kWh/m\(^2\)a, max primary energy demand 120kWh/m\(^2\)a
\(^{33}\) Available to download via http://www.passivhaus.org.uk/page.jsp?id=38 (accessed 12/12/2012)
The risk of possible summer overheating if internal wall insulation dislocates the internal air from large areas of thermal mass. PH only uses whole house average temperatures rather than individual room temperatures to assess this risk.

The potential for improving the performance of windows was limited to maintain heritage aesthetical appearance.

Electricity generated by Photovoltaic (PV) systems, although calculated, is not counted against the overall primary energy target although the use of SHW is counted towards the gas primary energy use.

There is no clear methodology for dealing with intermittent heating. Options are to reduce the internal temperature from 20°C (there is no data on how to establish the lower temperature; one possibility would be to use the BREDEM/SAP algorithms to calculated the decay and hence the average internal temperature and use this figure as the internal set temperature). Another more straightforward approach is to apply a reduction factor (annual heat demand page).

The results may overstate the expected savings as the “take back” or “rebound effect” is not catered for.

PHPP methodology deliberately avoids the carbon benefit of PV generated electricity (or any other LZC electricity generating technology) to prevent poor standards of energy efficiency being offset by the use of renewable energy. Given the importance of built heritage and the challenges in tackling CO₂ emissions in this dwelling typology, this rigid position may prevent a large number of dwellings meeting the EnerPHit standard. This study includes an assessment of the benefit of PV generated electricity on overall energy use and emissions.

It is worth noting that default energy use in PHPP is reported as primary energy, whereas the industry norm is to use delivered energy figures. This requires care when using conversion factors (that vary with time and from country to country), so results can be equally compared.

Case Studies

This study examines the potential for improving energy efficiency in three terraced Georgian dwellings in Bath, UK, constructed in 1826, see Figure 1. A range of retrofit adaptations and LZC technologies are examined to reduce CO₂ emissions within the historic built heritage context.

Figure 1  Case Study Dwellings, front and rear elevation

The buildings are Grade II listed. Case Study 1 and 2 are mid terrace and Case Study 3 is end terrace, they consist of two stories with solid dressed limestone walls. The roof is double pitched with a
central valley and parapet wall. The front elevation faces south south east. Windows are a mixture of timber single glazed sash windows and double glazed casement units. The ground floors are a mixture of suspended timber floors, stone paving and concrete slab, as built details are at Table 2. Case study 2 underwent refurbishment in 2004 and incorporates energy efficient improvements.

Table 2  Summary Details Table

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
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<tr>
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<td>1826</td>
<td>1826</td>
</tr>
<tr>
<td>Typology</td>
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<td>Mid Terrace</td>
<td>End of Terrace</td>
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<tr>
<td>Delivered Gas kWh/m²</td>
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<td>Delivered Electricity kWh/m²</td>
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<tr>
<td><strong>U value W/m²K</strong></td>
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<td>3.1</td>
</tr>
<tr>
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<td>3.1</td>
</tr>
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<td>0.3/2.7</td>
<td>1.9/2.7</td>
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<td>Roof</td>
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<td>0.4</td>
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<td>Boiler age (years)</td>
<td>15</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>TRV’s</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Draught proofing %</td>
<td>10%</td>
<td>60%</td>
<td>20%</td>
</tr>
<tr>
<td>Assumed start q50</td>
<td>16</td>
<td>9.8</td>
<td>16</td>
</tr>
<tr>
<td>Low energy lighting %</td>
<td>10%</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td>Conservatory</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Heated</td>
<td>Yes</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Appliances</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fridge Freezer</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>550 kWh a⁻¹</td>
<td>408 kWh a⁻¹</td>
<td>550 kWh a⁻¹</td>
</tr>
<tr>
<td>Hob</td>
<td>Electric 7.5 kW</td>
<td>Gas</td>
<td>Gas</td>
</tr>
<tr>
<td></td>
<td>Range type in operation 24/7</td>
<td>Electric</td>
<td>Electric</td>
</tr>
<tr>
<td>Oven</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>1.12 kWh cycle⁻¹</td>
<td>0.94 kWh cycle⁻¹</td>
<td>1.12 kWh cycle⁻¹</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5 kWh cycle⁻¹</td>
<td>Yes</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The roof space available in the valley, which would conceal the installations form view at ground level, permits one 3m² SHW panel and eleven 185 Watt PV panels giving a 2.03 kWp system. These
were considered feasible as Listed Building Planning Permission has already been granted in Bath for
similar proposals\textsuperscript{34}, see Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{1.8 kWp PV system, 19 Devonshire Buildings, Bath, before and after installation}
\end{figure}

