Impact of climate change and envelope performance dilapidation on dwellings

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Declaration

I hereby declare that the work presented in this thesis was solely carried out by myself at Edinburgh Napier University, except where due acknowledgement is made, and that is has not been submitted for any other degree.

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20/12/2019
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Date

Abstract

This research is based on results of building envelope and energy performance of thirteen dwellings. The dwellings, located in Dunfermline, Scotland, were part of the Housing Innovation Showcase (HIS) developed by Kingdom Housing Association to explore the efficiency and benefits of ten methods of construction.

The study focused on five key areas: 1) The longitudinal correlation between the building envelope and space heating energy demand, 2) Methods of assessing building envelope decline over time, 3) Estimated time stamps at which dwellings fail to achieve targets, 4) Explore retrofit intervention methods and 5) understand the impact climate change has on dwelling performance over time.

The research undergoes in-situ U-value and air permeability testing to measure the decline of the building envelope and how it affects energy demand over time. The use of steady-state calculation methods in combination with dynamic thermal modelling enabled a longitudinal approach of dwelling performance. The models estimated energy demand using a factor of dilapidation by calculating heat loss coefficient values as dwelling performance factors (DPF). Probabilistic climate change weather files were incorporated into calibrated models to simulate the effects of weather shifts on energy and CO_2 emissions. This led to a longitudinal trajectory analysis to estimate the effects of climate change and DPF scenarios linked to specific time stamps and tipping points above design standards and targets.

The results and analysis show that a conventional dwelling type (SD.6.17) reached its first tipping point by 2032 (100% DPF) followed by 2035 and 2042 considering medium (50%) and low (10%) DPF's. A *Passivhaus* built dwelling (SD.6.18) first reaches a tipping point in 2028 (100% DPF), followed by 2031 and 2037 with a medium and low DPF respectively. Dwelling T.7.19 reached tipping points as late as 2065, by using electricity as its main heating fuel; expected to be decarbonised during the 2050's. This analysis concluded that airtightness dilapidation deteriorated faster than U-value and that the interventions to remediate airtightness could be easier applied. Also, the sensitivity of the DPF's on dwelling environmental performance is critical; maintenance of dwellings and material deterioration can determine the intensity of dilapidation.

Publications arising from this research

Monographs

- Bros-Williamson, J. (2017). Review of actual energy demand and envelope performance of the Housing Innovation Showcase 2012. Edinburgh, Scotland: Edinburgh Napier University, Project Report. http://researchrepository.napier.ac.uk/output/1032755

- Currie, J., Bros-Williamson, J. & Stinson, J. (2014). Energy Performance of homes using Modern Methods of Construction. Edinburgh, Scotland: Edinburgh Napier University, Project Report. http://researchrepository.napier.ac.uk/output/172892

- Currie, J., Bros-Williamson, J. & Stinson, J. (2014). Housing Innovation Showcase 2012 Post Occupancy Evaluation Phase 1 – Part 2. Edinburgh, Scotland: Kingdom Housing Association. Edinburgh Napier University, Project Report. http://researchrepository.napier.ac.uk/output/175422

- Currie, J., Bros-Williamson, J. & Stinson, J. (2013). Housing Innovation Showcase 2012: Building Performance Evaluation, Phase 1-Part 1. Edinburgh, Scotland. Edinburgh Napier University, Project Report. doi: 10.14297/enr.2013.000001. http://researchrepository.napier.ac.uk/output/181453

Journal Papers

- Bros-Williamson, J., Garnier, C., & Currie, J. I. (2016). A longitudinal building fabric and energy performance analysis of two homes built to different energy principles. Energy and Buildings, 130, 578-591. doi: 10.1016/j.enbuild.2016.08.052

Conference papers

- Bros-Williamson, J., Stinson, J., Garnier, C. & Currie, J. (2017). Discrepancies between theoretical and actual heating demand in Scottish modern dwellings. In *PLEA 2017 Proceedings - Design to Thrive*, 361 to 368. ISBN 978-0-9928957-5-4

- Bros-Williamson, J., Stinson, J., Currie, J., (2015). Energy Performance Evaluation of a Passive House Built to Scottish Building Standards. International Journal of Housing Science. Vol. 39, 225 to 235. ISBN 978-989-98949-0-7

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List of acronyms and abbreviations

%RH	Percentage relative humidity
˚C	Degrees Centigrade
ACH	Air exchanges per hour
AR	Assessment report
ATTMA	The Airtightness Testing and Measurement Association
BAU	Business-as-usual
BEIS	Department for Business, Energy & Industrial Strategy
BPE	Building performance evaluations
BRE	Building research establishment
BREDEM	BRE domestic energy model
BS	British Standard
CDD	Cooling degree days
CERT	Carbon Emission Reduction Target
CfSH	Code for Sustainable Homes
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
COP	Coefficient of performance
CP	Closed panel
CV	Coefficient of variation
CVRMSE	Coefficient of variation of root mean square root error
DBES	Dynamic building energy simulations
DECC	Department for Energy and Climate Change, now BEIS
DER	Dwelling Emission Rate
DSY	Design summer years
EESSH	Energy Efficiency Standard for Social Housing
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
ESRU	The Energy Systems Research Unit
EST	Energy Saving Trust
EU	European Union
EWGECO	Energy, Water, Gas Energy Consumer Operation
FEES	Fabric Efficiency Standard
GHG	Green House Gases
GoF	Goodness of fit
HDD	Heating degree days
HEEP's	Home Energy Efficiency Programmes
HFM	Heat flux meters/ mats
HIS	Housing Innovation Showcase
HLC	Heat loss coefficient
HTC	Heat-transfer coefficient
HVAC	Heating, ventilation and air conditioning
IES	Integrated Energy Systems
IHD	In-house displays
IPCC	Intergovernmental Panel for Climate Change

ISO	International Organization for Standardization
KHA	Kingdom Housing Association
MBE	Mean Bias Error
MMC	Modern methods of construction
NMBE	Normalized Mean Bias Error
NOx	Nitrogen Oxide
nZEB	Nearly Zero-Energy Buildings
OP	Open panel
Pa	Pascals - barometric pressure
PIR	Post-implementation reviews
PM10	Particle Matter 10
POE	Post occupancy evaluations
ProCliPs	Probabilistic Climate Profiles
RCP	Representative Concentration Pathways
RdSAP	Reduced Standard Assessment Procedure
RIBA	Royal Incorporation of British Architects
RPP	Report on Proposals and Policies
RSL	Registered Social Landlord
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SBR	Scottish Building Regulations
SBS	Scottish Building Standards
SEEP	Scotland's Energy Efficiency Programme
SRES	Special Report on Emissions Scenarios
TER	Target Emission Rate
TM	Technical Memorandum (CIBSE)
TRY	Test reference years
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation

Chapter 1

Introduction

1.0. Chapter introduction

This chapter focuses on explaining the background, aim, research questions and research methods of this study, relating to the energy and environmental impacts caused by building envelope dilapidation over time.

The chapter is broken into three main sections. The first gives a background to the key elements of this research. The second section discusses the research scope; defining the primary aim, research questions and objectives. This is followed by section three focussing on the research methods and the hypothesis tested by combining quantitative and qualitative methods as part of an appropriate research design. A thesis structure concludes this chapter.

1.1. Background

There is a longstanding commitment for the house building industry to provide occupants a safe and comfortable home that not only complies with current building standards but also contributes to achieving current and future targets for the reduction of greenhouse gas (GHG) emissions. Equally relevant is changing the perceptions of the building industry from thinking that building energy efficient dwellings just costs more; to thinking that the long-term affordability and occupant well-being outweighs higher initial investment. There is therefore scope to evaluate whether dwellings energy demand and environmental impact over time is influenced by the building envelope.

Environmentally, new dwellings in Scotland have been expected to lead by example through the increased push to achieve healthy and affordable energy-efficient buildings following current building regulations; such as the Technical Handbooks Section 6 Energy (SBS, 2015) and Section 7 Sustainability (SBS, 2013). The introduction of The Sustainable Housing Strategy (The Scottish Government, 2013b) and the “Dwellings that don’t cost the earth” consultation on sustainable housing (The Scottish Government, 2012) proposes priorities and expectations that would push housing providers to build better dwellings. Private house builders, local authority and registered social landlords (RSL's) should comply equally to improve designs for new dwellings and improvement of existing stock to achieve criteria that reduces energy demand and CO_2 emissions impacting on the environment.

Equally, a problem in new and existing dwellings is delivering long lasting energy efficiency, not just during early occupation but throughout its occupation. One way of achieving this is by compliance energy calculations at the design stage that preserve energy performance post-construction. The difference between aspired and actual performance, often referred to as the 'gap in performance', can be detrimental to occupant's health and thermal comfort, particularly as a function of time and resilience to external climatic conditions (de Wilde, 2014). Identifying the disparities between as-designed and in-use energy performance at an early stage and during the lifetime of the dwelling, either by physical monitoring or prediction, can only lead to a better-informed housing industry with robust knowledge in delivering reliable energy efficient dwellings. In order to better recognise the disparities resulting from this performance gap it is important to recognise the changes in envelope performance by conducting repeated building envelope evaluation testing to show results during a specific period and trajectory.

Investigating the decline in envelope performance, and its impact on energy demand and the environment over time, can reduce any speculation about the 'real' performance of dwellings and their service life, providing better guarantees of long-standing performance. Most components in a building have a stated service life, however, as time passes, it is expected that components and technology have an end-of-life capacity where their performance declines depending on its use and operability. For example, the Green Guide to Specification by Anderson et al., (2009) assesses building elements and materials considering a 60 year period, however, this is not representative of its building life period; as many parts and components are expected to last longer (or shorter) with little or no maintenance. However, if the rate of decline is reduced and the investments into replacements and maintenance kept to a minimum, it will not only conserve building market value but also bring benefits to the occupiers. It also provides knowledge on the influencing elements that impact performance of dwellings, whilst pinpointing more accurately expected investments on maintenance.

Early consideration of improvements to energy efficiency of dwellings will give a realistic account to homeowners on energy expenditure over time, but equally informs policy makers on how the industry is due to perform and achieve environmental targets. Research by Stevenson and Leaman (2010) and Gill et al. (2010) conclude that there is a need to conduct post occupancy and building performance studies of domestic dwellings by validating actual performance against perceived calculated performance. Equally the study of dwellings over longer periods, identifying building fabric conditions, is identified by de Wilde (2014), Taylor et al. (2010) and Firth et al. (2008). The degradation of the building fabric and its effects on energy demand as analysed by Balaras et al. (2005), Itard and Meijer (2008), Chorier et al. (2010) and Stazi et al. (2009) point out the importance of maintenance for long lasting performance, something that both occupiers and RSL's should consider.

Building performance, including heat loss and space heating energy demand topics are studied in this research, from the evaluation process of building fabric efficiency to the impacts of climate change on a building performance over time.

1.2. Scope of the study

The research is an investigation of how the performance of occupied dwellings dilapidate over time. The longitudinal monitoring of building fabric efficiency and recorded space heating energy demand provided primary data for the study. Thus, this research focuses on the behaviour of the building envelope by testing heat loss transmission rates (U-value) primarily through walls and ventilation heat loss (air permeability) of the dwellings heated volume. It also seeks to find the relationship between heat loss and consumption of energy for space heating.

This research utilises data sets from occupied dwellings that form part of the 2012 Housing Innovation Showcase (HIS) developed by Kingdom Housing

Association (KHA) in the City of Dunfermline, Fife, Scotland. Such a scheme by this RSL contains twenty-seven dwellings built with ten different construction methods that strive to achieve low energy demand. Thirteen dwellings have undergone building performance and post occupancy evaluations, representing the performance of each construction method and design strategy. Further on in the analysis, three dwellings are analysed in greater detail, including a *control house* which forms part of the RSL's conventional house design standard, depicting a baseline house type in the development. The study spans a four-year period, from the summer of 2012 prior to handover, through a final heating season of the study in 2016/17. The continual building envelope evaluation of these dwellings linked to the energy demand profile obtained during occupation forms a central part of this research. Furthermore, these dwellings were designed to meet the 2010 Scottish Building Regulations, Section 6 (Energy). Since then some changes have come into place, related to legislation, the new Scotland Climate Act of 2018 (The Scottish Government, 2018) and enhancement of Scotland wide CO_2 emission targets. As a result, the expected CO_2 emission targets during its design are less onerous than those now in place, reflecting on results and outcomes of this research. Appendix 1a provides a description of the key design characteristics of each of the dwellings identifying the location of the dwellings on development site which form part of this research.

1.2.1. Aim

Prior to explaining the research questions in this study, it is essential to explore the principal aim of the study. As Robson (2002) explains, the aim should clearly state whether it will; explore the topic, describe it in detail or explain a particular phenomenon. The topic of 'performance gap' is well developed with a large supporting body of evidence through case studies and academic publications. The literature review surrounding the degradation and dilapidation of buildings primarily focuses on non-domestic buildings (Bordass et al., 2004, Menezes et al., 2012, Stevenson and Leaman, 2010, de Wilde, 2014) over short time spans, thus the research can arguably make the greatest contribution by exploring the long term effect of fabric efficiency by using in-situ measurements and applying them to techniques to predict dwelling energy demand over time and its impact on the environment. Also pertinent are the impacts and repercussions climate change has on the built environment. Therefore, the aim of the thesis is to: evaluate how climate change and dwelling envelope performance over extended periods of occupation contributes to emitting more CO_2 into the atmosphere, whilst comparing it against targets and calculations.

1.2.2. Research questions and objectives

According to Punch, (2014) a research project can be pragmatically driven, where it begins with research questions, used to help describe the specific aim and general focus of the study. It is then followed by specific objectives to answer the posed questions. Robson (2002) also alludes to Punch's (2014) statement by explaining that *"A research project will be difficult both to report and to understand, and will lack credibility as a piece of research, without structure in its research questions…"*

Therefore, the research questions and objectives developed for this research are as follows:

1. Does the building envelope performance of a new dwelling decline over time? And if so, how does it contribute to its heat energy demand?

Objective: To determine the relationship between the dilapidation of the building envelope and space heating energy demand.

2. What are the key variables used to quantify the impact of envelope performance over time?

Objective: To measure and provide a quantifiable result at set intervals of building envelope performance, then propose a factor of dilapidation that can be applied over time.

3. Is it possible to predict an environmental impact tipping-point where interventions are required?

Objective: To establish a time stamp or period during the lifetime of the dwelling where its environmental impact surpasses the aspired calculations, criteria set by standards or set targets.

4. To what extent can early predictions of dilapidation and the tipping-point time stamps can identify maintenance practices?

Objective: To identify the level of envelope underperformance at the estimated tipping-point and consider and plan interventions to overcome rising energy demand with environmental repercussions.

5. What effect does climate change have on the longitudinal energy performance of dwellings?

Objective: Source predicted climate change climate data sets to predict building energy performance over time while also measure the environmental impact.

1.3. Research Methods

For a research method to be developed, alignment with the research questions and methods is required; methods follow from questions (Punch, 2014).

1.3.1. Research design

A simple research design is adopted by proposing pre-empirical and empirical stages. A pre-empirical stage defines the topics and area of study, assisted by a literature review that identifies the gap in knowledge in order to propose research questions and a hypothesis. The empirical stage involves a data collection method leading to results and data analysis. These then can answer the research questions and tests the hypothesis.

Pre-empirical stage:

1. Definition of research area and topics
2. Literature review
3. Research questions
4. Theory and hypothesis

Empirical stage:

1. Research design and methodology
2. Data collection
3. Data analysis
4. Test hypothesis

1.3.2. Proposed Hypothesis

Determining a hypothesis derives from a proposed outcome or answer to the research questions (Punch, 2014). The research objectives in §1.2.2, state that a quantification of the building envelope performance at set timelines is required. Testing and measuring performance at set points in parallel with heating demand will provide important data sets to analyse further over longer trajectories. If compared under prescribed targets and design aspired levels, performance and environmental impact can be identified that may lead to estimated periods of planned maintenance and replacement. The determined improvements, such as addressing changes to the building fabric, leads to propose the following hypothesis: *The dilapidation of a dwelling's building envelope contributes over time to increased environmental impacts, therefore outstripping targets earlier than anticipated, leading to a premature refurbishment.*

1.3.3. Thesis structure

The thesis is presented as follows. **Chapter 1** introduced the topic to be researched, the scope, aim, research question and associated objectives and hypothesis. **Chapter 2** corresponds to a literature review that informs the theoretical framework based on current legislation and current methods of data gathering, analysis and interpretation of results. Different methodologies for testing and monitoring has been analysed, particularly on the building performance (BPE) and post occupancy evaluation (POE) surveys and their techniques. Important to this approach is the use of validation tools, such as statistical and dynamic model-based methods.

The adopted methodology for assessing the selected dwellings and conducting the tests and validation is explained in **Chapter 3**. The chapter explores the theoretical and best practice of in-situ tests for measuring building envelope performance, such as air tightness and in-situ thermal transmission testing. Also relevant in this chapter is the interpretation of data and subsequent analysis; applying the relevant error analysis and accuracy measures. This chapter also explains the methodology adopted to validate the measured data by statistically analysing it to predict building dilapidation over longer periods. Equally important is the method adopted for using test results in a dynamic modelling scenario and applying climate change weather files to predict longitudinal performance.

Chapter 4 presents the results obtained from the BPE's and POE's conducted on all thirteen selected dwellings over a four-year period. It also shows the energy and environmental impact calculations and the correlations between the results and the conditions and criteria set by each dwelling design. **Chapter 5** focuses on analysing the detailed results from three representative dwellings and explaining some of the trends observed, while also combining all methods of longitudinal performance, gap in performance baseline, climate change and the dilapidation of the building envelope. These are presented with quasi-steady-state calculations in combination with the dynamic building models and simulations. **Chapter 6** makes relevant conclusions on the research by discussing the contribution to knowledge and proposal for further study.

Chapter 2

Literature review

2.0. Chapter introduction

The literature review of this research covers five fundamental topics relevant to the building envelope performance and its environmental impact over time. The first covers the current policy framework surrounding energy efficiency and climate change targets. A second addresses the adopted techniques for the data acquisition and analysis of this research, focusing on quantitative methods of building performance evaluation and qualitative occupant survey techniques. The third topic describes the use of compliance steady state modelling techniques and dynamic modelling methods including the steps to calibrating models for more reliable simulation results. Relevant to the modelling is topic four which covers the application of future weather files considering climate change scenarios used for the longitudinal analysis of buildings. Finally, topic five focuses on the dilapidation and degradation of buildings.

2.1. Current policy framework

An important part of this research is predicated by the current policy that impact the design and construction of buildings. Primarily, government legislation impacts on the energy efficiency of new buildings and the incentives offered to retrofit existing buildings. Many legislative changes are interlinked and are the basis of environmentally conscious policy standards, particularly through climate change mitigation schemes that shape the built environment. Policy decisions are important as they set a standard for many to follow and when issued at different scales, it can help to achieve targets previously identified. This topic first explores legislation imposed by the European Union, followed by the UK and the enforcement of standards and targets, and finally how Scottish legislation impacts the built environment, pertinent to the dwellings analysed in this research.

2.1.1. EU legislation

The focus of the European Union on climate change is reliant on each European Member State's individual criteria and legislation. However, there are efforts in place of strategic resilience strategies that contribute to the mitigation of CO_2 emission from the built environment. The latest scientific evidence shows that allowing global warming equal to and above 2°C compared to temperatures in pre-industrial times can cause irreversible consequences to global climate (Daggash and MacDowell, 2019). Legally binding agreements set by the 2015 Paris agreement state that countries should contribute to achieving "well below" the 2˚C global temperature rise. The latest Intergovernmental Panel for Climate Change (IPCC) suggests a bigger challenge, to limit a 1.5˚C increase (UNFCCC, 2015). Daggash and MacDowell (2019) explore how this can be achieved by proposing pathways of energy system changes and their uptake in the EU.