Retrofit adaptations

The traditional definition of retrofit is to provide the same level of comfort using less energy (similar
to energy efficiency); this paper focuses on emitting less CO\textsubscript{2} emissions as the key parameter. This
distinction is important, as using LZC produced energy, although not necessarily significantly
reducing energy use, may deliver sizable CO\textsubscript{2} emissions emission reductions in the dwelling,
particularly when offsetting high carbon factor delivered energy.

The emphasis here is on energy by end use; this includes heating (active cooling not required in
UK/Northern Europe climate zone), hot water, cooking, auxiliary electricity, appliances and other
plug-loads. The benefits of this approach are measured by modelled delivered energy use before and
after retrofit.

The potential retrofit adaptations were divided into three packages and are summarised in Table 3.

**Retrofit Package 1 (RP1):** considered adaptions that are generally low cost and straight forward.
Under floor insulation was included although possibly difficult and not low cost, it is necessary to
achieve maximum draught proofing as well as to improve insulation levels. This package includes 12
interventions that were modelled collectively as a standalone retrofit step.

**Retrofit Package 2 (RP2):** upgrades the thermal performance of the external wall fabric. Internal
solid wall insulation was included as a separate measure to investigate the potential contribution this
element makes to reducing energy consumption. External wall insulation was eliminated due to the
potential negative effect on aesthetics, although there may be scope for this approach on rendered
dwellings or on some rear elevations that are of little or no heritage value. As there would only be
one opportunity to improve this aspect in a dwelling an ambitious U value was adopted. This
approach may require further research to consider possible implications. One issue is that driving rain
and absorbent stone may create a risk of fabric decay. Hemp batts and sheep’s wool were selected to
permit moisture movement through the wall construction as they have good vapour permeability and
hygroscopic performance. Another issue is that this construction amounts to 150mm and will reduce
internal floor area by approximately 4-5 \% (this is high as these are relatively small properties).

\textsuperscript{34} 19 Devonshire Buildings, 2011, 1.8kW PV system.
Retrofit Package 3 (RP3): assessed the potential for Photovoltaic Panels (PV) and Solar Hot Water (SHW) to reduce CO$_2$ emissions. Biomass was excluded as district wide application may present air quality issues. Heat pumps are an option, particularly air source. They were not included as they are only likely to be effective with low infiltration rates coupled very high levels of insulation. Micro wind is not included as its ineffectiveness in urban areas is unlikely to meet embodied energy costs [16].

Table 3  Details of retrofit packages

<table>
<thead>
<tr>
<th>Serial</th>
<th>Adaptation</th>
<th>Specification</th>
<th>Target</th>
<th>EnerPHit Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Retrofit Package 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Increase roof insulation</td>
<td>Minimum 270mm fibre glass</td>
<td>$U' = 0.14$ W/m$^2$K</td>
<td>0.12 W/m$^2$K</td>
</tr>
<tr>
<td>2</td>
<td>Install insulation to timber suspended floor</td>
<td>100mm foil backed polyisocyanurate board with breathable vapour membrane above insulation</td>
<td>$U= 0.27$ W/m$^2$K reduced infiltration</td>
<td>0.15 W/m$^2$K</td>
</tr>
<tr>
<td>3</td>
<td>Draught proof</td>
<td>Seal uncontrolled air ingress routes q50 9.6 ach @50pa (see section on infiltration)</td>
<td>$&lt;1.0$ ach @50pa</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Window thermal performance</td>
<td>Either replace single glazed sash windows with double glazed unit or overhaul window and fit secondary glazing (dependant on the condition/heritage value of the window). No works to existing double glazing was considered, allocated $U = 3.0$ W/m$^2$K</td>
<td>Double glazed sash window $U= 2.23$ W/m$^2$K Secondary glazed unit $U=2.30$ W/m$^2$K</td>
<td>0.85 W/m$^2$K</td>
</tr>
<tr>
<td>5</td>
<td>Central heating boiler</td>
<td>Upgrade to efficient condensing boiler designed to take advantage arising from low return temperatures. Include thermostatic radiator valves</td>
<td>Seasonal COP 90%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Central heating pump</td>
<td>Low power high efficiency pump</td>
<td>Auxiliary electricity power reduced from 100W to 25W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Insulate all service pipe runs and eliminate dead legs$^{35}$</td>
<td>40mm foam insulation, no runs in cold spaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Washing machine</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Fridge freezer</td>
<td>Upgrade</td>
<td>A++ energy rating</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Dish Washer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Clothes Dryer</td>
<td>Upgrade</td>
<td>A energy rating</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Lights</td>
<td>CFL or LED</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Retrofit Package 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Internal wall insulation</td>
<td>Comprising timber stud frame with 100mm sheep’s wool or Hemp batts insulation with 40mm wood fibre boards, finished with 12mm lime plaster.</td>
<td>$U= 0.24$ W/m$^2$K</td>
<td>0.3 W/m$^2$K</td>
</tr>
<tr>
<td></td>
<td>Retrofit Package 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Solar Hot water</td>
<td>Evacuated tube system</td>
<td>60% hot water</td>
<td></td>
</tr>
</tbody>
</table>

$^{35}$ A dead leg is a length of pipe between the hot water store and the draw off point; this should be kept as short as possible to minimise the quantity of heated water that cools to room temperature.
2 Photo Voltaic (PV) 2.05 kWp 850 kWh/KWp/pa 40-90% used within dwelling

1 U value calculated using PHPP work sheet

Model Assumptions

In order to provide ready comparison with other model results and databases of domestic energy use (consumer energy use, government energy use data and the English House Condition Survey [13]) all energy use reported is delivered energy. This is also appropriate as it reflects the energy performance of the dwelling rather than the inefficiencies of national energy generation systems.

The model assumed an internal set temperature of 20°C.

The IES model used electrical use data established in the PHPP, see table 4 for Case Study 2 example.

Table 4 Case Study 2 Electric Demand

<table>
<thead>
<tr>
<th>Column Nr</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>kW/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
<td>kWh/h</td>
</tr>
<tr>
<td>Dishwashing</td>
<td>11</td>
<td>1</td>
<td>0.85</td>
<td>0.80</td>
<td>65</td>
<td>2.0</td>
<td>88</td>
<td>50%</td>
<td>44</td>
</tr>
<tr>
<td>Clothes Washing</td>
<td>11</td>
<td>0.70</td>
<td>12</td>
<td>1.00</td>
<td>57</td>
<td>2.0</td>
<td>80</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Clothes Drying</td>
<td>11</td>
<td>1</td>
<td>1.20</td>
<td>0.80</td>
<td>57</td>
<td>2.0</td>
<td>109</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>Energy Consumption by Other</td>
<td>10</td>
<td>0.00</td>
<td>1.30</td>
<td>1.00</td>
<td>365</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>0</td>
<td>0.55</td>
<td>0.90</td>
<td>365</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>or Combined Use</td>
<td>1</td>
<td>1</td>
<td>0.85</td>
<td>1.00</td>
<td>365</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0</td>
</tr>
<tr>
<td>Cooking with</td>
<td>1</td>
<td>0.25</td>
<td>0.80</td>
<td>500</td>
<td>2.0</td>
<td>228</td>
<td>100%</td>
<td>0%</td>
<td>228</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>0</td>
<td>0.55</td>
<td>0.90</td>
<td>365</td>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td>1</td>
<td>1</td>
<td>80</td>
<td>100%</td>
<td>2.0</td>
<td>464</td>
<td>100%</td>
<td>0%</td>
<td>464</td>
</tr>
<tr>
<td>Consumer Electrical</td>
<td>1</td>
<td>1</td>
<td>80</td>
<td>1.00</td>
<td>2.0</td>
<td>88</td>
<td>100%</td>
<td>0%</td>
<td>88</td>
</tr>
<tr>
<td>Sat/Ad Appliances</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>1.00</td>
<td>1.00</td>
<td>100%</td>
<td>0%</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Total Aux. Electricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>279</td>
</tr>
<tr>
<td>Other</td>
<td>Range</td>
<td>0</td>
<td>1</td>
<td>4500</td>
<td>120</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Light Load</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1744 kWh</td>
</tr>
</tbody>
</table>