The European Commission through the department of Energy, Climate Change and Environment have set targets on the reduction of CO_2 emissions with two key dates in mind; targets by 2020 with 20% reduction of emissions compared with 1990 levels, 20% increase of energy from renewable sources and 20% increase in energy efficiency across all industries (Bel and Joseph, 2018). A roadmap to 2050 was set requiring each Member State to follow Kyoto Protocol commitments to reduce GHG emissions by 80 to 95% below 1990 levels. Explained further by Mikova et al. (2019), two interim targets were set; reductions of 40% by 2030 and 60% by 2040 below 1990 levels. The EU Parliament (2018) is set to achieve these targets by energy efficiency of buildings, to be reduced by 32.5% by 2030 based on 1990 levels.

In a publication by the European Environmental Agency (EEA, 2012) which analyses the trends of energy sector GHG emissions; the impact from buildings accounts for 25% of the total end-use emissions and housing as a whole accounting for 36% of that percentage. This represents 40% of total energy consumed (Bean et al., 2018). The creation of the Energy Performance of Buildings Directive 2010/31/EU (EPBD), discussed by Sutherland et al. (2013), explains that this is the main legislative instrument to reduce the energy consumption of buildings, requiring each Member State to have in place calculating methods of energy efficiency. In the UK, the implementation of the Standard Assessment Procedure (SAP) for residential buildings and the Simplified Building Energy Model (SBEM) for commercial buildings fulfilled this requirement. Also agreed, is for all new buildings to be designed and built as Nearly Zero-Energy Buildings (nZEB), however D'Agostino (2015) argues that implementing the criteria into mainstream design and construction has been difficult in most Member States. Bean et al. (2018) have indicated that these guidelines should be reported, stating methodologies and approaches covering cost-optimality, refurbishment of existing stock and the importance of lifecycle analysis covering the embodied energy of buildings. Kurnitski (2013) and Paoletti et al. (2017) explain that achieving nZEB requires a highly energy efficient envelope with innovative construction features and site specific, community and district led energy flows.

2.1.2. UK legislation

The proposed 2°C climate change boundary point, is considered differently in the UK. Wales and England have set their own targets, explained in the Climate Change Act of 2008 (HM Government, 2008), proposing to achieve the minimum 20% reduction of GHG emissions by 2020 and 80% by 2050 based on 1990 levels. Although ambitious in nature, Lockwood (2013) defines the Act as not being politically accepted in the UK and that its implementation remains at risk due to "incomplete investment effects" and "low political salience". Equally, Ling-Chin et al. (2019) argue that many of the built environment industry stakeholders in the UK are familiar with the targets but their perspectives do not align with the current legislation. This poses a big problem as the industry is disengaged with the targets despite accepting them.

The UK domestic building sector represents 27% of the total CO_2 emissions with an expected 6% rise each year (Williams, 2010). However, research by Fenner et al. (2018) argues that life cycle analysis of buildings both of its operational and embodied emissions has a larger impact in realising reductions. The UK government has aligned the building regulations to meet the expected criteria on the implementation of nZEB's. As a first approach the government set up the Zero Carbon Hub from 2010 to 2016 and the criteria set by the Code for Sustainable Homes (CfSH) as a mandatory standard from 2010 onwards with various carbon reductions leading to a denominated Code 6 or Zero Carbon. Later such standard/ criteria was integrated into the energy and CO_2 emission targets of the Building Regulations for England and Wales, Part L as described by Ling-Chin et al. (2019b). To achieve this, and described by Colclough et al. (2018) the potential od standards such as Passivhouse are as a determinant method to meeting the nZEB criteria in the UK without extra cost over traditionally built dwellings.

Osmani and O'Reilly (2009) explain that a more practical approach is required to achieve low carbon homes such as "legislative, cultural, financial and technical barriers" are required. McLeod et al. (2012) argue that Zero Carbon should not only be achieved at the design stage but also at the as-built stage once occupied in order to minimise the performance gap between aspirational performance and occupied performance.

Similarly, Wales have set a target of 3% reduction of CO_2 emissions starting in 2011 achieving a reduction over 1990 levels by 2020 of 40%, a target which will be measured against a baseline of average emissions between 2006 and 2010 and which will exclude heavy industry and power generation (Calverley and Wood, 2009). The Welsh Government is pushing to adopt a 'whole house' approach targeting on reduced fuel poverty and supporting communities.

2.1.3. Scottish legislation

Scotland's ambitious plans to tackle climate change have been proposed since the approval of the Climate Change (Scotland) Act of 2008 setting targets of reduced CO_2 emissions in a transition to a low carbon economy and a sustainable economic growth (Scottish Parliament, 2009). The target was to achieve 80% CO_2 emissions reduction by 2050 with an interim 42% target by 2020 using the 1990 baselines. To deliver such targets the Scottish Government proposed the Low Carbon Scotland: Meeting the Emissions Reduction targets 2010-2022 document or Report on Proposals and Policies (RPP1) (The Scottish Government, 2010). Subsequently a revised RPP2 document was proposed in 2013 (The Scottish Government, 2013) after updated targets and calculations based on new policies and criteria.

RPP1 and RPP2 documents focused on delivering energy efficiency measures such as; loft and cavity insulation in existing housing stock, gas central heating and community led renewables heat technology. For the new building sector it set improved criteria on; building fabric, space and water heating delivery, low carbon technology, reduced heat loss by ventilation and increased energy efficient lighting (The Scottish Government, 2012).

In a response to the EU regulations to adopt nZEB criteria and to contribute to creating sustainable and energy efficient buildings in Scotland a panel of experts was appointed by Scottish Ministers chaired by Lynne Sullivan. The experts proposed a strategic approach first set in 2007, followed by a second report in 2013 to update the criteria and recommendations at a post-2008 economic downturn and new RPP2 report (Sullivan, 2007 & Sullivan, 2013). The 2007 version focused on; upgrading the Building Standards to suit nZEB criteria, step-reduction of carbon in domestic buildings compared to the 2007 levels and the introduction of tougher building fabric efficiency and total-life zero carbon buildings (operational & embodied carbon) by 2030. The 2013 Sullivan report focused on new and existing building stock to achieve low carbon design, construction and cost driven solutions adapting to nZEB criteria using offsite and modern methods of construction (MMC) (Sullivan, 2013).

A revised Climate Change Bill presented to Parliament on May 2018 (The Scottish Parliament, 2018) proposed a new Climate Change Plan and third Report on Proposals and Policies 2018-2032 (RPP3) (The Scottish Government, 2018). It stated new 2050 carbon emission reduction targets, proposing 90% reduction based on 1990 levels. Interim targets were introduced; reduction of 56% by 2020, 66% by 2030 and 78% by 2040.

To achieve all targets, Scottish Building Regulations “Technical Handbooks” Section 6 (Energy) and Section 7 domestic (Sustainability) have been introduced and updated (SBS, 2015, SBS, 2011 and Musau and Deveci, 2011). Section 7 introduced a labelling system denominated by; Bronze, Silver, Gold and Platinum as indications of increasing dwellings performance above the 2010 and 2015 Building Standards. The standard contains a total of eight aspects which apply to both Silver, Gold and Platinum label.

Relevant to climate change and buildings are the adaptation strategies that make buildings resilient to uncontrollable meteorological changing conditions. A report by The Scottish Government (2019) on the climate change adaptation programme for Scotland concluded in many strategies involving communities, climate justice and policy, economy, society, natural environment and marine environment and international networks for adaptation. There are plans for Scotland to adapt to climate change by having resilient places, historic environment and buildings that can mitigate the risks of flooding and increased energy demand (heating or cooling). The built environment of Scotland is prone to increases in temperature with reduced rainfall during the summer alongside projected increases of rainfall in winter making buildings more susceptible to flooding and exposure to envelope risks unaccountable when first designed. In new buildings resilient design options can be easily implemented into the construction phase. However, in existing buildings this can be less practical and more labour and cost intensive. Historic buildings are particularly prone to the effects of climate change and strategies to avoid or mitigate any significant disruptions to the occupants and overall performance of the envelope should be considered. A recent guide by Historic Environment Scotland (2016) aimed at home owners and building professionals, outlines the potential for traditional buildings to adapt to climate change focusing on external envelope protection against outside extreme weather shifts. Buildings that have been neglected or have poor maintenance are at a greater risk as rain will increase decay and weaken elements hindering the performance and conditions for occupiers.

A more refined guide addressing the ways in which the built environment is prone to the changing weather is in a study by Historic Environment Scotland (Harkin et al., 2019). It looks at the potential measures to address the expected impacts and hazards with an approach to cope and plan or mitigate before irreversible damage. Hazards are also observed where temperature, rainfall, extreme weather, sea-level rise and flooding can negatively impact buildings. For example, in buildings wind driven rain can have physical damage to external building fabric causing structural integrity and adverse thermal risks. An adaptation option studied in the guide suggest that building components such as roofs or walls can look for installing additional fastenings to ridges and slates, increased lead protection, repair of mortar joints and an increased frequency of inspection and maintenance. Understanding the way buildings have been exposed to changing weather so far and being aware of what future trends, are useful starting points to reduce the impact and risk of unforeseen disasters or irreversible loss of existing buildings (Harkin et al., 2019).

2.2. Building performance evaluations

For buildings to achieve the prescribed criteria set by low and zero carbon emissions, it is important to recognise the differences between a theoretical building design and the real life as-built version presenting occupancy and performance complexities. There has been an over-reliance on the calculations and design aspirations, which has led to building consuming more than they should, contributing substantially to global CO_2 emissions. Verification of performance is one way to understand the real operation of buildings, involving in-situ tests and energy consumption monitoring as well as occupant comfort and behaviour studies. This section addresses these important methods and approaches; split between quantitative and qualitative data retrieval.

2.2.1. Quantitative evaluations

Quantitative research acquires data in the form of numbers which can be statistically analysed with the main aim of measuring, aggregating, modelling and predicting behaviour and relations (Hentschel, 1999). These methods, referred to as non-contextual, are designed to achieve breadth in coverage and analysis (Stevenson and Rijal, 2010).

2.2.1.1. Building envelope evaluations

Building envelope evaluations concern the measurement and verification of the components that encase a building, primarily those that maintain thermal performance and occupant thermal comfort (Guerra-Santin and Tweed, 2015a). Relevant to this research are evaluation methods that assess envelope heat loss efficiency and are a “crucial step for the energy diagnostics...” (Ficco et al., 2015).

2.2.1.2. In-situ U-value

The steady-state calculation of U-value of building components are based on the principles stated by BS EN ISO (2007), focusing on heat transfer within thermally homogeneous. The method is performed to understand the heat loss through various elements and is used to calculate and express the energy requirements of buildings (BS EN, 2007).

The calculations remain a theoretical account of thermal resistance and transmittance often used as default values of real performance. For this reason the verification of U-values is an indicator of heat loss from that component. Studies by Baker (2011) and Li et al. (2015) established that U-value calculations overestimate results and suggest that verification is required in the form of in-situ measurements. Evangelisti et al. (2015) carried out measurements of in-situ U-value in order to verify theoretical model effectives and concluded that large differences can be obtained, particularly if the material layers are unknown.

Performed under the guidance of the ISO 9869-1: standard of Thermal insulation In-situ measurements tests require an understanding of the thermodynamics of heat flow (BSI, 2014). Many studies are performed for retrofit projects in order to identify a baseline U-value of elements prior to upgrading and to measure the effect of the intervention (Hulme and Doran, 2014, Baker, 2011 and Rye et al., 2012). However, tests can also identify if elements are not performing well in new buildings and can be used in further energy performance related studies. Several studies by Guerra-Santin et al. (2013); Majcen et al. (2013) and Guerra-Santin and Christopher (2015) adopt a similar methodology when deploying logging equipment for in-situ U-value measurement. As mentioned by Li et al. (2015a) heat flux meters (HFM) and thermistor temperature sensors are attached to a data logger and set to record data at five minute intervals. The thermistors are placed to measure ambient and surface element indoor and outdoor temperatures. Previous studies by Baker, (2011) and Hulme & Doran, (2014) recommend a temperature differential (Δt) >10°C between the inside and outside surface of the elements to account for higher heat flows and greater accuracy.

Throughout field tests, HFM's record a voltage differential, later calibrated to provide the heat flow (Q_{in}). Internal (T_{in}) and external (T_{ext}) ambient temperatures applying the average method in accordance to ISO 9869 (BSI, 2014, p8). Equation 1 results in a U-value which derives from the mean (time averaged) heat flow in Watts per meter squared (W/m^2) divided by the mean difference between the inside and outside temperatures (Li et al., 2015).

$$U = \frac{\sum_{i=1}^{n} Q_{in.i}}{\sum_{i=1}^{n}(T_{in.i} - T_{ext.i})} \qquad \text{Equation 1}$$

Baker (2011) argues that there are drawbacks to using internal and external air temperatures and recommends using surface temperatures in conjunction with external (r_{ext}=0.04 m^{2}k/W) and internal (r_{int}=0.13 m^{2}k/W) surface resistances as shown in Equation 2.

$$U_i = \frac{1}{\frac{\sum_0^{i=t} T_{si} - T_{se}}{\sum_0^{i=t} Q_i} + r_{int} + r_{ext}} \qquad \text{Equation 2}$$

In some cases, the external surface temperature (T_{se}) is not possible to obtain, therefore it is substituted by the external ambient temperature (T_{ext}) and removing r_{ext} as shown in Equation 3.

$$U_i = \frac{1}{\frac{\sum_0^{i=t} T_{si} - T_{ext}}{\sum_0^{i=t} Q_i} + r_{int}} \qquad \text{Equation 3}$$

In order to account for the heat flux sensor's thermal resistance, a correction factor is applied to the calculation of <6.25x103 m^{2}k/W resulting in a final U-value.

The composition of the wall systems follows a rational understanding of the duration of monitoring. Light elements with a thermal capacitance less than 20 kJ/(m^{2}K) require short periods of 3 to 5 nights whilst heavier elements with more than 20 kJ/(m^{2}K) require more than 72 hours until obtaining 24hrs of isentropic U-value reaching ±5% of a final reading. A study by Gaspar et al. (2018) concluded that larger accuracy is achieved with much higher temperature differences (Δt), above 19˚C during a 72 hour test, if not assured tests duration should be extended.

Ficco et al. (2015) claim that despite the simplicity of the measurements, there are "metrological and practical issues" that lead to errors and uncertainties.

Meng et al. (2015) explore accuracy in the tests by placing the HFM’s in different locations, angles and at thermal bridges (mortar joints) with varying results. Rasooli et al. (2016) study the accuracy depending on the time of deployment of equipment and explored through various error techniques that differ on results and magnitude of error. Further information is found in Appendix 3b.

2.2.1.3. Air tightness testing

Air tightness or air permeability testing, measures the uncontrolled ventilation (infiltration) heat loss through the envelope of a building. Sherman and Chan (2004) define it as a “fundamental building property” that impacts building performance and dependent on the quality of the envelope as it measures the movement of air through gaps, cracks and “adventitious openings in the building envelope” (idem, 2004). Studies by Mortensen and Bergsøe (2017) describe air tightness as the movement of air through an element once it is subject to air pressure differentials impacting on the internal conditions of the building by enabling external air (hot or cold) enter. Gillott et al. (2016) claim that air infiltration contributes to one third of heat losses through the building envelope.

In the UK, standards set by BS EN (2001) and best practice set by CIBSE (2000) form much of the framework for conducting air permeability testing. The Airtightness Testing and Measurement Association (ATTMA) produced an industry best practice guide for the measurement procedure (ATTMA, 2010) Liddament (2012) explains that air permeability testing indicates an airflow rate in m^3/h for each m^2 of envelope area at a pressure rate of 50 Pascals (50 Pa). The Energy Saving Trust (2007) through its case studies of air permeability testing explain that a fundamental part of a new airtight building is the dwellings air barrier. It concludes that careful attention should be taken in ensuring that the air barrier is not perforated and should wrap around the dwelling envelope.

Measurements are obtained by doing a blower-door test where all openable ventilation outlets are closed and sealed, this includes window trickle vents, ventilation flues and other extractor fans (Korpi et al., 2004). A fan is fitted where the blower-door canvas is placed, usually a main door to the property (ATTMA, 2010).The conditions in which tests are performed depend on the outside wind speed influencing pressure readings. A study conducted by Wójcik and Kosinski

(2015) tested the impact of wind driven elevations on internal partitions; it concluded that despite achieving good air tightness, heat loss transfer coefficients remain high, leading to high demand of energy. Tests should be performed during calm, light air and light breeze conditions according to the Beaufort scale for wind force indication (BS EN, 2001, p 23). Prior to testing, building exposed areas (floor, roof and wall) are calculated and used in air permeability results at 50 Pascals building pressure, see Appendix 3a. If air exchanges (ACH) are required, the building volume is used instead (Carrié and Wouters, 2012).

As mentioned by Pan (2010) to account for accuracy of the tests performed, the correlation coefficient (r^2) as described by ATTMA, (2010) is applied as a measure of the strength of association between the measured values of building pressure ($\Delta\rho$) and the fan flow pressure. It is represented as a number curve fitting approximations available to produce a line of best-fit between the points. For a test to be valid and an accurate representation of the buildings air leakage, its r^2 value should be greater than 0.980. The air flow exponent (n) is also representative of accuracy and a good indicator of the type of leakage experienced across the envelope. It is used to describe the air flow regime through the orifice and should be in the range of 0.5 and 1.0 (ATTMA, 2010). Values close to 1.0 indicate a laminar flow through the dwelling, observed in more air-tight structures whilst values close to 0.5 show fully developed turbulent flow with air flow through large holes and indicate a less air tight envelope.

Uncertainty can be estimated by derived quantities and an estimate of the confidence intervals of the data and results using C and n values. However, this does not show the uncertainty of the measurement. Typically, the uncertainty of reference values ranges between 5% and 10% and it is estimated using error propagation calculation. Environmental conditions can give an estimation of uncertainty, where calm wind conditions will be less than ±15% and in windy conditions it can reach ±40% (BS EN, 2001).

In work developed by Sherman and Palmiter, (1995) uncertainty for measuring air tightness using fan pressurisation is introduced by exploring the uncertainties of the air flow and pressure measurements. It explores the precision and bias associated with air pressurisation tests. Carrié and Wouters, (2012) also refer to uncertainty appearing through derived quantities such as: building preparation, reference values accuracy, sampling assumptions, equipment uncertainty and software errors and wind and stack effects, reference pressures and analysis methods.

Erhorn-Kluttig et al. (2009) and Gillott et al. (2016) studied the different levels of air leakage in new homes across the EU Member States and the USA depending on the buildings ventilation strategy. For naturally ventilated buildings, Belgium and Sweden required the lowest level of air change rate of 3.0 ach@50Pa. Countries such as France, UK and USA were less lenient stating a result above 7.0 ach@50Pa. The distribution of results of air leakage is strongly related to the design of the elements and their integration and assembly as a completed building. A study by Korpi et al. (2004) analyses the relationship between different characteristics such as; ventilation system, year of construction, insulation type, construction type and groupings between these. It found that the highest values of air change rate were the timber dwellings built on-site using mineral wool (4.6 ach@50Pa), compared with prefabricated and pre-cut timber homes 3.8 and 2.6 ach@50Pa respectively. It also concluded that the naturally ventilated homes presented the highest results compared with those with mechanical supply and exhaust ventilation, 5.0 ach@50Pa and 3.6 ach@50Pa respectively.

Finally, in a study of non-Passivhaus and Passivhaus built dwellings by Gupta and Kotopouleas (2018) gaps in energy demand are shown being strongly related to building envelope performance and in-situ tests are encouraged to indicate the as-built conditions of the buildings. Sinnott and Dyer (2012) argue that quality of workmanship at the construction stage plays a leading role in achieving low levels of air leakage and that rigorous inspection throughout the construction stage is critical in order to maintain efficiency.

2.2.1.4. Infra-red thermography

Infra-red thermography (IRT) is both a quantitative and qualitative non-destructive test carried out which visually represents and detects surface temperature variations of building components using a thermal imaging camera (Taylor et al., 2012). The tests follow the criteria set by BS EN 13187: 1999 (BS

EN, 1999) by setting out survey methods and evaluation techniques. Taylor et al., (2013) describes it as a tool that identifies building defects by highlighting areas where conductance of heat is intensified by the lack of insulation and thermal bridging. The interpretation of IRT images (thermograms) require a good understanding of heat transfer principles, thermodynamics, optics and electronics (Balaras and Argiriou, 2002). Hart, (1990)explains that for a test it is necessary to ensure the control of internal and external conditions by ensuring a temperature gradient of >10°C between the interior and the exterior ambient temperatures. Additionally, Lu and Memari (2019) explain that external weather conditions also determine a correct evaluation of building components by ensuring they remain dry in the absence of precipitation and ensuring building surfaces are not damp or have traces of moisture. Also, of importance are external wind speeds, which should remain <2m/s as its influence can distort images and readings. Surveys are typically conducted with the absence of solar radiation at least four hours after dusk or before sunrise (Guerra-Santin and Tweed, 2015).

Other applications of thermography include identifying delamination of tapes, poor detailing and missing seals around airtight envelopes by evidencing uncontrolled air leakage paths ways (Lo & Choi, 2004). Similarly, O'Grady et al., (2018a) O'Grady et al. (2018) and Fox et al. (2014) focus on the evaluation relationship between qualitative and quantitative thermograms of conduction losses and thermal bridging in junctions and around doors and windows.

2.2.1.5. Whole house heating

As described by Latif et al. (2016) whole house heating or co-heating is a method of determining the in-situ whole building energy performance and it involves a quasi-steady state approach applying envelope performance evaluations and detailed energy consumption demand over set periods. First developed by Farmer et al. (2016) it involves continually heating a building to temperatures above 25 °C for a period of between 7 to 21 days. A large focus is made on measuring the energy demand required to maintain the set ambient temperatures over the period of testing to produce the buildings daily heat input (DHI) in Watts. The measured DHI can be plotted against the daily difference in temperature to calculate the daily heat loss coefficient (HLC) of the building (Gupta and Kotopouleas, 2018). This method of measuring heat loss through the building envelope relies on the thermal transmittance of the components and the reduced air permeability as these to define the envelope and ventilation losses that influence temperature decline.

In order to make this evaluation buildings are evaluated considering solar radiation corrections and during a heating season to obtain reliable temperature differences between the inside and outside building surfaces (Jack et al., 2018). The UK's compliance energy modelling tool SAP, make reference to the use of HLC as a useful metric to determine levels of heat loss between dwellings (Johnston et al., 2014). Jack et al. (2018) have clearly indicated that conducting a co-heating tests requires dwellings to be un-occupied to minimise the influence of internal gains and that external gains from solar radiation are measured accurately corresponding as closely to the evaluated building.

A study by Butler and Dengel (2013) for the NHBC Foundation outlines the results from co-heating tests to understand the methods accuracy and wider application. The results showed that after analysing results from coheating tests of the same dwelling by different project partners, that there are a variety of methods adopted which produced many variations in the analysis of results. Robust execution of co-heating methods can obtain accuracies of 8-10% and a standardised methodology should be adopted to accurately measure the as-designed and as-built differences contributing to the reasons for the performance gap in buildings energy demand. Additionally, it was concluded that the impact of solar radiation creates the largest dispersion between results affecting accuracy and repeatability. The biggest factor affecting accuracy was determined by the length of time external weather conditions were measured as solar aperture can be achieved more efficiently with a large spread or range in external temperatures and solar radiation values. The shorter the test duration the less accurate results were. This led to conclude that night-time results largely increase accuracy of results as the influence of solar radiation was negligible and factors were not applied to correct the readings. Also explored were the impacts of light weight and heavy weight structures and the influence of thermal inertia and mass, however this study explains that more samples of these are needed.

2.2.1.6. Building energy monitoring

The consumption of energy is directly related to the composition of the building users and the efficiency of the building envelope and delivery of energy through HVAC systems (O'Leary et al., 2015, p4). Operational energy concerns the controlled and un-controlled energy demand in buildings. Controlled type such as heating, cooling, lighting, ventilation, hot water and auxiliary sources (pumps and fans) are those that can be operated by the user and used in energy calculations (D'Agostino, 2015). A study by Firth et al. (2008) explains some of the trends in the variants of un-controlled energy demand such as plugged-in appliances which cannot easily be estimated for its intricacies and close relationship to hours of use by an occupant. Equally as important is the embodied energy of buildings, often not considered in whole building performance analysis. A study by Koezjakov et al. (2018) explores the relationship between operational and embodied energy demand; it concludes that from the total lifespan of a building, embodied energy contributes 10-12% in standard dwellings while a 36%-46% in energy efficient ones. Shadram and Mukkavaara (2019) also study the trade-off between embodied and operational energy through design optimal energy efficient measures such as building shape and other design choices. The investigation concludes that designers and developers chose building shape based on occupant requirements but neglect the benefits of reduced energy use and embodied energy through optimisation of shape.

In order to address the growing concerns over the difference between the theoretical calculations of energy and the as-built occupied buildings, better known as "the performance gap", the Chartered Institution of Building Services Engineers (CIBSE) produced the Technical Memorandum (TM) 54 guidance. It points out the methods associated to measuring operational energy at the design stage and to bridge the gap mentioned (CIBSE, 2013). However, for the monitoring and assessment of energy in as-built buildings, TM22 publication (CIBSE, 2006a) highlights the best methods for accurate building energy measurement. Guidance in TM39 (CIBSE, 2009) describes the best practice approach to assess and report using standard energy suppliers metering apparatus and also using more articulated devices for sub-metering and inform users of consumption. Guerra-Santin et al. (2013) discuss the uses of monitoring equipment, particularly for low carbon technologies to account for performance and comparison with theoretical estimates.

2.2.1.7. In house displays of energy

A simple approach to monitoring and measuring energy demand over periods of occupation is the use of alternative measuring methods, such as those provided by third party measuring devices, most offered by energy suppliers. Linked with the announcement of the UK Department for Energy and Climate Change (DECC) of its intention to roll out the installation of “smart meters”, the use of in-house displays (IHD) of real time demand of energy act as the interface between the fuel meters (natural gas or electricity) and the monitoring of hourly power consumption (Ofgem, 2004). Often linked to the behaviour of users to energy demand, household IHD energy meters can be a short-lived device for changing occupant’s response to energy consumption. Hormazabal et al. (2012) studied the impact energy meters with real time display have on the behaviour of occupants over energy demand. In a study by Currie et al. (2011) and Stinson et al. (2015) during a three-year field study between subjects, a sample of dwellings with IHD’s managed to consume 27% less gas compared with a control group without an IHD. Likewise, electricity consumption where a reduction of 21% was identified. However, the study concludes that the visual engagement was vital in the reduction of energy. On the other hand, BEAMA, (2010)argue that IHD’s have the potential to save energy through demand management and reduced peak demands.

2.2.1.8. Meter readings and interpretation

For verification purposes, metered energy during occupation accounts for the utility delivered energy for a given period and fuel type. TM22 by CIBSE (2006), describes the need for reliable reconciliation of energy by other means, as that obtained with IHD units. Loss of signal and accuracy of the data stored is commonly experienced with such IHD’s, thus this reconciliation is aimed to act as a verification and best practice approach between timelines. The Energy Saving Trust (EST, 2003) reported a methodology on the verification of space heating energy demand (natural gas) of newly insulated homes. It included the annotation of dwelling characteristics as a first approach: the dwelling location, built form and number of rooms, tenure, and household type. As a next step it took the date of meter readings before retrofits took place followed by date of meter readings after the measures took place. Methodologies adopted by Aksoezen et al., (2015); Bedir et al., (2013) and Majcen et al., (2013) use metered data by comparing readings between timelines to account for energy consumed.

Sub metering is particularly useful as it provides energy demand for specific zones within a building for different uses and occupants. Often ignored is sub metering or segregation of energy by the actual use. This is the case of heat energy; subdivided into energy for space heating and water heating, including energy for cooking. TM46 CIBSE, (2008) recommends separating energy uses to define and use adequate benchmark categories. For example, a measure of energy efficiency and dwelling performance is the heated floor are normalised energy demand per year (kWh/m^2/yr) of space heating often required by standards such as the Scottish Building Standards, Section 7, Sustainability (SBS, 2011). It requires dwellings aligned to the Silver and Gold labels to achieve 40 kWh/m^2/yr and 30 kWh/m^2/yr respectively. Also required to fulfil the Passivhaus criteria is 15 kWh/m^2/yr (Feist, 2015; Feist et al., 2001; Müller and Berker, 2013; Schnieders and Hermelink, 2006).

2.2.1.9. Heat energy segregation

Meter readings of the energy use, if not sub metered, include total delivered energy accounted by the same fuel. For benchmarking and verification purposes, energy demand requires to be separated according to the end use such as for space or water heating. A methodology proposed by the (BRE, 2014) in the compliance energy demand calculations for existing buildings (RdSAP), suggests that when conducting dwelling surveys of existing buildings in combination with occupant surveys, it is possible to re-calculate the actual energy demand for water heating. The calculation process described combines actual occupant demographic data together with hot water usage in baths, showers and Kitchens (Guerra-Santin et al., 2009). To account for cooking energy, Guerra-Santin and Itard, (2010) estimate that it represents 5% of the total metered heat energy. However, Wingfield et al., (2009) consider 0.5 kWh/ day for cooking.

The calculations are useful as they produce an actual account for water heating which can then be subtracted from the total yearly energy demand of the dwelling. This segregation between cooking, space and water heating energy demand permits a streamlined comparison between benchmarks. In a study by Biaou and Bernier, (2005), different water heating technologies are modelled to provide an account for their efficiency and alignment to the nZEB criteria set by the EPBD. It concludes that solar thermal collectors provide a more energy efficient solution particularly if combined with a Solar PV powered pump. As mentioned by Firth et al., (2010) average water heating accounts for 20% of total energy demand in dwellings. Space heating can account for 53% of the total demand and cooking another 5%.

2.2.1.10. Indoor and outdoor ambient conditions

The use of indoor and outdoor ambient conditions in calculations and actual performance evaluation of buildings depends on the adequate sourcing or logging of indoor air quality and outdoor weather data. It impacts directly on the requirements for comfort conditions responding to set point temperatures and other indoor air quality levels with an influence on occupant thermal comfort and energy demand. The EU Directive 2018/2002 (EU Parliament, 2018) mentions that there is a positive impact on air quality from increased energy efficiency as well as its capacity to reduce expenditure in heating fuel. Monitoring indoor conditions; such as temperature and humidity or other ambient air quality factors (CO_2, dew point, NOx, PM10, PM2.5 etc.) have the potential to improve thermal performance by creating a better controlled dwelling with stable conditions (Refaee and Altan, 2012). A recent study by Poortinga et al. (2018) explores the impacts of energy efficiency on internal conditions particularly in fuel-poor housing where-by setting indoor air temperature between 18-24°C reduces health related problems by 37%. However, there are studies that indicate that as dwellings become more energy efficient, there is a higher dependence on good ventilation strategies that contribute to better occupant health(Ormandy and Ezratty, 2016). Sharpe et al. (2015) suggest that a sample of indoor conditions such as, air temperature (°C), relative humidity (%RH) and carbon dioxide (CO_2) can be taken every 5-minute intervals in three rooms of the dwelling. Such study concludes that interior conditions are equally affected by construction changes and differences between as-designed and as-built dwelling performance. A study by Morgan et al. (2017) on overheating in Scottish dwellings suggests that measurements are represented in two ways; (1) as measured using quantitative data of recorded temperatures and, (2) as a matrix of overheating factors based on occupancy factors and measurements. For longer periods of study Asumadu-Sakyi et al. (2019) suggest a temperature and relative humidity recording interval of 30 minutes in a study of the relationship between indoor and outdoor temperatures. It concluded that for every 1°C increase in outdoor temperature, an effect of 0.4°C increase in indoor temperatures was recorded. An analysis of living rooms in Passivhaus dwellings in Austria by Rojas et al. (2016) showed that increased temperatures and low air permeability in dwellings had a correlation with the ventilation system employed and relative humidity levels.

Outdoor conditions are obtained by a localised weather station or from amateur citizen weather stations available online. Most professionally deployed weather stations follow the good practice guide suggested by the World Meteorological Organisation (WMO) in their “Guide to Meteorological Instruments and Methods of Observation” (WMO, 2018). A study by Jenkins, (2014) between different citizen weather stations shows that the temperature recordings have a considerable scatter and a poor agreement between them, however it is difficult to conclude on the reasons as it depends on sensor accuracy. The comparison between relative humidity readings is much better, as it was taken during the night-time and it showed an offset of only 3%RH. Overall, Bell et al. (2015) and Begeš et al. (2015) argue that weather station data can provide some instrument biases by errors attached to them, therefore its data should be used with caution.

The use of recorded and quoted baseline temperature in energy related studies is fundamental for the prediction and understanding of the thermal performance of buildings. For the prediction of degree day data, the use of internal and external temperature readings is used to set a baseline temperature (CIBSE, 2008). Although the set point temperature is commonly used for predictions, as in studies by Delghust et al. (2015), Clarke et al. (2004) and van den Brom et al. (2018) it is true that in real-life situations the adaptive comfort method is more representative, particularly in households that adjust and accustom themselves to a temperature that typically responds to the conditions of their dwelling. A study by Nicol (2017) used the adaptive temperature method in several dwellings and locations arriving to the conclusion that the use of mechanical systems in dwelling was a good way for occupiers to adjust the indoor conditions to their own comfort level and lifestyles. The study suggests that the use of set indoor temperatures in modelling or best practice in dwellings are inappropriate and should be more flexible to suit the particular needs of each occupier. Such study also suggests that these temperature acclimating can have a great influence on energy demand. There are also ways to combine set point temperatures and the adaptive thermal comfort method, such as the work done by Sánchez-garcía et al. (2019) that combines both present and future scenarios to predict the impacts buildings have from climate change. It concluded that adaptation and resilience to climate change often leads to higher energy demand but are required to obtain more realistic predictions of buildings performance. Work by Nicol and Humphreys (2010) also conclude that indoor comfort is directly related to outdoor temperature and that adaptive comfort responds to occupants and their particular thermal circumstances.

Internal heat gains from human activities and equipment/ appliance use, as well as latent sources from showering and cooking are vital in determining the comfort temperatures in a dwelling as well as the thermal load and useful energy demand. Evidence from a study by Elsland et al. (2014) reveals that internal heat gains are underestimated when calculating energy demand particularly when comparing steady state and dynamic energy demand calculations and models; a 10-15% contribution can differ between the two methods and temperature set points particularly in energy efficient designed dwellings. The effects of occupants and the heat contribution is analysed by Blight and Coley (2013a). It analysed dwellings designed using the Passive house method by applying a regression equation that estimated space heating demand based on occupancy; it concluded that in general these are less sensitive to behaviour and occupancy than anticipated.

The impact of internal gains are calculated and used to determine baseline temperatures for degree day data analysis linked to estimated energy demand (CIBSE, 2006b; De Rosa et al., 2014a). Of particular concern is the degree of impact at various times in the day linked to occupancy and appliance use which in real life situations is not constant and determined by occupant occupancy patterns (Aras and Aras, 2004; Moreci et al., 2016; Woods and Fuller, 2014).

2.2.2. Qualitative evaluations

Qualitative testing involves observational methods that tend to produce data that are stated in prose or textual forms (Hentschel 1999). Often referred to as contextual research, it includes ethnographic techniques, such as participant observation, interviews and participatory tools that are often group-based and visual techniques (Gupta & Chandiwala 2010 & Stevenson & Williams 2007).

2.2.2.1. Post occupancy evaluations and the Gap in performance

Post occupancy evaluations (POE) involve both quantitative and qualitative studies of the post-implementation reviews (PIR) set out by the British Standard 8536-2:2016 (BSI, 2016). It outlines that PIR's should be "undertaken at prescribed intervals during a defined period of extended aftercare" recording the "lessons learned and stored in an asset information model" and later available to other building stakeholders. The PIR's form part of the work stages that a building should undertake: part 6 of the "Hand over and Close-out" or training users, operators team and handover members on how to use the building and part 7, "Operation and End of life" involving steady state operations, aftercare and linking results with benchmarking and lessons learnt. Stevenson, (2019) argues there is little the building industry is doing to implement POE's into practice and although they are mentioned in the RIBA Plan of Works stage 7 (RIBA, 2013), UK Government fails to enforce it, including a lack of engagement from industry.

POE's are stringently linked to the study of the performance of buildings but as Pretlove and Kade (2016) argue, it is also linked to occupant behaviour. The studies involve detailed evaluations of services, envelope performance and occupant led operation that influence the demand of energy in buildings. The POE's investigate the as-built conditions of a building once operated and can do so through building performance evaluations (BPE) and occupant evaluations involving questionnaires and surveys. Often the outcomes of the evaluations reveal a gap in performance defined as the difference between the as-designed assumptions and expectations and the as-built actual performance affecting energy demand, in some cases exceeding by a factor of three (Gupta et al., 2018 and Kampelis et al., 2017).

A recent study by Lambie et al. (2017) reveals that there is potential for bridging the gap in predicting performance by using measured temperature data from similar buildings located nearby to create in-situ temperature profiles instead of mean values from compliance models. Also revealing are the lessons learnt from envelope performance monitoring; for example, actual air permeability and thermal transmission in-situ results. Fedoruk et al. (2015) in their publication about "Learning from failure…" show that having building energy monitoring results gives a better understanding of how services operate at critical periods, hence reducing performance gap. Work by (Alencastro et al., 2018) de Wilde (2014) outlines three types of gap in performance differences; (1) between prediction modelling and measurements; (2) between input parameters and output parameters and (3) between prediction and display certificates such as energy performance certificates (EPC's). Differences in certificates is explored by Majcen et al. (2013) in a large study involving standard parameters and theoretical fuel demand, concluding that the theoretical values used are often quoted by government reports with many discrepancies creating doubts over the accuracy of figures. A study by Stevenson and Leaman, (2010) revealed that in housing projects there is little evidence of POE and gap in performance studies compared to non-domestic buildings. One reason is the lack of a representative sample size with adequate access to conduct the studies. Similarities on the constrains of a sample size and a gap in performance are evident in a study by Johnston et al. (2014). It reveals even in newly build dwellings there can be a performance gap of 100% and suggests that good detailed design with a high-quality control during construction can lower the gap.

2.2.2.2. Occupant surveys

A method of revealing the more qualitative aspects of buildings is by understanding the perceptions of the building users and operators. A study by Gill et al. (2010) monitored the performance of dwellings by using comfort and satisfaction surveys of users. It created a method of assessing behaviour through the use of face-to-face interviews, revealing high and low energy users. However, it concludes that the “human factor” is important when considering low-energy dwellings. Guerra-Santin et al. (2009) suggest that physical building characteristics contribute a 42% variation of consumption whereas occupant led characteristics only 4.2%. However, it concludes by saying that in practice occupant influence can be larger. Further analysis by Guerra-Santin and Itard (2010) reveal that there are certain characteristics that determine behaviour and energy use, such as; occupied hours, temperature control and lifestyle. Stevenson and Leaman (2010) argue that it is often the occupant factors and lifestyles that influence high energy demand and often occupants are un-aware of the control systems inside new low-energy homes. A lack of training; starting through commissioning stages on to occupant operative inductions is at fault.

Gupta and Chandiwala (2010) developed short- and long-term occupant feedback techniques that influence energy use. It revealed wide gaps between theoretical and as-built energy demand, poor indoor air quality among other problems. The techniques first determined occupant numbers in each dwelling, their age and occupancy patterns through various means such as questionnaires at set points of the analysis, diaries, open-ended semi-structured interviews (long and short term), activity log sheets, heating schedule diary, thermal comfort diary, appliance energy usage questionnaire, user behaviour through observations, occupant video diaries and focus groups.