Carbon Factors

The carbon factors are taken from SAP [17] as it includes a recent significant revision to assumed CO₂ emissions per kWh of fuel used, these are at Table 5. It also includes a figure for displaced grid electricity from PV.
Table 5 Carbon Factors

<table>
<thead>
<tr>
<th>Delivered energy Carbon Factor</th>
<th>kg CO₂/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.198</td>
</tr>
<tr>
<td>Grid Electricity</td>
<td>0.517</td>
</tr>
<tr>
<td>PV generated electricity</td>
<td>0.09³⁶</td>
</tr>
</tbody>
</table>


Infiltration

CIBSE [18] describes air leakage as the adventitious infiltration and exfiltration of air through a building envelope or component due to imperfections in its construction. It is given the term air permeability³⁷ and is denoted as q50. It is reported as air changes per hour (ach) per m² building envelope area at a forced pressure of 50 Pa (m³h⁻¹m⁻²). The advantage of this unit is that applying Kronvall’s rule of thumb [19], dividing by 20, gives (at normal pressure and exposure conditions) a widely used approximation of the air infiltration rate in ach at normal pressure conditions.

Building Regulations (England and Wales) Approved Document L1A [20] currently sets a maximum limit for airtightness of 10 m³h⁻¹m⁻² at 50 Pa (q50) for new buildings and alterations to existing buildings.

CIBSE Guide to building services for historic buildings [21] suggests a “rule of thumb” of 8 l/s/occupant or 0.4 ach (applying Kronvall’s rule, this equals 8 ach at q50) for occupants and an additional 0.4 ach for the dwelling, to reflect the different way historic buildings work with regards to movement of moisture in and out of the fabric, this gives a total of 16 ach at q50.

This may be a high figure to adopt for infiltration, measured q50 results as low as 10.5 ach for historic buildings have been recorded without reports of occupant discomfort or associated fabric decay[22].

Reliance on a “rule of thumb” for historic buildings suggests that further work is required in this area to establish minimum ventilation rates that avoid both unhealthy internal conditions and increased risk of fabric decay.

³⁶ Derived from Allen et al., 2008 [18]. Carbon Trust suggests for electricity generated on-site using renewable energy, a factor of zero may be used [19]. House of Parliament (2011), Parliamentary Office of Science and Technology [20] suggest 0.05kgCO₂/kWh.

³⁷ A method for pressure testing of dwellings is outlined in CIBSE technical memorandum TM23 (CIBSE, 2000) [21]. The recommended good practice air permeability for naturally ventilated dwellings is given as 10 m³h⁻¹m⁻² @ 50Pa, and 5 m³h⁻¹m⁻² @ 50Pa for dwellings with balanced whole house mechanical ventilation.
Building Regulations Approved Document F [20] shows that 7.0l/s is considered sufficient to deal with pollutant accumulation, including moisture build up. In the case studies, ventilation was calculated for two occupants, using 7.0 l/s/occupant. This equates to 0.24 ach for two occupants. In line with CIBSE guidance, an additional 0.24 ach was added for the fabric, giving a model value of 0.48 ach (q50=9.6).

Results

The case study dwellings actual energy consumption was analysed over an 18 month period from June 2010. The first 6 months data were discounted to eliminate the Hawthorne effect. Energy use for heating was normalised using 20 year degree data (Seven Valley region).

The results of predicted delivered energy use against actual delivered energy use for all three case studies using PHPP, IES and SAP software is at Figure 3. Model default occupancy was used in SAP and, an occupancy of two was used in the IES model and PHPP.

![Model Results](image)

**Figure 3  Comparison of Model Results for All Delivered Energy Use**

This shows that all the models overestimate energy use compared with actual energy use. SAP returns a much lower electricity use and over estimates gas energy compared to both IES and PHPP.

A key explanation for this is that the case studies have individual intermittent heating patterns and varying levels of occupancy that are not reflected in standard model analysis. This suggests the need for a reduction factor to reflect actual occupancy.

Data collected from the case studies indicated an average 8 hour heating every day. The models were then re-run with a reduction factor to reflect this intermittent heating (IH) pattern. This was not possible with the SAP model as there is no user input to adjust this parameter. The IES model was repeated using 8 hours heating a day (Oct–Apr inclusive). In the PHPP model, a reduction factor

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38 Default setting 07.00 – 09.00 and 16.00-23.00 weekdays and 07.00-23.00 weekends.
39 Annual Heat Demand Sheet, line 41
although primarily aimed at commercial/industrial buildings that are only in use Monday–Friday, was adopted to represent 8 hours domestic intermittent heating in a 24 hour period (i.e. 8/24 = 33%). The results are at Figure 4.

![Model Results](image)

**Figure 4 Model Results for All Delivered Energy Use with Intermittent Heating for IES and PHPP**

This shows that when intermittent heating is factored in to the model analysis the results are closer to actual energy use. The PHPP returns results within 10% of actual energy use for Case Study 1 and 3. The SAP results are unchanged as there is no alteration to the heating pattern.

Figure 5 makes a comparison on a percentage difference basis for both gas and electricity use. It shows both the default and the intermittent heating pattern results for both IES and PHPP. With the use of intermittent heating PHPP provides the closest representation of actual gas energy use.

The results for electricity use have been presented and are shown for completeness. This shows that the SAP model underestimates electricity use, particularly so in Case Study 1 as there is no option to reflect the use of an electric range or to input actual electrical demand. The PHPP electrical use is based on an inventory of electrical loads within the dwellings (Table 4), the IES model used the PHPP inputs so has the same result. They both provide an accurate result for Case Study 1 (+4%) but over predict energy use in Case Study 2 and 3 (+52% and +19% respectively).
Retrofit packages (RP) 1-3 were then modelled using the PHPP software without any allowance for intermittent heating. This methodology was adopted as the aim of this research was to establish the merit of using the PHPP as a planning tool for retrofit adaptations. The use of a reduction factor to reflect intermittent heating appears appropriate but requires considerable further research to establish an accepted methodology to define empirically this parameter.

Figure 6 shows PHPP predicted delivered energy consumption (based on surveyed construction details with no reduction factor for intermittent heating) compared with actual recorded delivered energy use.

Figure 6  PHPP predicted delivered energy v actual delivered energy use

This shows that for gas (heating and hot water) use, PHPP estimates a considerably higher demand than actual. For electricity use it is much closer to demand. There may be several reasons for the difference in gas use; occupants do not heat the whole house to the same temperature, different heating thermostat set points, the use of intermittent heating patterns, varying occupancy regimes and model simplification of building physics. This further reinforces the challenge of how to define a realistic heating pattern that reflects accurately occupant behaviour, particularly when faced with draughty dwellings with poor thermal performance.

Within the case studies there is also a noticeable variation in energy use. Case study 1 has significantly higher electricity use. This is due to occupancy by a semi-retired person with high occupancy and the presence of an electric range and an electrically underfloor heated conservatory. The higher gas use in case study 3 is attributable to end of terrace typology.