2.3. Energy prediction tools and software

2.3.1. Compliance and steady state models

The current UK building compliance energy demand calculation models are based on the early versions of the BREDEM models developed by the Building Research Establishment (BRE) (Uglow, 1981). Based on energy monitoring of low-energy dwellings between the 1970’s and 1980’s (Reason and Clarke, 2008, p 5), the steady state calculations used simple heat balance equations, considering heat loss and heat gains to assume the space heating requirements to set temperatures (Shorrock and Henderson, 1990). Since the introduction of the Energy Performance of Buildings Directive (EPBD), European Directive 2002/91/EC (Popescu et al., 2012 and Anderson, 2014), in 2002, each Member State is required to have a calculation method of energy performance of buildings delivering energy performance certificates (EPC). In the UK the Standard Assessment Procedure (SAP) for dwellings and the Simplified Building Energy Model (SBEM) for non-domestic buildings were introduced, based on BREDEM to calculate; space and water heating, ventilation (mechanical and natural), lighting, auxiliary needs and renewable energy systems. The software calculates energy requirements converted into a dwelling emission rate (DER) of normalised annual carbon emissions. Regulations require the DER to be lower than the target emission rate (TER) obtained from a notional building of similar dimensions. Kelly et al. (2012) in a review of the SAP model, state that there are many gaps in the adequate prediction of energy demand and that the model instead of calculating energy efficiency, shows a cost-effective performance of a building without providing the real impact of CO_2 emissions.

2.3.2. Heat loss coefficient

A fundamental part of the calculation are considerations of the heat loss coefficient (HLC), also known as heat-transfer coefficient (HTC). The relationship considers the envelope heat loss of components U-value and thermal bridging and the ventilation heat loss from infiltration. It also considers heat loss from mechanical ventilation systems as a function of its efficiency to supply and extract air. Johnston et al. (2014) describe the HLC, measured in Watts per Kelvin (W/K) using Equation 4 below:

$$Q + R.S = (\sum U * A + Cv) * \Delta T \qquad \text{Equation 4}$$

Where:

Q: total power input into the dwelling (W)

R: the solar aperture of the dwelling (m^2)

S: the total amount of south-facing solar radiation (W/m^2)

$\sum U*A$: total fabric heat loss (W/K)

C_v: ventilation heat loss (W/K)

ΔT: temperature difference (K or ˚C)

Central to the calculation are the heat-transfer coefficient results from testing. A study by Jack et al. (2018) reveals that HLC measurements provide a ±8% accuracy and can be used to show the gap in performance between the compliance results and the actual as built performance. A validation study of in-situ tests of HLC by Butler and Dengel (2013) show that when compared with the SAP calculated values there can be a maximum difference of 17%. However, the effects of orientation and solar radiation increase the uncertainty of the results.

2.3.3. Degree day calculations

Linked to the prediction of energy demand is the use of degree day data to estimate energy performance considering set point indoor temperatures and the impact of climatic data (De Rosa et al., 2014b). Degree day data can be a powerful way of analysing weather dependent energy demand, but equally it can identify trends in energy performance, identify changes in the operation of a building and can be a simple tool for building managers to quantify future energy demand (Carbon Trust, 2012). In a study by Belcher et al. (2005) degree day data was useful to predict future design weather data using outdoor temperatures.

2.3.3.1. Heating and cooling degree day calculation

Degree days are calculated considering the time in days over a whole year when temperatures fall below a given set point internal temperature (˚C), weighted by the number of degrees below the threshold (Belcher et al., 2005). CIBSE (2006b) describe degree day calculation as one that is the “summation of temperature differences over time, and hence they capture both extremity and duration of outdoor temperatures”. The temperature differences are dependent on the internal reference temperature and the external temperature for a given season of the year. Assuming the internal conditions are required to be similar over the occupied time, the variation comes from the external conditions considering the location of the building. The reference temperature or baseline temperature varies according to thermal inertia, and sensible gains (internal, solar, etc.). When the external temperature is below the baseline temperature, the building requires energy to maintain the required conditions, hence providing heating or cooling to the internal space (Aras and Aras, 2004, Bhatnagar et al., 2018).

The baseline temperature employed is essential in the adequate calculation of degree day data. However, the difficulty is in calculating casual and sensible gains that vary throughout the day and between periods of occupation making the calculation challenging (CIBSE, 2006b). Equally important are the external temperatures which can vary between seasons and years with varying uncontrolled periods of high and low temperatures, now more relevant with climate change (Christenson et al., 2006). For a simplified set of assumptions, baseline temperature is calculated using recorded mean hourly internal set point temperature and gains temperature as shown in Equation 5.

$$\theta_b = \theta_i - \theta_S \qquad \text{Equation 5}$$

Where:

θ_b: Base temperature (˚C)

θ_i: Hourly recorded internal temperature (°C)

θ_S: Sensible heat gains to building (K)

In most parts of the UK a traditional baseline temperature is employed of 15.5˚C, however this considers that internal temperatures have a set point of 19˚C with a mean calculation of sensible gains impacting approximately 3.5˚C (BRECSU, 1993). Woods and Fuller (2014) explore the impact of errors in the base temperature calculation, particularly for economic energy estimates. They conclude that fixed base temperatures can have a large discrepancy resulting on yearly heating degree days (HDD) and cooling degree days (CDD) due to the large error identified. To consider intermittently occupied buildings Equation 6 below is used to calculate the base temperature.

$$T_b = 24h\ T_i - \left(\frac{g_d}{HLC}\right) \qquad \text{Equation 6}$$

Where:

T_b: Baseline temperature in °C

$24h\ Ti$: 24 hour mean internal temperature in °C

g_d: Mean daily gains in Watts (W)

HLC: Heat loss coefficient (W/K) based on calculations in §2.3.2

The calculation of degree days has been studied extensively using many methods. The Met office in the UK method uses daily maximum and minimum out door temperatures (Jenkins et al., 2009 and CIBSE, 2006b). Hitchin (1990) uses the factor method developed by using a simple calculation with mean monthly temperatures and the standard deviation throughout the month adding a location specific constant factor into the formula. However, the simplest method is the daily mean temperature which assumes that heating systems will only operate if outdoor temperatures fall below the base temperature, used extensively by the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) (ASHRAE, 2009). The difference between the indoor base and outdoor hourly temperatures are accumulated to estimate the degree-hours which are then divided by the hours in the day (Meng and Mourshed, 2017). Taking only positive differences into account, Equation 7 and 8 are given:

$$HDD_d = \frac{\sum_{i-1}^{24} \theta_b - \theta_{o,j}}{24} \qquad \text{Equation 7}$$

$$CDD_d = \frac{\sum_{i-1}^{24} \theta_b - \theta_{o,j}}{24} \qquad \text{Equation 8}$$

Where:

HDD_d: Heating degree day cumulative value

CDD_d: Cooling degree day cumulative value

$\sum_{j=1}^{24}$: Sum of hourly values

θ_b: Base temperature (˚C)

$\theta_{o,j}$: Outside temperature in a recorded hour (˚C)

Cooling degree baseline temperature calculation is complicated if the dwelling or building has a ventilation system. However, a simplified step-by-step method is proposed by CIBSE (2006b) and explained in Appendix 2a.

Finally, for reference between other locations and subsequent years of building occupation, cumulative monthly and annual degree days can then be used to further calculate predicted energy demand.

2.3.3.2. Energy demand prediction

Degree day data for estimating heating and cooling demand uses various techniques simplified by using location specific data sets and estimated building energy efficiency coefficients (Borah et al., 2015 and Mourshed, 2012). Fuel for heating derived from heating degree day data uses Equation 9 below.

$$F_{heating} = \frac{U' x\, D_d\, x\, t_h}{\eta_{hs}} \qquad \text{Equation 9}$$

Where:

$F_{heating}$: Fuel demand for heating (kWh)

U': overall heat loss coefficient (kW/K)

D_d: Heating Degree days

t_h: heating time in a day, assumed 24 hours if continuously heated

η_{hs}: heating system efficiency (factor, %)

Cooling energy demand and its fuel requirements contain added latent loads and system variations including solar gains analysis. The approach considers an energy balance on the cooling element, chiller energy consumption, heat rejection, fans and pumps and for efficiency the coefficient of performance (COP) (De Rosa et al., 2014a). Equation 10 is then adopted:

$$F_{chiller} = \frac{mC_p\, D_d}{COP} \qquad \text{Equation 10}$$

Where:

$F_{chiller}$: Fuel demand of chiller (kWh)

mC_p: Heat carrying capacity of air (kW/K)

D_d: Cooling degree day

COP: Coefficient of performance of chiller (factor, %)

2.3.4. Dynamic building energy simulations (DBES)

For a more representative building energy calculation at the design stage, building energy models require less assumptions on the model creation, resulting in credible building performance simulations. The steady state models and calculations rely on the use of assumed values that only account for building behaviour at one moment in time or at the very most a mean value over a given month. Although compliance models are based on in-situ tests and have been calibrated using in-situ results, they lack the dynamism and irregularity that occurs in real-life situations. To minimise the impacts of steady-state static modelling of energy the use, dynamic building energy simulations (DBES) are adopted to calculate energy demand to account for performance and optimisation of different scenarios and conditions. The best practice guide proposed by the CIBSE (2013) TM54 describes the building energy evaluation of steady-state models as well as the use of dynamic simulations. A study by Olofsson and Mahlia (2012) argues the effectiveness of reliable input parameters in DBES software and that they are increasingly being accepted in compliance and building regulation assessments and reviews. Patidar et al. (2012) make the case for dynamic simulations as a tool for estimating cooling demand and explain that it is capable to produce hourly cooling loads with an ability to allow different in input variables.

There are many studies that explore the potential of DBES as a tool for optimising energy performance of buildings. Clarke et al. (2012) describe the use of DBES as an integrated building performance simulation with varying input and output parameters. The geometrical attributes of the building are often sourced from architectural drawings and dimensions, however for further optimisation, different conditions are possible to achieve better performance results, such as window to wall ratio for solar gains and adequate illuminance levels, or the improvements of fixed and moving solar shading for overheating analysis. Moreover, a determinant factor in the gap in performance are the unpredictable and dynamic occupant behaviour in some buildings. This is explored fully by Cuerda and González (2017) who say that occupant presence in dwellings via a dynamic building simulation increases the accuracy of results. The study integrated actual occupant measurements to produce patterns of use or schedules, concluding in a better match with the actual energy demand and useful for optimisation proposals.

There are many types of software available in the market, some with more fixed parameters than others providing flexibility for modifying assumptions and add monitored data to calibrate and refine models. In the UK a popular open-source software is ESP-r, developed by The Energy Systems Research Unit (ESRU) at Strathclyde University, Glasgow, UK, used by Patidar et al. (2012b), Patidar et al. (2014), Clarke et al. (2012), Murphy et al. (2011) and Strachan et al. (2008). Also popular is the use of EnergyPlus, developed by the USA Department of Energy. Studies by Coakley et al. (2014a); Griffith et al. (2008); Jentsch et al. (2008); Mauro et al. (2015); Schwartz and Raslan (2013); Silva and Ghisi (2014) and Tian and de Wilde (2010) demonstrate the different input parameters and uses for modelling at the design stage with optimisation scenarios or modelling existing building optimisation scenarios. Also used are algorithmic models such as Matlab and the CARNOT dynamic state components and varying plug-ins and interlinking software, used by De Rosa et al. (2014b); Mauro et al. (2015), Herrera et al. (2017), and Olofsson and Mahlia (2012). A system also employed is provided by Integrated Energy Systems (IES) and its Virtual Environment that offers a user-friendly modifiable parameter dynamic model with the ability to generate simulations with modelled data for many parameters. Its geometry is three dimensional (3D) considering zonal conditioned spaces. It provides graphical outputs of indoor conditions, energy demand and carbon emissions (CIBSE, 2015, Coakley et al., 2016, Blight and Coley, 2013).

2.3.4.1. Integration of measured data

DBES models have the capacity to integrate measured data for the refinement or optimisation of the results. Existing literature on the use of varying measurements into the building model facilitate the calibration and validation with as-built parameters and conditions. Reddy (2006), provides a literature review of many methods and options available in most software to calibrate models with measured data. The data inserted from measured sources can “tune” a simplified model to match closely predicted energy with retrieved energy demand data. He explains that this approach allows for a more reliable identification of energy savings, increased confidence in monitoring and implementing measures. Also explored are the steps towards this calibration and its benefits, identified by Reddy and Maor (2006). A study by Coakley et al. (2014b) explores the current approaches to DBES calibration and use of monitored data. The study employs manual and automated calibration methods and highlights the uncertainty of them. A study by Menezes et al. (2012) explain that different models can use monitored and steady-state parameters to further lower the performance gap between as-designed and as-built. Wei et al. (2014) were able to retrieve occupant behaviour data to understand the influential drivers in modelling a building. The study creates two dominant factors, the building representation and operational conditions. One dominant factor is the use of measured indoor temperatures demonstrated in studies by Love (2008) and de Meester et al. (2013). Others use measured energy demand over a period of occupation to calibrate models. Dall’O’ et al. (2012) show that some of the energy requirements modelled were lower than the real requirements, however occupancy was not accounted for in this study.

2.3.4.2. Weather files

An important input parameter for calibration is the integration of measured weather conditions such as; air temperature, relative humidity, solar radiation, wind direction and speed and precipitation levels. Retrieved data from a weather station, configured and converted into a manageable DBES weather file can easily be added, studies by Hacker et al. (2009), Herrera et al. (2017) and Coakley et al. (2016) demonstrate this. A study by Bellia et al. (2015) retrieved weather files and compared the source of them for reliability and results of light exposure and dynamic daylight performance. It concluded that these can be reliable but more so if using annual and monthly exposures. Building simulations by Kočí et al. (2019) showed that using recent weather data in the simulations increases precision into energy calculations and compared against mean values of test reference years (TRY). A similar study by Lupato and Manzan (2019) compared actual weather with TRY data in an EnergyPlus simulation, resulting in decreased heating energy and increased cooling.

2.3.4.3. Uncertainty and sensitivity analysis

Within building simulations, it is important to realise that there is a level of uncertainty which requires care and attention before considering results as final. These include uncertainties in the physical ability, suitability of scenarios, design differences and the algorithms employed. Others include the uncertainty of performance of certain parameters, such as materials and services and to some extent, weather files and heat/ cooling mass transfer calculations (Silva and Ghisi, 2014 and Nik et al., 2012). Common uncertainty analysis, such as Monte-Carlo method uses a sampling method of multiple model simulations with random samples generated from different variables (Domínguez-Muñoz et al., 2010 and Gentle, 2003). Zhang and Brani (2005) explain how uncertainty can be devised by the Monte-Carlo method using uncertainties which involve probability distributions creating a randomly generated parameter for simulation. Such analysis is data driven and can be laborious and time consuming (Coakley et al., 2014). Coakley et al. (2016) explains that a sensitivity and uncertainty analysis involves the understanding of model input parameters and variables, the dependencies of those variables and influencing factors of any estimates that may impact the simulation. The process of a sensitivity analysis helps the calibration process until the simulations have met the criteria and are close to the assumed values of comparison (Delgarm et al., 2018). These stages of uncertainty can be performed to different aspects of the model, for example, building envelope parameters, building services, and other influencing parameters (weather, occupancy, etc.).

2.3.4.4. Error analysis

Measured parameters and the outputs of simulations during a sensitivity and uncertainty analysis can be evaluated through an error analysis acting as an assessment agreement between outputs (simulations) and measured data. A method that is often adopted is the Altman and Bland method which is based on the “quantification agreement between two quantitative measurements by studying the mean difference”. It proposes a simple analysis between mean differences to obtain an agreement interval and assess its alignment and uniformity (Vesna, 2009). However, this method is a good comparison of internal air temperature as it assesses the degree of closeness between readings. Various other techniques, such as energy demand are used that in combination can provide an assurance of the closeness of the simulations and subsequently used for optimisation.

To evaluate the models, the use of CV% is particularly important as it acts as a standardised measure of dispersion from the mean of the simulated data. Higher CV%, shows a greater dispersion around the mean (Kats et al., 2002). Also often adopted as an error analysis method between the measured and simulated data is coefficient of determination through linear regression and the Pearson (R^2) methods to determine the proportion of variation between the variables; values closer to 1 had less variation and were closer to the “line of best fit”. However, R^2 on its own is not advised for best fit and error analysis (de Wilde and Tian, 2010).

Often used is mean bias error (MBE). It is a good statistical indicator for evaluating simulations against actual measured data (Marini et al., 2016). It is a sum of errors between the measured and the simulated data, considered a non-dimensional bias measure (Coakley et al., 2014). It often is combined with normalized mean bias error (NMBE) as a percentage magnitude of the error; where positive values mean that the model under-predicts measured data and negative one means over-prediction (Burman et al., 2014). They are quantified as shown in Equation 11.

$$MBE\ (\%) = \frac{\sum_{i=1}^{Np}(m_i - S_i)}{\sum_{i=1}^{Np}(m_i)}\ x\ 100 \qquad \text{Equation 11}$$

Where:

m_i: Measured data points

S_i: Simulated data points

The above based on the model instance “*i*” and “N_p” considering each data point at the interval “*p*”, for instance $N_{monthly}$ = 12 and N_{hourly} = 8760. Normalised MBE (NMBE) calculated using Equation 12.

$$NMBE\ (\%) = \frac{\sum_{i=1}^{Np}(m_i - S_i)}{N_p\ x\ M_i}\ x\ 100 \qquad \text{Equation 12}$$

Where M_i is the mean of the measured data values during period N_p.

Also used is the determination of root mean squared error (RMSE) of the predicted mean and the coefficient of variation of root mean square root error (CVRMSE), both used to measure the uncertainty of the model and variability of the errors between measured and simulated values (Marini et al., 2016). Every interval difference is squared and then accumulated as sum of squares errors (SSE) they are then added and divided by the respective number of points of the mean squared error, shown in Equation 13.

$$RMSE(\%) = \frac{\sqrt{\left(\sum_{i=1}^{Np}(m_i - s_i)^2\right)}}{Np} \; x \; 100 \qquad \text{Equation 13}$$

Where m_i and S_i are the respective measured and simulated values and Np are the intervals for monthly (12) or hourly (8760) figures. Often the coefficient of variation (CV%) is used with RMSE therefore the result in Equation 13 is divided against the measured points.

As a last measure is the goodness of fit (GoF) that shows how well the simulated values fit the measured one, calculated with Equation 14.

$$GoF\ (\%) = \frac{\sqrt{2}}{2} \; x \; \sqrt{NMBE^2} + CVRMSE^2 \qquad \text{Equation 14}$$

Lower values mean lower dispersion; therefore, a closer match between the measured and simulated (Figueiredo et al., 2018). Studies by Q. Li et al., (2015) and Monetti et al. (2015) the application of the above error analysis for calibration of building energy models.

2.4. Climate change studies in building performance studies

The CO_2 emissions emitted since the last industrial revolution from man-made sources such as; agriculture, transport, manufacture, business and buildings are now recognised as the cause for the increased temperatures experienced throughout the globe (The Scottish Government, 2017). It is estimated that “global average temperatures have risen by nearly 0.8 ºC since the late 19th century, and rising at about 0.2 ºC/decade over the past 25 years” (Jenkins et al., 2009b). Considering these changes in climate, the Intergovernmental Panel on Climate Change (IPCC) proposed “illustrative” emission scenarios used to drive climate models to account for potential changes to future climate (Jentsch et al., 2013). IPCC through the work by Nakicenovi´c and Swart (2000) reported on the Special Report on Emissions Scenarios (SRES) proposing four main emission scenarios to indicate the extent of climate change projections that would describe pathways in which our climate would develop. The main scenarios were A1, A2, B1 and B2, with furthermore subdivisions of A1, adopted in the UK as AIF1, A1B and B1, see Figure 2-1 (Murphy et al., 2009). Explained by Jentsch et al. (2013), these three represent expected rise in global air temperatures relative to 1990 baselines; B1 a range of 1.1 -2.9˚C and for A1FI between 2.4-6.4˚C.