Case Study 1
The summary of the modelled retrofit adaptations for delivered energy use and CO₂ emissions are shown in Figure 7. In this dwelling the use of an electric range (7.5 Kw) for cooking distorts the results in that it makes a useful contribution to heating that cannot be discerned in the model. Total delivered energy use following all retrofit adaptations was reduced by 74% from 473 to 125 kWh/m², CO₂ emissions were reduced by 64% from 121 to 43 kg CO₂/m².

Figure 7  Case Study 1 Summary of Retrofit adaptations on delivered energy use and CO₂ emissions

Case Study 2

The summary of the retrofit adaptations are shown in Figure 8. Total delivered energy use following all retrofit adaptations was reduced by 54% from 197 to 91 kWh/m². CO₂ emissions were reduced by 55% from 48 to 22 kg CO₂/m².
Figure 8  Case Study 2 Summary of Retrofit adaptations on delivered energy use and CO$_2$ emissions

Case Study 3
The summary of the retrofit adaptations are shown in Figure 9. Total delivered energy use following all retrofit adaptations was reduced by 85% from 529 to 81 kWh/m². CO₂ emissions were reduced by 83% from 115 to 19 kg CO₂/m².

Figure 9  Case Study 3 Summary of Retrofit adaptations on delivered energy use and CO₂ emissions

Comparison of results of the retrofit package on total delivered energy use and CO₂ emissions are shown in Figure 10.
Figure 10 indicates that basic measures in RP 1 make modest progress to creating low energy historic buildings. The benefit of RP 1 is less in Case Study 2 as it already had many energy saving adaptations. Likewise RP 2 delivers a smaller saving as it had some internal wall insulation fitted previously.

The final reduction of emissions from the base case was between 54-85%, but only with the contribution from improvement to the thermal performance of external walls. Without internal wall insulation improvements would range from 20-48%. 

Figure 10  Delivered energy use and CO₂ emissions following retrofit packages
Infiltration

Following RP 1 the effect of further reduction in the infiltration rate from a q50 of 9.6 to 5.0 was modelled (q50 of 5.0 is considered the point beyond which MVHR is beneficial in energy saved [27]). This resulted in a further reduction of the heating load of between 16 (9%) – 21 (11%) kWh/m²a of the heating load, see Figure 11.

![Figure 11](image)

**Figure 11 Benefit of reducing infiltration in RP 1 on Delivered Energy**

Electricity CO₂ Emissions

Contrary to Passivhaus methodology where no benefit is attributed from PV generated electricity, here we allocated PV generated electricity (RP3) according to demand. For Case Study 1, 90% of electricity was allocated due to the constant demand of the electric range and full time occupation. As weekday daytime occupancy was minimal in Case Study 2 and 3, 40% of PV generated electricity was allocated as used on site.

Total Carbon emissions from electricity use varied between the case studies and are shown in Figure 12. Case Study 1 has higher emissions due to a 7.5 kW electric range cooker in operation 24 hours a day throughout the year. It was not possible to change this for a gas type model as there was no feasible option to provide the necessary flue arrangements and the occupant considered it an important life style choice.
There is a small reduction in CO$_2$ emissions for all the case studies following retrofit package 2 (internal wall insulation) attributable to reduced electricity use for boiler and auxiliary electricity (e.g. central heating pump).

Unused PV generated electricity was exported to the grid and not considered to reduce the dwelling’s carbon emissions in Figure 12. This is a point that requires further discussion as this low carbon electricity could be considered as offsetting carbon emissions. Figure 13 shows the effect of allocating all PV generated electricity. For case study 1 there is little difference as most PV electricity has already been allocated (90%). For case study 2 and 3 allocating all PV generated electricity would reduce CO$_2$ emissions from electricity to zero, just placing them into carbon negative overall electricity use.
There are limited options to further reduce CO₂ emissions from the current demand. One would be to install additional PV capacity, using the front elevation of the double pitch roof (or garden space). This would be visible at a distance (properties located on a hillside) on the main elevation but would permit an additional 2.4kW system (larger system possible as no space required for the SHW system), producing an additional 2040 kWh of electricity annually.