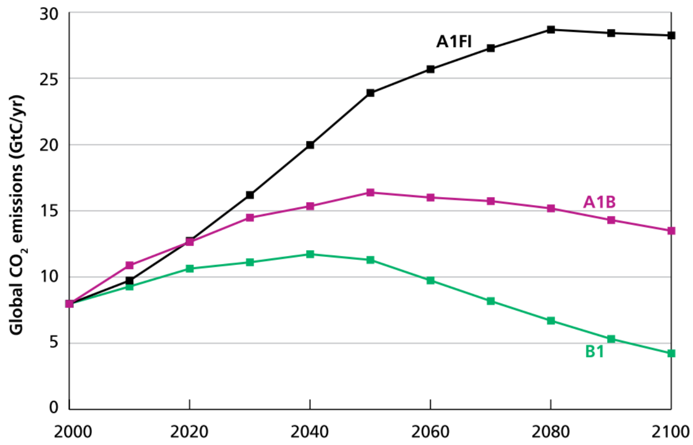


Figure 2-1: IPCC AR4 emission scenarios

Furthermore, at the recent IPCC's Fifth Assessment Report (AR5) (IPCC, 2015) scenarios show the Representative Concentration Pathways (RCP's) that are GHG emissions scenarios for the 21st century resulting in CO_2 equivalent atmospheric concentrations and categories, shown in Figure 2-2.

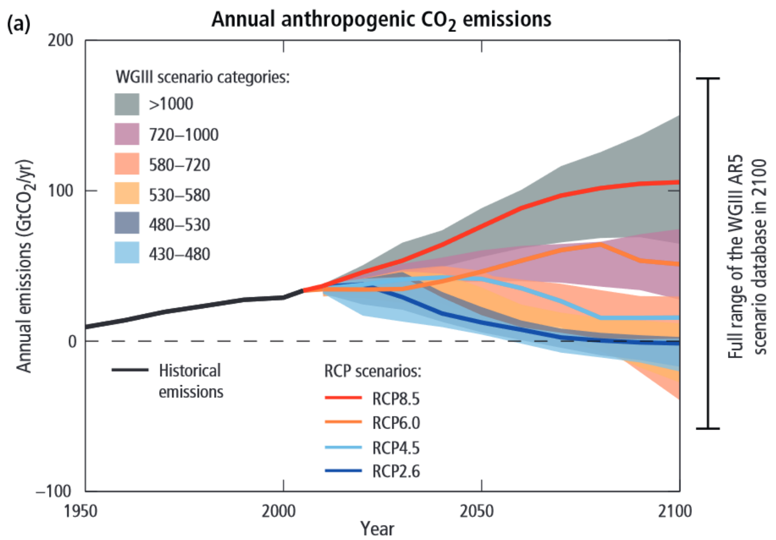


Figure 2-2: Emissions of carbon dioxide (CO_2) alone in the RCP's (lines)

Note on Figure 2-2: Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories used in WGIII (coloured areas show 5 to 95% range). The WGIII scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2-eq concentration levels (in ppm) in 2100. Source: (IPCC, 2015)

Each scenario corresponds to different pathways of interventions or business-as-usual (BAU) conditions. For example, the RCP4.5 would correspond to 4.5 W/m^2 of heating into the atmosphere following a downward projection and moderately aggressive mitigation. However, the BAU scenario of RCP8.5 would create devastating consequences to global atmospheric temperatures. (Dickinson and Brannon, 2016; Troup and Fannon, 2016).

2.4.1. The UK climate change strategy and adopted weather files

The IPCC AR4 assessment and projections (IPCC, 2007), provided a larger confidence on the effects of global climate change which would more than likely impact on the UK. For this reason, the UK proposed effective adaptation strategies to minimise consequences and maximise opportunities of climate change (Jenkins et al., 2009a). As a result, many studies have emerged on the topic regarding the threats and possible effects on the UK, primarily on; buildings, coastal regions, and increased energy for cooling during periods of "heatwaves" or increase rainfall creating a larger risk of flooding (Daggash and MacDowell, 2019; Elizondo et al., 2017; Gambhir et al., 2019; Gething, 2010; Leissner et al., 2015; Lockwood, 2013; Morgan et al., 2017; Wang et al., 2010).

The projections led to the creation of atmospheric models, first projected by the UK climate projections in 2002 (UKCP02) as "augmented global model results" produced by the Meteorological Office, Hadley Centre's models and they were the first to take into account the IPCC projections (IPCC, 2001). The climate model data of UKCP02 proposed weather data of the 21st century on how the UK would adapt and mitigate under several scenarios. It first achieved this by a process of "Morphing" historical weather data into future time frames based on the IPCC projections. A study by Jentsch et al. (2013) explains how the UKCP02 climate scenarios conformed of 50km grid spacing during three time frames (2020's, 2050's and 2080's) using four CO_2 scenarios. Belcher et al. (2005) describes various methods of constructing weather data from future projections and climate scenarios; the first an "analogue scenario" and another by global circulation models. The latter can be done by varying methods such as; dynamic downscaling, stochastic weather generation, interpolation and by morphing or time series adjustments.

Furthermore, based on the projections by IPCC's Fifth Assessment Report (AR5), a new method and projections strategy was proposed that took into account uncertainty due to natural variability in the climate system (Jenkins et al., 2009a). The UKCP09 climate projections proposed future weather up to 2090 and for various probabilistic projections of climate change using the Weather Generator portal, a tool created by DEFRA to create weather files (Jones et al., 2009). The tool uses reference years of different locations in the UK at a 25km grid resolution for 2020's, 2030's, 2050's and 2080's time periods, under three scenarios; low, medium and high, see Figure 2-3 (Shamash et al., 2014).

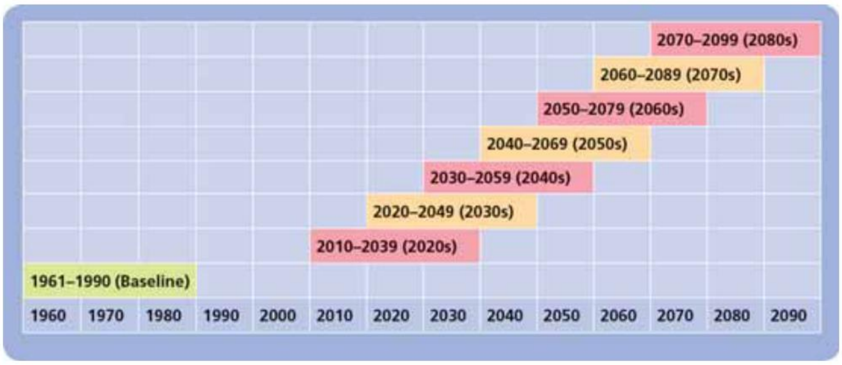


Figure 2-3: Time periods used in UKCP09

Carbon emission uncertainty was simplified in the UKCP09 methodology taking the IPCC projection into three main scenarios; A1FI regarded as a high emission, A1B medium emission and B1 as the lowest emission scenario, see Figure 2-1. Additionally, UKCP09 gives probabilistic projections of atmospheric variables under different temporal and spatial averages (Eames et al., 2010). UKCP09 is the first in proposing climate projections using probabilistic statistical variables as cumulative distribution function (CDF) atmospheric variables under different temporal and spatial averages (Tian and de Wilde, 2010).

Projections made by Eames et al. (2010) use the current CIBSE (2015b) test reference years (TRY) typically used for energy analysis and the design summer years (DSY) typically used for overheating analysis for 14 locations in the UK. TRY weather data uses historical data sets of the most average month from 22 years of data (typically 1983 to 2004). Shamash et al. (2014) summarise the use of the UKCP09 climate projections of locations by creating Probabilistic Climate Profiles (ProCliPs) using mean daily temperatures. A central estimate of climate change happening would be regarded as a 50% probability level, but two additional percentiles are used; 90% as the very unlikely scenario of achieving greater than a change in weather (temperature, rain fall) for a given month, or a 10% probability level of very unlikely to be less than (Jenkins et al., 2009a) see Figure 2-4. This weather data can be used into different software to predict effects on buildings energy demand and indoor ambient conditions.

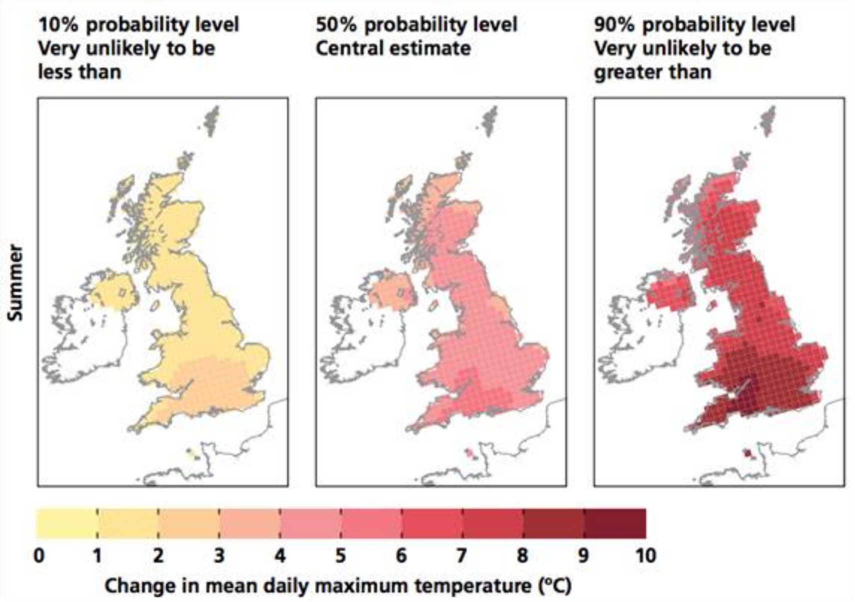


Figure 2-4: Maximum UK summer temperatures in the 2080s

2.4.2. Climate Change projections in building design & optimisation

Buildings play a key role in the mitigation of CO_2 emissions that contribute to climate change. A study by Al horr et al., (2016)states that we spend nearly 90% of our time indoors, thus it’s pertinent that the conditions inside buildings are comfortable without relying on increased levels of energy to reach comfort levels. The indoor conditions and comfort levels of buildings are predicated on the external conditions, thus the importance of designing and optimising building design to reach low levels of energy use and maintain comfort. The Future Weather project involving the Weather Generator tool for creating future weather files under the UKCP09 methodology produces reliable probabilistic weather files that are transferable into many DBES software for design and optimisation against overheating and reduced energy needs for heating and cooling. A study by Jenkins et al., (2015) has analysed the future climate projections for energy assessment in buildings through modelling such scenarios at different timelines and carbon scenarios considering probabilistic percentiles. It particularly looked at overheating potential of buildings that failed certain thresholds, such as the ones by CIBSE (2015b) of indoor temperatures reaching >25˚C where occupants felt warm most of the time and >28˚C where overheating became an issue (de Wilde and Tian, 2010 and Simson et al., (2017) and Jankovic and Huws, (2012)

To predict these scenarios in buildings, DBES software uses probabilistic climate change files to model future conditions and account for trends identified under UKCP09 scenarios. The methodology proposed by CIBSE TM48 (Hacker et al., 2009b) follows many steps to create the weather files from retrieved weather data of a location, however to obtain the required data large computing power and knowledge is needed. To simplify the process several open source files are available for DBES software to use. One such source is from research by The University of Exeter through the PROMETHEUS funded project (Eames et al., 2010). It generated future climate files for 35 locations compatible with building simulation models, using the extension EPW using TRY and DSY baseline files. Studies of such projects by Hacker et al., (2009b); Mylona, (2012) and Costello and Mylona, (2014) explain the application of such files.

A study by Shamash et al., (2012) produced a methodology for obtaining weather files and integrating them into building simulation software for optimising and designing for overheating, heating and cooling energy demand and boiler sizing for future demands. Jentsch et al., (2013) on the other hand performed an overheating analysis of an office building to predict the % of hours when occupants would experience above 25˚C and 28˚C in order to propose changes to the building (shading, and cooling strategies) and to predict the energy requirement and CO_2 emissions to maintain comfort temperatures. Williams et al. (2013) on the other hand has predicted performance of existing buildings and climate change scenarios. Work by Herrera et al., (2017) does a useful review of the current and future weather data for building simulation which aids future weather file requirements for a well-executed simulation. A study by Kočí et al. (2019) observes the changes in cooling and heating compared with TRY base files leading to a 4% decrease in heating and the equivalent increase in cooling in a short period between 2013 and 2017.

The studies mentioned above show there is a large body of evidence of the application of such methods and data sets to predict energy demand and overheating into the future.

2.4.3. The role of the decarbonisation of the electrical grid

In order to meet the recent targets set by The Scottish Parliament (2018) in the Climate Change Act (Scotland), the reduction of CO_2 emissions and decarbonisation of various sectors has been proposed. This includes not only the control of operational emissions from each sector but the decarbonisation of the supply of energy, both electricity and heat. A pathway set by the resultant document from the Climate Change Act, denominated as The Report on Proposals and Policies 3 and Climate Change Plan (The Scottish Government, 2018), has set a pathway for the decarbonisation of the grid system by 2032 that includes supply of energy for electrical and heat use and transport, lowering the carbon factors associated with energy use by electricity. Such target will be ensured by the implementation of diverse generation technologies for gas generation, storage, renewables and smart grids with an incorporated interconnectivity between them that maximises use and reduces losses in the grid system (Sithole et al., 2016). In buildings the focus is to first reduce demand of energy, and with the uptake of low carbon heating (heat pumps and district heating) including self-generation and low carbon grid systems by 2025, contribute to the pathway set for 2032. However, such plans fall into two mind sets predominant in the UK; one based on the reliance of nuclear power and renewables and the other a continued use of gas with carbon capture storage (CCS) or instead an alternative approach, to use hydrogen gas to provide heat to homes (National Grid ESO, 2019).

Despite de plans for decarbonisation and a shift towards electrical heating in buildings; it is important to guarantee security of supply, cost factor, sustainability and feasibility of technology deployment (Pfenninger and Keirstead, 2015). An important factor is the costs for the government and consumer, arguably a political and sector based debate as explained by Lockwood, (2013), and which is dependent on the investment made to reach a decarbonised grid system and the expected unit costs set after the 2030's for electricity. Hobley

(2019) argues that these proposals mean that natural gas in the UK will be phased out and not used as we reach the 2050's. But in the foreseeable future it will still play a big role in the UK's energy mix with a reliance on CCS rather than nuclear energy if a scenario of renewables and some fossil fuel heat and electricity prevails (Speirs et al., 2018a).

One nock-on-effect from the pathways set is the phasing out of the installation of gas boilers in all new homes from 2025. A report by the Committee on Climate Change (Committee on Climate Change, 2019) has indicated that this approach is taken on the basis that homes will be more energy efficient and will be reliant on heat from electrical generation such as renewable energy sources and other low –carbon options. However, as Adefarati and Bansal (2019) state, economic savings from the abolition of gas boilers in homes can only come if there is a planned use of renewable energy by co-generation of technologies, use of microgrid systems, demand response and performance indicators.

2.5. Dilapidation of buildings – envelope and services

The performance of buildings and efficient operation is determined by the adequate condition of building envelope and services. To understand the as-built performance of buildings, it is important to comprehend the state in which they operate and how they have endured over time and whether changes, maintenance or replacement is required. Studies of longevity of building performance are based on how materials and technology have degraded or dilapidated over time.

The Oxford Dictionary of English (OUP, 2010) defines dilapidation as: "The state or process of falling into decay or being in disrepair" and it is often a term used in tenancy Law as a cause of action to force a tenant to pay for dilapidations in a building. However, more appropriately, dilapidation concerns the degradation of performance commonly included in studies of building conservation, historical building repairs and maintenance.

2.5.1. Dilapidation of building envelope

Studies by Caccavelli and Genre (2000) and Cavalagli et al. (2019) refer to the resilience of historical buildings on the context of materials degradation and how they have withstood time. Ximenes et al. (2015) models degradation of masonry and exacerbates the impacts particularly into the future considering climate change. A study on un-insulated existing buildings by Balaras et al. (2005) focuses on the thermal impact of buildings through the aging process.

Degradation and dilapidation studies focus on the behaviour of building materials over time. Jelle, (2012) argues that the durability of building materials, components and structures needs to satisfy the requirements of expected service life, which in many cases is shorter than expected. Such shorted life spans result in increased costs due to maintenance, replacement and conservation. Work by Chorier et al. (2010) studies the replacement and service life of certain components and materials, impacting on their economic life cycle. It concludes by explaining the importance of in-situ performance of materials and how they are relevant during building design. Blom et al. (2010) perform a similar study in windows and doors by describing the life cycle methodology applied to assessments and environmental impact. However, the study argues that maintenance should only be done when needed; conflicting with other studies such as one by de Wilde et al. (2011) who argue that maintenance methods should be adopted as; reactive, preventive, predictive and reliability centred.

Pertinent to the performance of buildings is the deterioration and dilapidation of the thermal envelope. The performance of insulation materials can impact the whole envelope and influence many more aspects in buildings (structure, wellbeing, acoustics and air quality). A study by Alencastro et al. (2018) acknowledges that a gap in energy performance between design and as-built can be attributed to the quality defects of certain materials and components. A study by Zirkelbach et al. (2011) analyses the degradation of foam based insulants in roofs with an effect on moisture accumulation leading to larger thermal transmission values. Also relevant, is a study on the envelope performance of external thermal insulation in a block of flats 20 years ago by Stazi et al. (2009) It found that after this period, the insulation was still effective keeping its thermal conductivity values and acting as a barrier to thermal bridging. It also concluded that mechanically fixing external insulation is the best approach compared with adhesive or mortar bonding. Some cracks did emerge due to expansion and contraction in exposed surfaces to solar radiation, mainly caused by unstaggered positioning of board. Equally important to the performance of the envelope over time, is the air tightness of buildings. A study by the NHBC Foundation (2011) analysed the relationship of aging and increased air permeability (less air tight). The study re-tested dwellings after 2 to 3 years post completion and found that two-thirds of the sample became leakier after re-testing them 1 to 3 years post-occupation. The reasons for this change vary, from occupant intervention, settlement and shrinkage, but these reasons were not fully investigated. The study also reveals that the remaining third of the analysed dwellings can achieve higher levels of air permeability demonstrating that such dwellings require ventilation and control to provide adequate air quality levels. This work confirms that continuous in-situ monitoring of building envelope and components is needed to provide more accurate historical data to understand better how buildings degrade and to create larger evidence to calibrate models.

The building envelope and its dilapidation of the thermal performance is caused by driving rain, wetting of components, delamination of tapes around vapour control membranes and layers, seals around openings not working as they should be. The sources of dilapidation can be classified into its root cause such as; sustained meteorological effects (driving rain and uncontrolled wetting, wind exposure, solar exposure), premature end of life material and product failure, ageing and disrepair after end of life or a combination of all in various. Such displays of envelope failure cause air leakage and increase thermal conduction of materials which have a direct effect on the overall building performance over time. Ishak et al. (2007) and Alencastro et al. (2018b) explore how some failures in design results in faults and unplanned maintenance and implications due to improper material selection, ignorance of materials physical properties causing thermal expansion, paint decay, cracks, dampness and staining. Similarly if a ventilation system fails to deliver the appropriate levels of ventilation as specified, increased dampness, mould growth, surface decay and rot in wood can be experienced, all causing thermal discomfort and increased energy demand.