If this electricity was also used to offset all electricity it would make little difference to Case Study 2 and 3 emissions as PV generation is already greater than consumption, though this would mean they were carbon negative dwellings for electricity in that they would generate considerably more electricity than they consumed. For case study 1 this would reduce final CO₂ emissions to 13 kg CO₂/kWh, a reduction of 72%, see Figure 14.

![Figure 14](image)

**Primary Energy**

When making comparison with the Passivhaus standard primary energy must be considered. The primary energy demand includes all energy for heating, cooling, hot water, auxiliary electricity, lighting and all other electricity uses. This limiting value in the EnerPHit standard is 120 kWh/m²/a. This formula applies to residential buildings, offices and schools.

The primary energy used by the case studies was calculated from primary energy factors in the Data Sheet of the PHPP (1.1 for gas and 2.7 for electricity). The results following RP 1 and 2 and the inclusion of Solar Hot water in RP3 (PV not included here as this is not considered in the total primary energy figure in the PHPP) are at Figure 15.

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This shows that total primary energy use in all case studies exceed the maximum energy demand of 120 kWh/m²/a. The total primary energy can be reduced further if PV generated (2.05 KWp) is taken into account, allocation 90% Case Study 1 and 40% Case Study 2 and 3), (Figure 16).

This shows that Case Study 2 and 3 use approximately 6 and 15% less total primary energy respectively than a Passivhaus (EnerPHit) compliant solution although they could not obtain PH compliance due to their heat energy use exceeding the maximum of 25 kWh/m²/a.

Discussion and Conclusion
The PHPP provided assessment of energy use in line with current alternative models. Accuracy in predicting actual energy use was improved through reflecting actual occupancy patterns.

CO₂ emissions savings of 55-83% are possible but only when the thermal fabric is significantly improved, this option may not always be possible or desirable. The model showed that the use of PV made a significant contribution to reducing emissions; this suggests that in the case of historic buildings the adoption of LZC technologies may be considered alongside rather than after the “fabric first approach”.

PHPP presents challenges when attempting to predict actual energy use from the existing housing stock. It may be argued that this is asking too much of a model that relies on high levels of thermal insulation, low levels of infiltration and MVHR, with a constant and evenly distributed internal temperature in the heating season and applying it to draughty, thermally inefficient and intermittently heated historic dwellings. However, the model’s failure to initially predict accurately gas energy use is due no defined parameter to reflect intermittent occupancy, heating demand and variable internal set temperatures. This can be addressed in the model through the adoption of a reduction factor for occupancy, as shown. It could also possibly be achieved by reducing the internal set temperature, reducing the contribution of the boiler to full season heating and subdividing the dwelling into separately heated zones. This requires further detailed analysis to develop confidence in this approach.

The present work emphasises that establishing a realistic heating pattern is key to developing accurate energy and CO₂ emissions savings; this applies to all dwelling types. The reality is that occupants have varying lifestyles and comfort levels. For modelling purposes a standard is defined to enable comparison. But there is a danger if the standard over estimates energy used for heating as monetary or carbon savings from retrofit measures may be seriously over estimated. This suggests the need for additional research to align the model to reflect the occupancy effect on energy demand. The use of an occupancy reduction factor shows potential to achieve this.

This paper highlights the uncertainty in what is an acceptable infiltration rate for historic buildings to prevent fabric decay and maintain occupant comfort. In the case of existing dwellings there are numerous sources for good practice, yet there is no empirical evidence for what is a minimum acceptable standard for historic buildings. A q50 of 9.6 may be capable of further reduction without increased risk to occupant comfort or fabric performance. To make future use of any model it is necessary to define accurately this parameter as reducing infiltration to a q50 of 9.6 to 5.0 reduces CO₂ emissions by approximately 10%.