Unexpected wetting of building components combined with increased solar radiation can be the product of a changing climate (Gething, 2010). Exposure of rain, more specifically wind driven rain can be decisive for water penetration into vertical surfaces that are exposed to outdoor conditions (Giarma and Aravantinos, 2011a). Diving rain provides the severity of exposure and an approximate wetting potential on vertical surfaces such as walls in buildings providing moisture loading and a moisture index which Giarma and Aravantinos (2011) allude to. The correlation between wetting and drying of building components linked to moisture index of certain locations requires more investigation, however this exposure can provide some understanding of how the envelope performance deteriorate over time. Pérez-Bella et al. (2013) explores how wind-driven rain and water penetration increases the risk of building envelopes to deteriorate; the study produces a map of exposed sites in Spain where buildings may be at risk if not designed to consider such impacts helping define cladding and render solutions and inform future building regulations and climate change adaptation. Unless dwelling envelopes are built considering heat and moisture transfer in multilayer components, the risk of poor outside surface condensation or evaporation will not occur creating negative vapour balance and increased and continued wetting of components rising the risk of material degradation, increased thermal conductance and heat loss (Liu et al., 2017).

The exposure to unexpected solar radiation during summer months can also affect the performance of the envelope, particularly if there is a fast transition between moist surfaces and solar exposure exacerbating the appearance of render cracks and uncontrolled apertures over time (Paolini et al., 2017). A study by Sleiman et al. (2014) used accelerated weathering techniques of roofing materials exposed to water, sunlight, and high temperatures. Their experiments show that an accelerated ageing was identified when using time cycles of ultra violet radiation. Elevated temperatures from exposed solar radiation accelerate chemical reactions and diffusion of material components affecting moisture decay of wood, metal corrosion, staining and freeze-thaw damage (Berdahl et al., 2008). Also explored are the effects of soiling created by biological growth, deposits of airborne particles and soot from combustion can also contribute to the performance of reflective and non-reflective surfaces exacerbating the ageing process (idem, 2008). Synthetic polymers such as plastics also suffer from increased solar ultra-violet radiation, which Andrady et al., (1998) measured and explained as impacting on building degradation.

Relevant to the thermal performance of buildings through the dilapidation of the building services and envelope is the use of climate change models to predict a longitudinal set of scenarios. Building simulations can predict how buildings age and have an impact on the environment through changes in its thermal response. Building aging studies, such as the one done by Waddicor et al. (2016) show climate and aging factors can be modelled to observe how building heating energy demand changes. The work by de Wilde et al. (2011) includes statistical models and the use of building simulations to understand the degradation and maintenance requirements of buildings from the scenarios proposed by the UKCP09 scenarios. It focuses on the building service life taking into consideration the physical properties of envelope and services.

2.5.2. Degradation of building services

Building performance is also influenced by the efficiencies and performance of the services that provide comfort within its premises. The work by de Wilde et al. (2011) explores the use of reliability-cantered maintenance to lower the impact of services dilapidation and maintenance work. Predictions of deterioration are modelled using the Markov Chain method relying on past performance data to predict life expectancy. Likewise, work by Loy et al. (2004) seeks to implement Stochastic modelling against reliability predictions using retrieved monitored data to enhance the reliability and quality of building services.

A study by Gupta et al. (2018) has evaluated the influence of services and other factors on the actual performance of low energy social dwellings. The publication highlights that there are limited studies reviewing the commissioning of services and systems but recommends that seasonal commissioning is undertaken to minimise the impact of differences between specified and actual performance influencing on the overall performance of dwellings. A method used by Huang et al. (2016) using Bayesian Markov Chain Monte Carlo method on the capacity degradation of a chiller plant concluded that each year a degradation factor of 0.02 can be applied to services seldom maintained. This is particularly useful as it can be used to predict the tipping point at which the equipment reaches a lower limit of reliability and have a larger energy capacity (kW) and therefore larger energy demand (kWh).

Although the overall performance of services is important during its service life period, the fuel type, impact on the environment and the cost of that fuel are equally as important (Speirs et al., 2018b). The recent Climate Change Plan for Scotland (The Scottish Government, 2018) has focused on reducing carbon emissions of heating by electrifying heat and the use of heat pump technology. However, heat pumps may be cheap to install but there is evidence that running costs and fuel costs aligned to heat pumps are greater than natural gas boilers, particularly as the latter is likely to be phased out in new dwellings by 2025 in the UK (Hobley, 2019b). Although electricity currently has a higher carbon content than gas, this is in the downward fall and since 2017 the emission intensity was 210 gCO_2e/kWh and by 2030 it is deemed to reduce as the source of electricity switches from fossil fuel to renewable energy down to 105 gCO_2e/kWh (BEIS, 2017). However, the cost of electricity is deemed to increase and remain after 2020's at 20 £p/kWh making it costly to run but environmentally less of an impact (idem, 2017).

Pertinent to the role services have on energy demand over time particularly in low carbon homes is a publication by (Huang et al., 2018) which studies the adequate sizing of systems linked to parameter uncertainty, component degradation and maintenance to achieve the required comfort levels in dwellings. The proposed study impacts on the life cycle cost through the planning stages, sizing and maintenance schedules while also providing satisfying thermal comfort, energy balance and grid dependence. This study shows that deterioration of services gradually increases energy demand but could be avoided with planned maintenance or replacements.

2.5.3. The role of building service life

Service life calculations are an important stage of the building design and building planning and procurement. The relevant legislation behind service life relies on British and ISO standards such as BSI 15686-1 (2011) and BSI 15686-2 (2012) covering prediction procedures and a framework to the calculation process. These calculations, deterministic in nature, can yield inaccurate results and an alternative approach is to use weighted average techniques and Markov Chain models (Kirkham and Boussabaine, 2005). A study by Rauf and Crawford (2015) seeks to link service life predictions with life cycle embodied energy in buildings by producing a better methodology and accurate calculations. Calculating the correct service life of buildings links with accurate determination of the deterioration of buildings as both provide an understanding of the impacts, they may have over time on energy demand and the environment. A better prediction can accurately estimate when maintenance programmes can be introduced and are replacements in place (Rauf and Crawford, 2015 &).

Work by Monticelli et al. (2011) develops methods to evaluate the environmental impact of buildings and the decay of building materials over time by conducting life cycle analysis and embodied energy and energy requirements over a 60 year building service life. It specifically analysed the degradation of thermal insulation over time my applying Monte-Carlo simulations to determine types of building envelope type were sensitive to degradation over time. It found out that ageing over time and the energy demand are influenced envelope render systems and how they are affected by humidity and temperature variations.

2.6. Chapter conclusions

This review began by highlighting the importance of legislation in the framework of energy efficiency and climate change mitigation. Reduction of CO_2 emissions from the built environment and methods to lower the impact from new and existing buildings are central to meeting targets. Important to consider are the in-situ evaluations to measure the envelope performance of buildings, coupled with the measurement of energy demand. Qualitative evaluations, such as surveys also play an important role in understanding the as-built and as-occupied conditions of the buildings. Energy demand predictions and the quality of the results are relevant when showing the extent of a gap in performance between the as-designed and as-built conditions and both well executed steady-state and dynamic models are important in bridging this gap. Climate change scenarios and their use in longitudinal energy demand predictions should be implemented into all buildings in order to optimise designs that lower environmental impacts and are identify resilient methods. From the literature search, the following gaps in knowledge have been identified:

- More studies are needed of buildings in operation to understand the problems and behaviour
- Studies analysed in this review tend to be for short periods of time and in isolation – more occupied longitudinal studies are required
- Most studies concern non-domestic buildings and have a focus on envelope retrofits; BPE studies of large developments with different building types are needed.
- Climate change scenario modelling focus on overheating and energy demand analysis, however, most rely on assumed performance and more are needed using BPE monitored data over longer periods.
- Dilapidation and degradation studies are isolated and rarely involve BPE monitored data. Most use statistical models to predict maintenance and replacement and more should focus on envelope performance and service life.

The next chapters will consider the gaps in knowledge and implement them in the methods applied in this research and fulfil some of the longitudinal analysis required in dwelling energy performance. The use of case study analysis over longer periods of occupation by evaluating dwellings and observing the changes in envelope performance will help to clarify the impacts and the changes that can exacerbate energy use into the future. This review not only identified some gaps in research, but additionally helped define a clear methodology in the use of testing and measurement techniques. It also provided knowledge in the most appropriate data sets and data processing for the analysis of this research.

Chapter 3

Applied Methodology

3.0. Chapter Introduction

This chapter explains the adopted methodology for the primary data collection and analysis used to address the main aim, research questions and objectives; to then test the hypothesis stated in Chapter 1.

The chapter has been divided into four main stages that explain the process of data collection, leading to the results, analysis and conclusions that are discussed in the thesis. The first stage is distributed between quantitative data collection; obtained by longitudinal building performance surveys and energy demand over the period of study, followed by qualitative data collection through household occupancy and comfort surveys to characterise the dwellings. The second stage deals with the processing of data by statistically analysing qualitative and quantitative results. Stage three uses a mixed method of data of occupant trends and field test data to calibrate and validate the simulation models and to observe the effects of future climate change weather scenarios on carbon emissions. The fourth stage combines the climate change weather scenarios with a steady-state heat loss coefficient calculation defining a method of dilapidation that can be observed over time.

This research involved human participants agreeing to several face-to-face/ door-to-door surveys of the heads of household in each of the dwellings. Additionally, dwellings were visited to install data loggers and conduct non-invasive testing of the building services and envelope; these were followed by a second visit to retrieve data and equipment in their homes. All tests were conducted in full compliance with current research ethics regulation, and more specifically the codes and practices established in the Edinburgh Napier University Research Ethics Policy (Barkess, 2013).

Furthermore, Figure 3-1 below shows the strategic approach to the methodology applied for completing this research. This chapter will describe these stages in detail to explain the proposed methodology and how the data and analysis provided the primary output of this research.

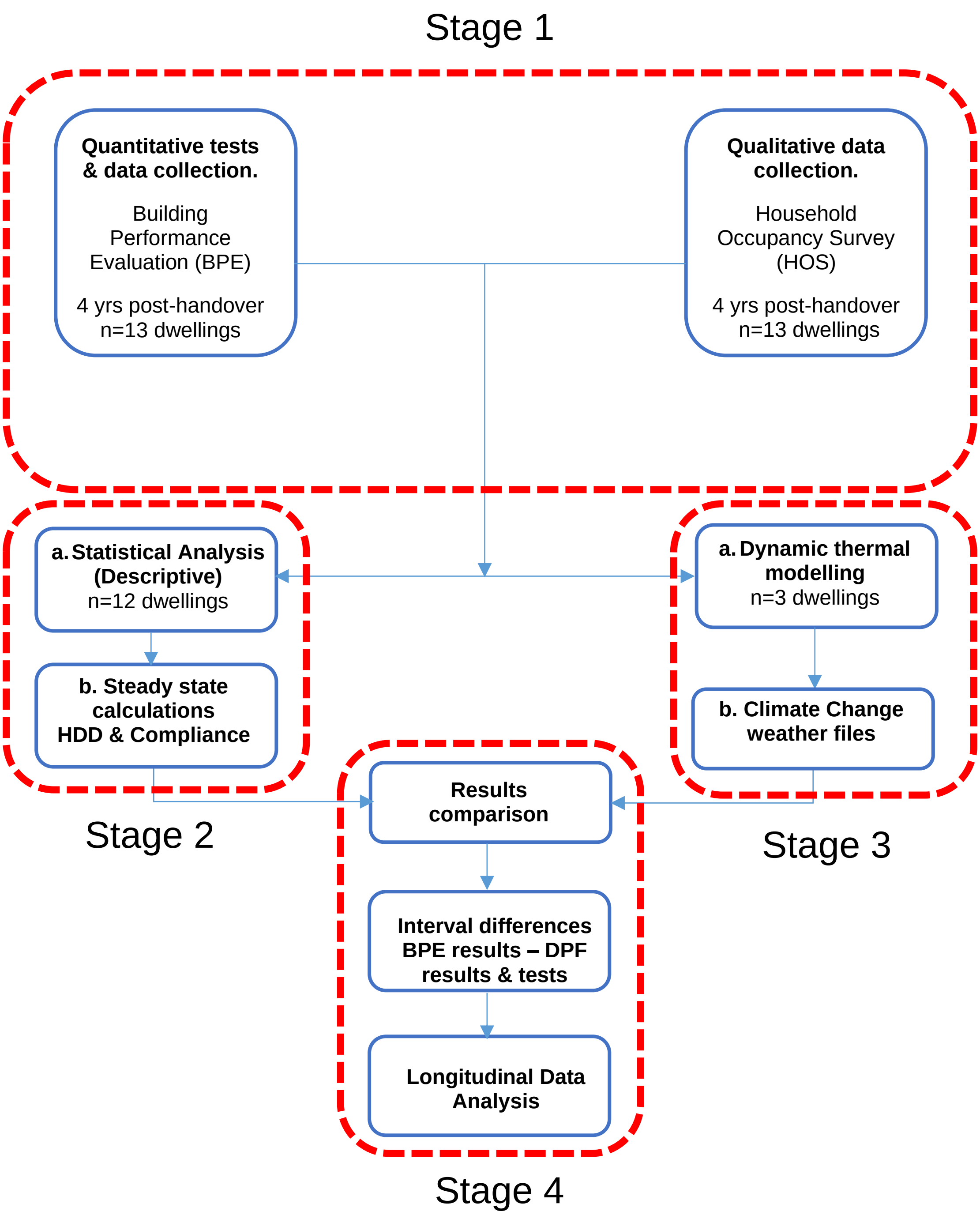


Figure 3-1: Flow chart of the research methodology

3.1. Selection of dwellings and defining the best sample size

The Housing Innovation Showcase (HIS), used in this research, as described in Appendix 1a, compromised of ten blocks and a total of twenty-seven dwellings. The dwellings were used as they presented a good selection of construction methods within the same development and surveys during construction stage took place before this study, hence providing a wider knowledge of the construction quality and pre-occupation stages involving handover and early occupation. Also, access was agreed by residents and RSL for further testing providing an in-depth case study analysis. Random sampling is not recommended in small number of cases, therefore “more purposive modes of sampling are needed” as explained by Seawright and Gerring (2008). This case study analysis determined the dwellings for further study based on how they exemplify different cases, such as construction method or occupancy type providing a diverse sample. However, influential configurations of the independent variables also formed part of the sample selection. This study also applies a statistical approach on the results obtained from the monitoring, in most cases statistical studies aren’t applied to small samples of a population, however statistics are used to show the level of correlation between as-built monitored data and the as-designed compliance data generated by architects. Such statistical approach helped to distinguish the magnitude of difference between the results and to show the best variables to compare in subsequent chapters (Korzilius, 2012).

Determining a sample size was an important task in starting the case study analysis. An inappropriate or excessive sample sizes can be time consuming and costly (Bartlett et al., 2001). However, the smaller the sample size the higher the uncertainty or sampling error, therefore it is important to accurately calculate it (Cochran, 1977).

In order to obtain a statistical representative sample, two common factors were used in determining error estimation which are central to sample size estimation, as stated by Cochran (1977). The first is commonly called the margin of error and the second the alpha level error or Type I error (Bartlett et al., 2001). The alpha level used in determining sample size in most academic studies is either p=<.05 or p=<.01 (Ary et al., 2010). Cochran's, (1977) formulas are more complicated as they require actual data retrieved from the population where standard deviation data are quoted. A simplified formula for target sample can be calculated using (Yamane, 1967)Equation 15 as below:

$$n=N/(1+N(\alpha)^2) \qquad \text{Equation 15}$$

Where:

n: Number of samples to test

N: Total population

α: (alpha) level of error

The above sampling equation is taken when no information about the population is known and is particularly useful for small population sizes and uses a p=<.05 alpha level error (Israel, 1992).

Equation 15 uses the total sample size in the development to define the most appropriate sample size for field tests.

$$n= 27 / 1+27*(0.05^2)$$

$$n= 25.29 \sim 25 \text{ dwellings}$$

The formula states a sample size for a research of this nature of 25 dwellings which was not possible in such a constrained study with a small population size. Given the constrains of the reduced population size, the research would benefit in analysing one dwelling of each block in the development, therefore ten dwellings. This gave the study a good representative sample of all the construction systems and techniques. However, three more dwellings were added of additional interest; such as two dwellings with prescribed Sustainability Section 7 Standards and a dwelling designed to the *Passivhaus* standard. Therefore, in total thirteen (13) dwellings were analysed and monitored.

Table 3-1 below lists the ten blocks and thirteen dwellings in the study, describing the archetype, construction system and method of construction.

Table 3-1: List of the blocks and the archetype and method of construction

Block No.	Plot	Dwelling code	Archetype	Construction system	Method
1	4	F.1.4	4-in-a-block	Steel volumetric system	Off-site
2	5	F.2.5	4-in-a-block	Timber closed panel	Off-site
3	12	F.3.12	4-in-a-block	Timber closed panel	Off-site
4	14	B.4.14	Semi-detached bungalow	Insulated clay block	On-site
5	16	B.5.16	Semi-detached bungalow	SIP (timber)	Off-site
6	17 & 18	**SD.6.17, SD.6.18**	Semi-detached 2 storey dwelling	Timber open/ closed panel	On & Off-site
7	19, 20, & 21	**T.7.19**, T.7.20, T.7.21	Terraced 2 storey dwellings	Timber closed panel	Off-site
8	23	SD.8.23	Semi-detached 2 storey dwelling	Timber closed panel – breathing wall	Off-site
9	24	SD.9.24	Semi-detached 2 storey dwelling	Timber closed panel	Off-site
10	33	SD.10.33	Semi-detached 2 storey dwelling	Concrete wall-form	On-site

Within the thirteen analysed dwellings, three were selected for a detailed longitudinal study. Three are selected as they had common variables but also distinctions that would provide varying conditions for comparison and to provide time and enough scope within the research. The first, with dwelling code SD.6.17 is denominated as the control house, chosen for its simple construction method and typical dwelling design used by the developer. Next to it is dwelling SD.6.18, selected for its distinctive *Passivhaus* energy efficient standard. The third dwelling T.7.19, is designed under the SBS Section 7 Sustainability standard following the Gold label criteria. The three have similarities including; orientation, all have gable ends and bedroom quantity. A feature also common amongst all dwellings in this research is the use of triple glazing throughout. The RSL made this decision predicated on the cost to U-value ratio which if compared with double glazed units provided higher efficiency with little cost difference. Glazed openings provide large quantities of heat loss (conductive and infiltration) and by minimising these effects across all dwellings, it turned a focus on the wall efficiency of each dwelling. Table 3-2 below describes the three dwellings and their construction methods in detail. The three distinguish themselves by having different; design aspired energy efficient standards, as-built varying occupant patterns, thickness of walls, open and closed timber panel construction, and heating services technology.

Table 3-2: As-designed construction variables between the three dwellings

Dwelling code	SD.6.17	SD.6.18	T.7.19
Certification	2010 SBS Baseline for HIS	2010 SBS *Passivhaus*	2010 SBS Section 7 “Gold”,
Space heating demand	>40 kWh/m^2/yr	15 kWh/m^2/yr	20 kWh/m^2/yr
Typology	2 storey semi-detached	2 storey semi-detached	2 storey end-terrace
Floor area	96 m^2	94 m^2	83 m^2
Layout	3 bedrooms Open kitchen/ dining room & living room	3 bedrooms Open kitchen/ dining room & living room	3 bedrooms Open kitchen/ dining room & living room
Fenestration	Triple Glazing, low-e, uPVC	Triple Glazing, low-e, uPVC	Triple Glazing, low-e, uPVC
Space & water heating	Gas system boiler (88% eff), 180lt cylinder	MVHR, gas system boiler (88% eff),	Air source heat pump (ASHP), 180lt cylinder
Envelope U-value (W/m^{2}K)	Wall: 0.23 Floor: 0.15 Roof: 0.1 Windows: 0.8 Door: 1.4	Wall: 0.1 Floor: 0.15 Roof: 0.1 Windows: 0.8 Door: 1.0	Wall:0.15 Floor: 0.15 Roof: 0.1 Windows: 0.8 Door: 1.0
Design Ach@50Pa (n50)	4.8 (Depressurised)	0.6 (mean value)	
Ventilation	Natural – window trickle vents, extract fans.	Mechanical with heat recovery - MVHR	Natural – window trickle vents, extract fans
Renewables	None	None	1.4 kW PV

3.2. Quantitative tests and data collection

Stage 1 of the research obtains its quantitative data from the four years of building envelope monitoring and results of occupied dwellings, with a direct link to the heat loss from the building, the energy demand and environmental impacts.

3.2.1. Building Performance evaluation (BPE)

The literature review in chapter 2 clearly explains the varying techniques and tools that can be applied to evaluate the building envelope performance. The use and on-site application of some of these tools were out of scope or were deemed intrusive to the occupants. Discarded as a technique was the whole house Co-heating testing which collectively, as it involves several tests, requires dwellings to be un-occupied between 2 to 3 weeks, which for the study dwellings in this research was impossible to schedule as all were fully occupied households. Also not considered was the use of infra-red thermography. Deemed as a more qualitative tool, the survey thermograms were not accurately comparable means between several surveys. Such tests are highly sensitive to outdoor conditions and temperature differentials at the time of the survey and assuring a constant set of conditions was not possible given the little control over environmental and occupant changes. Testing that was deemed to have a high level of control within the occupants and dwellings, hence guaranteed repeatability; included wall in-situ U-value and air permeability testing of the heated volume. Walls was chosen as it was the single building component that varied amongst the different dwellings analysed; roofs and floors were the same throughout the development hence not providing enough variability between dwellings. Indoor and outdoor temperature and humidity amongst other meteorological readings, were chosen to understand the variances between the controlled occupied heated space and the uncontrollable outdoor conditions.

Tests other than dwelling envelope were also not included in this study. For example, tests done on the actual efficiency of the building services and the use of renewable technology. Although very relevant to the study, in order to accurately record services efficiency, and above all its decline over the years of occupancy, circuit and technology power consumption and output would be required which included the use of sub metering and circuit specific voltage/

recording devices which were not available during the time of the surveys. Instead, the use of compliance efficiencies were relied upon.

Following the construction, handover and occupation periods of the development, this research opted for testing the envelope every two years (bi-annual). During the summer of 2012 at the pre-occupation stage, initial building envelope testing was performed. Tests that were not temperature dependent such as, air permeability testing and the occupant surveys, were achieved either in-line with those that were temperature dependent or in between the bi-annual periods. To account for delivered heat energy consumption, the properties were visited yearly to download hourly aggregated consumption figures stored in an in-house display (IHD) monitor, however these were corroborated by meter readings during the same 12-month period of occupation. Table 3-3 below describes the selected tests and tools and a schedule followed in this research.

Table 3-3: Testing periods during research, abbreviations below

Summer 2012	**Winter 2012/13**	**Winter 2013/14**	**Winter 2014/15**	**Winter 2015/16**	**Winter 2016/17**
ATT[1]	IUV[2] MR[3]	IHD[4] MR	ATT IUV MR IHD T&RH[5] WS[6]	IHD MR T&RH WS	ATT IUV MR IHD T&RH WS

Abbreviations:

[1] Air Tightness Testing

[2] *In-situ* U-value testing (Walls)

[3] Meter readings

[4] In-House display (IHD) of energy consumption – data retrieval and processing.

[5] Indoor temperature (°C) & Relative Humidity (%) - download/deploy loggers.

[6] Weather station deployment/ data retrieval and processing.

3.2.2. Air permeability

Dwellings were designed and modelled for compliance to achieve an energy efficient envelope. In this research, measurements of the as-built air permeability of dwellings before and at subsequent years of occupation provided a baseline of comparison against design predictions.

As a quantitative measure of ventilation heat loss and quality of the dwelling's envelope, repeated tests were carried out as explained in Table 3-1 above. The tests were conducted following approaches identified from previous literature discussed in Chapter 2, the methodology adopted is explained below.

3.2.2.1. Test methodology

During the post-handover stages of testing, air permeability tests were conducted in parallel with other field tests. Bi-annual testing gave the study longitudinal results over the course of the dwelling's occupation.

Two test methods are possible; Test method "A", adopted if results show a building in use representing its condition during the season in which heating or cooling systems are used or Test method "B", used to measure the air leakage considering the building envelope only and all unintentional gaps and holes are left open to show the performance of the envelope only. For this research, test method "B" was adopted where dwellings are considered as single-zone buildings by opening all interior doors and in flats inducing equal pressures in adjacent zones (BS EN, 2001). During each test, pressures of up to 50 Pascals (Pa) were reached to comply with standards by CIBSE (2000) & ATTMA, (2010). The test involves taking fan pressure readings of at least five incremental building pressure points with a pressure difference sequence of no more than 10Pa, culminating with a reading that considers total fan pressure, the envelope area, considering all wall, floor and ceiling internal surface areas.

Two test cycles were applied to the building envelope; pressurisation, (positive pressure) and depressurisation (negative pressure). The two procedures, tested the envelope at different airflow directions exposing internal seals and representative leakage pathways.

Incorporation of formulas and accuracy validation calculations used a configured test file in a Microsoft Windows compatible software developed by The Energy Conservatory named *TECTITE Express*^{TM} (Ver. 3.6.). The accuracy of the air permeability results is strongly related with the accuracy of measurements and the tolerances of individual apparatus that were yearly calibrated by a UKAS accredited laboratory. To determine the accuracy, a coefficient of determination analysis was performed that uses a curve fitting equation applied to a set of results. This analysis is based on the recorded air flows at set pressure points conducted using a Pearson (R^2) method. Each test carried out this regression analysis to determine how the results were suitable and closer to the line of "best fit", producing a correlation coefficient between 0 and 1; the closer the number to 1 the more the regression model can be relied on. Tests that returned a correlation coefficient below 0.980 were regarded as failed tests and certain pressure points would need to be repeated. Such instances are caused by adverse environmental conditions or substandard test methods (ATTMA, 2010).

Equally important for the validity of the tests conducted was the air flow exponent result derived from the constants C and n from the power law relationship. It describes the airflow regime through this orifice and values should range between 0.5 and 1.0 tests with values beyond these limits are not valid. Results closer to 0.5 are regarded as turbulent flow and a spread of large apertures (ATTMA, 2010). If values reach closer to 1.0 they indicate laminar flow with a myriad of very tiny holes, typical of air tight buildings (idem, 2010). Further specification of equipment and calculation used are described in Appendix 3a.

3.2.3. In-situ thermal transmission (U-Value)

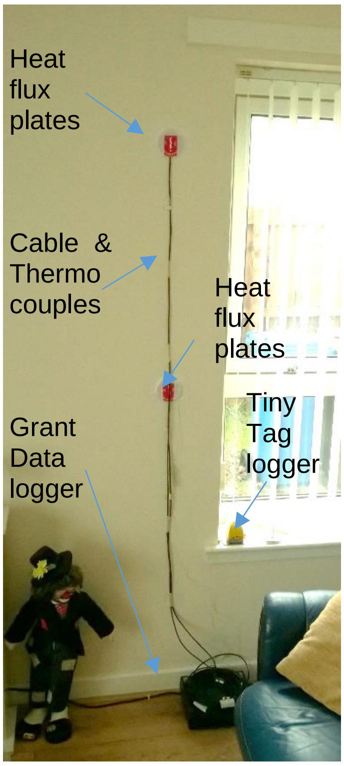
Another test performed included the thermal transmission measure of envelope performance using *In-situ* monitoring, better known as U-value, of walls in the selected dwellings of this research. Typically, building thermal transmittance of components at the design stage calculated the sum of all the thermal resistance values of individual layers (BS EN ISO, 2007 & Anderson, 2006). Such calculations are assumed as steady state in which fluctuations in temperatures, surface and radiant temperatures and the effects of thermal inertia are not considered. Such calculations are a measure of an assumed value of performance with often large discrepancies, however they are important to predict design total energy demand of buildings (Hulme and Doran, 2014). Following the calculated U-values of various components at the design stage, the *In-situ* tests were used to provide a more realistic and reliable method as it accommodated real-time boundary conditions which were dynamically responding to actual internal and external conditions.

3.2.3.1. Test methodology

Table 3-1 explains the test schedule that began at the first heating season during the first year of occupation. The tests included the placement of two heat flow plates (HFP) at different heights, close to windows and on a northerly orientated wall to avoid interference from solar radiation. The proposed methodology chose to use the same wall and location of heat flow plates (HFP's) in order to have a consistent longitudinal performance of the measured walls. The outputs of the evaluation produced three measured values compared with as-designed calculated values. The field tests required resident approved access for deployment and collection of equipment. The installation began by surveying the most wall and suitable placement of the HFP's and the internal/ external loggers.

For each dwelling, two HFP's and four thermocouples were connected to a data logger. Each was placed on the internal face of the wall, at 1000mm and 2000mm directly above each other, as shown in Figure 3-2 and Figure 3-3. Additional internal and external hygrothermal temperature loggers were used as a back up to the thermocouples. The monitoring time period is determined by the walls specific heat capacitance and effects of thermal mass (thermal inertia) of the walls (BS EN, 2001). Wall achieving a thermal capacitance ≥20 kJ/m^2K requires monitoring for at least 15 days at five-minute intervals. The selected walls, despite being a mixture of lightweight (timber and SIP panels) and heavyweight (masonry & concrete) systems all were assessed under these conditions. Appendix 3b describes the equipment used.

The HPF's were placed firmly against the wall with double sided tape providing good thermal contact and a non-permanent fix. Additional one-sided tape was placed around the edges away from the centre of the plate. HFP's were installed avoiding thermal bridges, cracks or cavities and sources of heat or draughts. The appropriate location of the plates was assisted by an infra-red thermography camera through the analysis of thermograms in accordance with the British and European Standard 13187 (BS EN, 1999). The installed monitoring equipment obtained datasets that were used in calculations set by the ISO and British Standard 9869-1 (BSI, 2014). These were followed to obtain final U-values over the monitored period considering accuracy and an uncertainty and error analysis on each monitoring period and set of results, see Appendix 3b for more details.



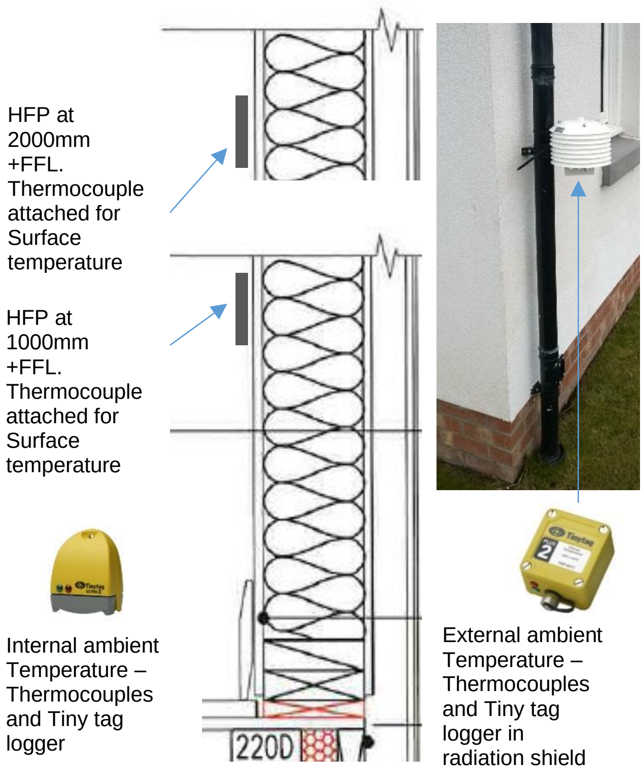


Figure 3-2 (left): Logger and heat flux plates

Figure 3-3 (right): Typical installation in wall section

3.2.4. Internal and external climatic conditions

3.2.4.1. Indoor temperature & humidity analysis

Measurement of indoor dry bulb temperature (°C) and relative humidity (RH%) was part of the indoor dwelling analysis to understand occupant heating patterns across the house types. Results were compared against set temperatures used in the compliance models at the design stage for assumed energy demand calculations.

Recordings were obtained from Gemini Tinytag Ultra TGU-4500, logging temperature at a resolution of ±0.01°C and a range of -25°C to +85°C and humidity with a resolution of ±3.0% and a range of 0% to 95% RH, Appendix 3b explains further. Loggers recorded at average hourly intervals for 12 month periods and were placed in the main living room clear from direct sources of heat and solar radiation at a height approximately 1800mm above the ground. All loggers required information to be downloaded manually onto a computer with the Gemini Tinytag explorer 4.11 software that converted readings into comma-separated values (CSV) and later analysed in Microsoft Excel. To further analyse the data it was plotted in line graphs against external meteorological data observing fluctuations and indoor habits to account for resident's thermal attitudes and comfort/discomforts.

Design compliance models base their mean internal temperature on heating requirements and patterns in the dwelling and its residents. To account for ambient conditions, loggers were placed around the available space that can be unreachable by residents but equally representative of mean room conditions. For the analysis and energy demand calculations the use of set point temperature was used as a mean over recorded periods of study. This method was applied as opposed to the adaptive comfort temperature as it was difficult to determine the occupants change in temperature and conditions as there were many influencing aspects that impacted on this. The influence of incident solar and internal gains such as latent or appliances and occupants all impact on internal set point temperatures which in most dwellings can vary throughout a study of tis nature, particularly over the longitudinal periods. Further use of recorded temperatures to obtain baselines consider gains in buildings, such as degree day data, which provides some assurance that an energy balance in calculations is considered.

3.2.4.2. External weather monitoring

Throughout the monitoring stages of the research, external weather was monitored by two sources; one on site and another nearby. The two weather sources were used mainly to account for a missing weather station at the start of the study, which was then installed near one of the dwellings in the development. The remote weather data was accessed through Weather Underground (2012), from a nearby local weather station located in Crossford, Dunfermline, Fife, approximately 4.5 miles from the properties, from June 2012 to September 2014.

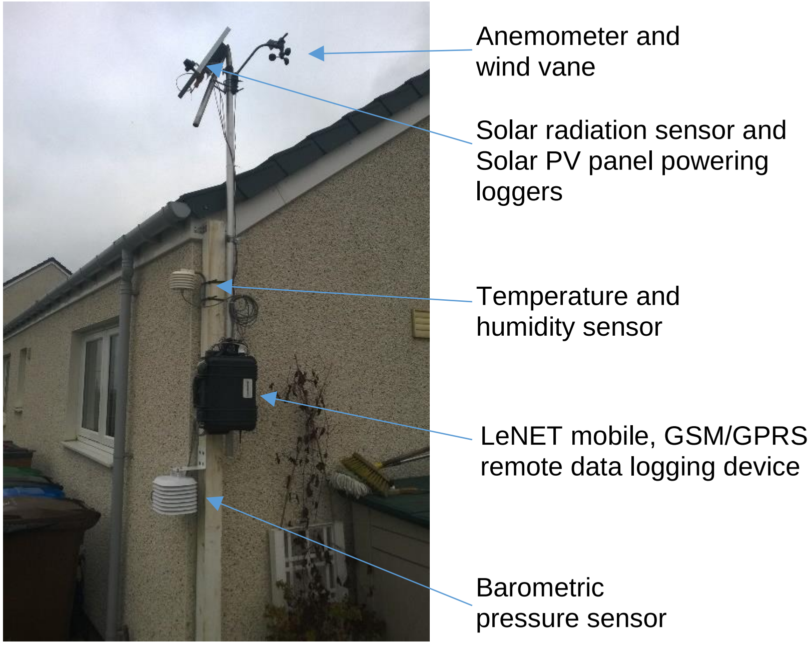


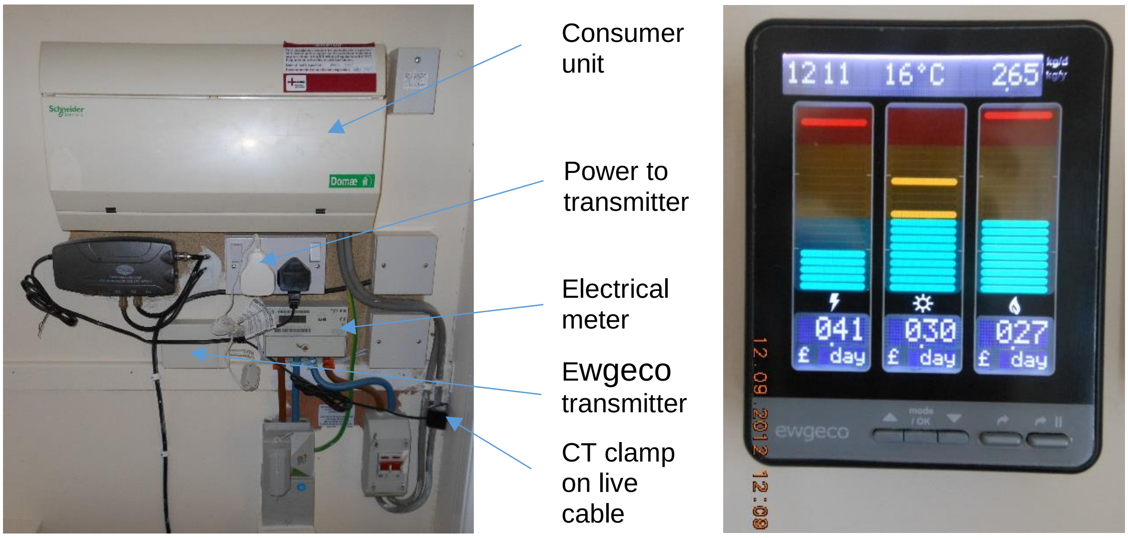
Figure 3-4: Weather station located in the site

The second source of weather came from the installed weather station on the site recording: dry bulb temperature, relative humidity, wind speed, wind direction, barometric pressure, and solar radiation. The on-site weather station, shown in Figure 3-4, was installed in September 2014 and recorded data until the end of the study in spring 2017. It provided ten minute interval data logging with remote live displays analysed over the required period of study. The weather stations shared a similar exposure to the outdoor weather with small differences appearing between the location of the station and its altitude and the remote stations capability to record solar radiation. The outputs are essential for creating dynamic thermal model weather files for model calibration and to weather correct energy demand over the period of study. Appendix 3c describes further.

3.2.5. Energy consumption data collection

Each dwelling in the development was fitted with an In-home energy display (IHD) unit that displayed and stored real-time power consumption at hourly intervals, converted into larger aggregated values. Household energy demand, in kilowatt hours (kWh's) during set periods of occupation were recorded, focusing on consumption of gas and electricity and generation of electricity from renewable sources, typically solar photovoltaic (SPV) energy or solar thermal water heating.

The IHD was manufactured by Ewgeco Ltd with model variants depending on the fuels and technology being recorded (Stinson, 2015). The installed IHD in the selected dwellings was the H300 model that displays electricity, gas and solar PV or solar thermal. Appendix 3d provides more specifications on the IHD devices. Figures 3-5 (a) & (b) and Figure 3-6 show the display and installation.



a

b

Figure 3-5 (a): Traffic-light display unit in dwellings. (b): Typical transmitter and CT clamp installation of electrical energy.

Figure 3-6: Gas meter with pulse block to transmitter.

The study focused on obtaining yearly consumption data in line with the handover and first occupancy periods, supplemented by utility metered data at full 12 month periods as this is the simplest approach to determining annual billed consumption (CIBSE, 2006a). Data was individually analysed to obtain total monthly and yearly consumption figures in kilowatt hour (kWh) gas consumption as well as from heat meters in devices such as air source heat pumps (ASHP). The monitoring and calculation procedure was performed under the CIBSE TM22 methodology (CIBSE, 2006a) for best practice comparison of predicted energy for space and water heating against delivered heat energy. Electricity, unless used for heating purposes (ASHP), was excluded from this study as it was regarded as un-controlled energy led by occupant's lifestyle, size of household and behaviour and not directly related to building envelope performance. Meter readings were taken of delivered heat energy as a precautionary measure to corroborate the readings obtained through the IHD's. Data from the first heating season provided a starting point and subsequently every 12 months thereafter.