The methodology adopted a simplified approach regarding thermal bridges, the effect of which increases in significance as fabric heat loss decreases. The calculation of the thermal bridges is complicated and requires specialist software (such as THERM). In the case of historic buildings there remain challenges in defining material properties in unknown construction which vary greatly depending on the moisture level in the fabric.

The benefit of allocating all PV generated electricity was demonstrated. Additional PV capacity would reduce Case Study 1 emissions by almost 80%. For case studies 2 and 3 they would become carbon negative dwellings. This raises several issues. Firstly, should exported electricity be considered for offsetting domestic CO₂ emissions? Also, as the case studies are listed buildings, under current planning constraints they would be unlikely to gain planning permission for PV installation on the front façade. This restricts the potential for these dwellings to achieve optimum CO₂ emissions reductions. Given the challenge in meeting the UK’s 80% CO₂ emissions reduction target, is the increased carbon saving from additional PV on the front facade worth the toll on aesthetics?

This analysis has considered three distinct retrofit options as stand-alone packages. To some extent the solution is not that simple. The point is not to implement a suite of separate unconnected retrofit
adaptations but to consider the impact of combined adaptations. For example, the use of hygroscopic materials for internal wall insulation may be able to cope with lower rates of natural ventilation; whereas the effect of internal wall insulation with a vapour barrier on ventilation rates is unsure, particularly as the previous buffer effect of walls will have been dislocated. This may require additional ventilation if moisture within the dwelling previously moved in and out of external walls in a seasonal rhythm.

This is further complicated by the impact of “take back” in the form of improved internal heating duration and set temperature, as this will also affect the previous equilibrium of moisture movement subsequent to any retrofit adaptations as well as affecting any financial payback calculations.

Energy use was reported as delivered energy; this is effectively the fuel or electricity used within the dwelling. This allows direct comparison with international energy end use. However, for true comparison, and to reflect the inefficiencies of centrally generated electricity, primary energy should also include the effect of on-site generation. In this study this approach demonstrated that historic buildings can achieve lower overall energy use than the current Passivhaus EnerPHit standard (although exceeding the 25kWh/m²a heating limit when on-site generated electricity use is included).

PHPP has shown that as a model it can provide assessments of the benefits of retrofit adaptations in historic buildings in a straight forward, user friendly and cost effective way. But more importantly, and with regard to aligning the conservation of energy to the conservation of heritage, it can provide empirical data to evaluate the benefit of decisions that affect fabric and/or aesthetics. This has even greater potential for wide scale adoption at the district level.

Future Work

The case studies have shown that energy efficiency is not solely dependent on the performance of the building.; occupants play a vital role. One way to mitigate this effect is to collect empirical data on actual energy use to improve the accuracy of energy use software prediction. PHPP for new build was developed over time, analysing the results of as built performance against predicted results. Clearly more case study analysis will develop similar accuracy for retrofit in historic buildings.

Additional research is required to compare steady state PHPP simulations in historic buildings with actual energy use and energy performance following retrofit adaptations. This should be done at scale and is required to develop confidence in the model for use in this building category.

It is of prime importance to establish a methodology to define a realistic and effective minimum infiltration rate for historic buildings undergoing energy efficiency retrofit adaptations. Without optimising this parameter energy saving opportunities will be missed and, if set too low, may lead to fabric decay.

The risk of overheating may increase following the installation of internal wall insulation. The effect of the remaining thermal mass on preventing over heating or its ability to make use of solar gains is unsure. Additional work is required to explore future climate scenarios to ensure dislocating part of the thermal mass does not lead to a cooling load that may negate any CO₂ emissions savings arising from heating demand reduction. When using PHPP this is particularly important as it assesses overheating on a whole house basis and not room by room.

The effect of thermal bridging was not extensively explored in this paper. The adoption of internal wall insulation will increase the risk of fabric decay if this aspect is not dealt with; examples are joist penetrations in external walls and solid lintels over openings. Part of the problem is that actual construction details can be challenging to establish accurately (thermal imaging may assist in identifying areas of concern). This is an area where once projects have been undertaken following detailed software analysis on-site knowhow will begin to accumulate.
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