Normalisation of energy use was made by heated floor area (kWh/m^2) however a normalisation study by coefficient of variance (CV%) also suggested that normalising by number of occupants (kWh/ppl) in the dwelling was a reliable method (Bros-Williamson et al., 2017).

3.2.5.1. Data analysis

Delivered heat energy data retrieved from meter readings and the IHD came in the form of gas volumetric units (m^3) that required figures to be convert into energy consumption (kWh). In the case of meter readings and to account for 12 months of data, end readings were subtracted away from the start meter reading and total units V_{gas} (m^3) converted into kWh's using Equation 16 below:

$$Q_{gas} = \frac{V_{gas}\ x\ 1.022640\ x\ 39.2}{3.6} \qquad \text{Equation 16}$$

Where:

Q_{gas}: Heat energy from gas in kWh

V_{gas}: volumetric units of gas in m^3

Volume correction: 1.022640

Calorific value conversion: 36.2 (for Dunfermline, Fife)

Factor of conversion from Joules into kWh: 3.6 J

Downloaded real-time gas consumption from IHD the installed pulse blocks required additional pulse factor conversion with a value of 1 with the Ewgeco A.03.24.2 firmware version, hence using Equation 17 below instead.

$$Q_{gas} = \left[\frac{V_{gas}\ x\ 1.022640\ x\ 39.2}{3.6}\right] \div 100 \qquad \text{Equation 17}$$

This sequence of data analysis of the IHD download and meter readings with their respective calculations were conducted from December 2012 during post-handover and thereon at yearly intervals until January 2017.

3.2.5.2. Accuracy of IHD and gas meter readings

Ofgem, (2004) states that gas meters are typically within the prescribed limits of accuracy ± 2%. Stinson, (2015) compared the difference between Ewgeco IHD readings and meter readings, that concluded in a deviation of 3% but in most cases 0.5% and closer to 0% when performed continually under strict timelines. Most of the difference was due to rounding-up errors of meter readings and the time difference when meter readings were captured. In this research meter readings were taken to account for full 12 month of delivered energy. When this was not manageable, it was done as close to the due date of meter taking and subtracting or adding same daily (kWh/ day) energy consumption obtained from the same week’s delivered energy download from Ewgeco IHD.

3.3. Heat energy consumption segregation by proxy

In the UK, the preferred methodology and one adopted by many software providers is the Standard Assessment Procedure (SAP); further explored in this research and chapter. At the design stage of dwellings architects or consultants apply factors and assumptions or predicted values into algorithmic formulas used in SAP software obtaining building-specific predicted energy demand.

In the case of heat demand, calculations to obtain space and water heating fuel consumption are dependent on dwelling envelope design, specification and services technology providing a varying efficiency and fuel use. For the monitored dwellings in this research, an account for heat energy consumption where natural gas was the predominant fuel used, included a combination of space and water heating. This therefore required an approach to segregate space and water heating from the total delivered, whilst natural gas consumption for cooking purposes if a gas cooker is used.

Scotland experiences distinct heating seasons with fairly temperate weather patterns, thus the use and amount of fuel for water heating can be expected to have small variation throughout an occupied year. Water heating in most households follows a pattern aligned with the number of occupants, daily use of showering/ bathing facilities and kitchen requirements.

The Standard Assessment Procedure (SAP) model includes number of occupants, amount of water heating volume, factors of use of water heating and losses from the selected heating technology to calculate water heating requirements. In order to directly compare delivered (as-built) and assumed (as-designed) space and water heating, it was essential to find ways to separate them to recognise the differences and the impacts on dwelling energy performance. In the selected dwellings, not all water heating came from once fuel type, for example, some dwellings that used natural gas for water heating in kitchens and toilets, were also equipped with at least one electric shower system, hence the split between fuels.

Considering the above, this research applied a bottom-up approach to segregate both energy uses by accurately calculating actual water heating within the household. Qualitative data collection in the form of occupant demographics and water use refined the calculations, as it provided accurate data of number of occupants and number of showers, baths and kitchen water use, this was an important part of the re-calculation of heat energy as it provided an accurate amount of water heating aligned directly to the number of occupants in the dwelling. The following calculations were used to calculate the new water use.

As a first approach, total floor area (TFA) and actual number of occupant in each dwelling were collected to use in Equations 18, 19 and 20 considering demand for baths, showers and other uses, which were later applied into Equation 21 to obtain an actual volume of heated water ($V_{\mathrm{d,average}}$). Such calculations were developed by Henderson (2008) & BRE & DECC (2011, p166) to account for post-construction survey data that substitutes assumptions initially considered during the as-designed SAP calculation.

$$V_d,shower\ (litres/day) = Sd \times Qs \qquad \text{Equation 18}$$

$$Vd,bath\ (litres/day) = Bd \times 50.8 \qquad \text{Equation 19}$$

$$Vd,other\ (litres/day) = 9.8\,N + 14 \qquad \text{Equation 20}$$

Where:

Sd: Showers per day

Qs: hot water per shower as per Table V1 in Appendix 3e

Bd: Baths per day

N: Number of actual occupants in the household

$$V_{d,average}\ (litres/day) = Vd_{,shower} + Vd_{,bath} + Vd_{,other} \qquad \text{Equation 21}$$

Following the actual calculation of volume of hot water per household the following calculations were also applied:

Apply hot water use factors, obtaining daily Volume (m^3) per month:

$$V_{d,m} \sum_{n}^{12} = V_{d,average}\ x\ Q_{factor} \qquad \text{Equation 22}$$

Energy content of water is calculated:

$$Q_{water} = \frac{4.190\ x\ V_{d,m}\ x\ n_m x\ \Delta T_m}{3600} \qquad \text{Equation 22}$$

Where:

ΔT_m = temperature rise for month from Appendix 3f

Following the calculation of energy use per volume of water used over a total year of occupation, these are applied into the system losses and efficiencies from the heating system as per the original calculations considered by Henderson, 2008; & BRE & DECC, 2011, p166.

Also considered was fuel used for cooking purposes, where an estimated 7% of total energy has been deducted from the total delivered heat energy in the year (Guerra-Santin et al., 2009) or 0.5 kWh/ day (Wingfield et al., 2009). Finally, the new as-occupied water heating energy was subtracted from the total delivered energy for the whole household which gave an estimated account for space heating.

3.4. Qualitative data collection

3.4.1. Household occupancy survey

An occupant survey was used in this research to obtain qualitative data which was used in a range of calculations, calibration and for clarification of results and outcomes from the dwellings performance. The survey provided household details of occupants and their conditions and patterns of use. Four main sections were used to obtain the details required.

Section 1: Household demographic data

This section required the participant to list the names, ages, daily activity and relation to the head of the family living in the dwelling. It also required a detailed account of how many hours during the working week and weekends the mentioned occupants were awake. These questions were selected to obtain information about the type of occupants in the dwelling over the years of observation. Interesting to this research was how the ages and daily activity of the occupants impacted on the use of energy for space heating. Given the diversity of the dwelling tenure, it was important to record the changes over the years in the family structure and employment status. For example; some families at the start had young children and at least one adult stayed at home more hours in the day than the working adult. As children grew, they migrated to nursery and then primary school, allowing the adult to return to part- or full-time employment. Other dwellings were occupied by retired couples with an active lifestyle and others who were more sedentary at home. The circumstances changed and therefore the dwelling used changed impacting on the energy use over time.

Section 2: Perception of comfort and satisfaction of the dwelling

A Likert scaled set of questions used in this section were aimed at understanding occupants comfort levels towards temperature, air movement (ventilation,) lighting and noise levels. This section in the survey required the occupant to scale their thermal comfort and general perception of the dwelling's conditions. Of interest was their perception of temperature inside the dwelling and if they felt comfortable. The air movement question focused on their perceptions of ventilation and quality of air, including if they felt uncomfortable cold draughts or if there was uncontrolled ventilation that impacted on thermal comfort. Lighting was aimed towards their perception towards natural light and if artificial light was needed during the daytime. Noise levels were particularly aimed at the acoustic performance between adjoining and opposite dwellings including outside noise. Such results on noise, despite them being important to occupant comfort levels, they were not analysed in detail as a direct relationship with energy demand could not be found, however it does relate to the envelope performance and level of acoustic insulation between dwellings and to the outside; including windows and other openings which does have a link to the overall envelope efficiency.

Section 3: Energy efficient practices

This section used a combination of Likert and ranking scales that focused on occupant's frugality to energy use in the household and if the dwelling itself was providing comfort. It asked for example, their use of curtains at night, opening of window trickle vents, leaving appliances on stand-by, etc. The questions in this section are aimed to understand the occupant's level of awareness of energy efficient practices that have the potential to reduce energy wastage and save energy in space and water heating. The results from these questions were used on a qualitative manner and not to extract any quantitative values that could be used in calculations.

Section 4: Energy use and appliances

This final section required the participant to list the appliances including showering, bathing and kitchen water practices, as well as an indication of number of times the appliances were used throughout the day. The results from these questions will be used in the re-calculation of water heating applied to steady state calculations and to compare with the compliance assumptions. Also important are the range of appliances used throughout the dwelling which can be used in the dynamic thermal models of the selected dwellings. Adding such appliances, both in quantity and power rating provided and account for internal gains in the dwellings which considered in the total heat loss calculation and energy balance.

3.4.2. Methodology

All the surveys were conducted face-to-face with the head of the household and the researcher in the participant's dwellings. A paper version of the survey was handed over and assistance was given to answer questions if required. To complete the survey the outmost care and attention was taken to explain, in appropriate detail, what the research was about to participants. Every research participant was contacted prior to the visits via the principal RSL officer and subsequently contacted individually to obtain a date and time for a visit. For the qualitative survey each participant was given a one-page 'project information sheet' that outlined the purpose of the study, who was undertaking and financing the study, and how it would be disseminated and used.

The first survey was conducted at post-handover during the early occupation period, and then in line with Table 3-1, every year during the heating season. Visits to conduct the survey were linked to the energy data retrieval and envelope performance testing periods, and questions were focused on the current year of occupation. The surveys were conducted mainly to obtain occupant details and characterisation of the dwelling use. Occupant characteristics can clearly define the controlled and uncontrolled energy use of the dwelling (Guerra-Santin and Itard, 2010). This is particularly evident in the heating patterns which can influence the performance of the dwelling itself.

A copy of the sample survey issued to occupants of the selected dwellings can be found in Appendix 3g.

3.4.3. Data analysis

The results from the survey were not analysed for statistical significance, however were useful for collecting some key parameters and occupant feedback on the dwellings. They were not used to build an accurate occupancy behaviour score that is often used to distinguish and quantify frugal and profligate patterns of energy consumption (Gill et al., 2010). However, occupancy plays a big role in the energy use, and it could not be ignored.

Primarily results were used to profile the occupants and use the qualitative results and observations to inform the latter chapters on the calculations and their results. A longitudinal survey of this nature, linked to an early occupation post occupancy evaluation (POE) enriches the research with qualitative data on the prolonged use of the dwellings, helping to minimise the assumptions used in the baseline dynamic modelling and the statistical analysis used. The data retrieved was particularly useful when comparing the compliance modelling (SAP 2009) with actual occupant characteristics and calculating revised energy consumption figures, particularly those influencing space and water heating. Also relevant are the occupancy hours linked to ambient dry bulb temperature recordings for space heating to create more accurate schedules of heating.

For the purposes of this research, the answers to the survey will be the dependent variable that will shape the analysis and interpretation of results, this is because the outcome of the survey will help to understand the results, trends and changes over the years of occupation. To do so, the survey was split into stages with numerical or ranking scale responses that once results are extracted between the survey years can show longitudinal changes. Furthermore, the comfort questions, if observed as predominantly negative or positive, would be used to understand the household's preferences rather than an important determinant in answering the main research questions of this research. The results of the surveys will be analysed separately to create the following:

- **Occupant profiling**

Occupant profiles (OP's) are to be defined from Section one of the survey related with the results of the occupant's demographic status focusing on the hours they occupy the dwelling during the working week and a typical list of the activities they do over the non-working days.

- **Actual number of occupants**

The demographic survey, as well as defining the schedule of occupancy in their dwelling, were also used to account for the actual number of people living in the dwelling and how these changed over the years of the study. This information was important in order to compare against the calculation made in the compliance model which considers the treated floor area in an occupancy calculation as defined by BRE & DECC (2011) and Henderson (2008). The actual number of occupants was important to obtain, not only to analyse the energy consumption results, but to also calibrate the dynamic thermal models and re-run the hot water calculations for the steady state calculations.

- **Dwelling occupant comfort levels**

The questions related to the occupant's perceptions of comfort were analysed separately over the years of occupations. These were useful when analysing the recorded indoor temperature and to compare against the recorded external weather conditions reacting to some of the identified energy demand trends of each dwelling.

- **Overall occupant comfort**

Following from the individual questions on the comfort levels, an overall occupant comfort over the years of occupation summarises the whole dwelling comfort level. Such results provide an understanding of how occupants found their homes and the trend this shows which can be analysed further alongside results on energy consumption.

3.5. Statistical analysis & as-built steady-state heat loss calculations

3.5.1. Introduction

This sub section forms part of Stage 2 of the research methodology as described in Figure 3-1. It is split into two-parts, part a. includes the method employed for the descriptive statistical analysis of the data obtained in the monitoring stages. It summarises and observes correlations and trends between energy demand data and dwelling specifications and design characteristics over the monitored years. It follows a methodology used to compare between as-designed compliance results and values with the retrieved data; part b. forms part of the processing and further analysis of the retrieved data which includes the post-processing of the data using the steady state heat loss compliance calculations and also the use of heating and cooling degree day data for longitudinal analysis. The techniques explained in parts a. and b. are used in the data collection and results and the analysis and interpretation chapters.

3.5.2. Descriptive statistics

Analysis of data sets for statistical relevance and normality of data, (parametric or non-parametric tests) focused on the retrieved heat energy consumption of the thirteen analysed dwellings, as well as the tests conducted for thermal transmission (U-value) of walls and air permeability.

Descriptive statistics remains, in its simpler form, a good way to understand the data, particularly when comparing it against predicted values. A more complex statistical analysis is easily conducted with larger samples of participants but as Majcen et al. (2015) argues, to detect a normal distribution and parametric test, a large enough sample size of $n > 30$ is suggested. For smaller sample sizes, a non-parametric test is better suited and more useful for comparison of data, particularly between dwellings and years of occupation.

3.5.2.1. Comparison against as-designed calculations

To begin with, the descriptive statistics depict the simpler relationships by stating mean, standard deviation and median. Dwelling analysis often uses dwelling archetype to compare benchmarks but there are other means related to the amount of energy used or the construction type used in the different blocks of dwellings. For this research, the mean (average) delivered heat demand results over the four years of monitoring against the heating predicted SAP results were plotted over monitored years. Also used in this research is a normalisation condition applied onto the data retrieved, used to compare against benchmarks and contextualise the data. The Coefficient of Variation (CV), as a percentage, was used to describe which normalisation condition was a best fit for the data. The lower the percentage CV, the closer each individual data point is to the group mean. This suggest that the mean is a good representation of the whole data set of that sample. Most energy related studies will use delivered energy over a set period, normalised by the heated floor space of the building (kWh/m^2/yr). However, other conditions such as yearly energy demand per volume (kWh/m^3), number of people (kWh/ppl) and predicted over actual energy consumption (kWh/kWh) can be used (Stinson, 2015).

A method adopted to compare between the calculations obtained at the design stage using compliance models against the actual measurements recorded over time is percentage difference (% diff). This method was adopted as a measure of the percentage displacement and variation between the as-designed and actual and thus an indicator of performance gap. The smaller the percentage difference, the smaller the displacement between them. This method is calculated following these steps:

Step 1: Difference between designed and actual for a given period (DBDA).

$$Actual\ (measured) - Design\ (As\text{-}designed) = DBDA \qquad \text{Equation 24}$$

Step 2: Measure the percentage difference between them:

$$DBDA \div Design\ (As\text{-}designed) = \%\ difference \qquad \text{Equation 25}$$

The %diff used this ranking method to display the performance gap between many of the measurable elements of the dwellings. Of interest were the differences over the years and the mean of all measurements for a given dwellings used to calculate the compliance energy demand at the design stage. For example, differences between measurements of air permeability at a given interval of time or equally wall U-Value and space heating energy demand.

All descriptive statistics in this research used the mean normalised energy for space heating (kWh/m^2/yr) of each dwelling over the four years of occupation against relevant dwelling variables. Such comparison is made to determine the best variable that influences space heating demand and therefore analyse it further in subsequent chapters. The following variables were compared:

- **Building standards:** Influence of space heating demand against the adopted design criteria. Three were used; Scottish Building Standards (SBS) set in 2010, SBS2010 and Section 7 levels of sustainability (Gold, Silver, Bronze) and SBS 2010 and the Passive House German standard.
- **Construction type:** Relationship between space heating demand and the method of construction; off-site or fabricated away from the building site

and then assembled on-site and on-site, all assembly and building work occurring in the building site.

- **Dwelling type:** whether flats, bungalows, terraced homes or semi-detached against the space heating demand.
- **Heating type:** Efficiency and type of heating device; combi gas boiler with ≤90% efficiency and an electric air source heat pump (ASHP).
- **Ventilation type:** Whether space heating demand is influenced by the use of a mechanical ventilations and heat recovery (MVHR) system or just a mechanical extract (ME) in kitchen and bathrooms.
- **Household composition:** Dwellings occupied by adults with children or without children.
- **Occupancy schedule:** Relationship between space heating demand and dwellings mostly occupied all hours of the day, only occupied during the day during early mornings and evenings or a mixed occupancy where both situations can happen throughout the week.

From the characteristics and variables explained above, the data is presented to indicate key statistical measures such in relation to the number of dwellings that are associated with the variable. In most cases the analysis included; mean, median, and standard deviation. To provide a measure of the statistical accuracy, the standard error is calculated using equation 26:

$$SE = \sigma/\sqrt{N} \quad \text{Equation 26}$$

Where:

SE: Standard Error

σ: Standard Deviation

$\sqrt{N}$: Square root of the sample number

The standard error is shown in all space heating and its variables as a descriptive analysis to account for the possible error among the variables and the results obtained. It represents the standard deviation of the mean within a dataset. However, it is also inversely proportional to the sample size and therefore, the larger the sample size the lower the standard error.

3.5.2.2. Correlation between dwelling variables

Two statistical methods are used for determining if results are correlated and associated to a given set of parameters. These can be applied depending on whether the datasets are parametric or nonparametric.

In parametric tests where the dataset is normally distributed, the coefficient of determination defined by Pearson (R & R^2) performs an analysis on the means; typically used in larger sample sizes and datasets. The standard covariance of Pearson (R) coefficient lies between -1 and +1 to show the relationships between a set of dependent variables. A coefficient of + 1 indicates a perfect correlation (as one variable increases the other also increases) whilst a coefficient closer to -1 indicates a negative relationship (as one variable increases, the other decreases). A coefficient of zero indicates no linear relationship. A way of interpreting the effects is by observing the values; where ±.1 represents a small effect, ±.3 is a medium effect and ±.5 is a large effect. Alternatively, Pearson (R^2) is a measure of the amount of variability and proportion of shared variance between one variable and another; a value close to 1 has a higher relationship under standard significance criteria $p<.05$ (95% confidence interval). High relationship values are often $r=>.75$. Medium relationship between variables have values $r=<.75$, whilst low or no relationship often are shown with values $r=<.40$. Using an x–y scatter plot of the retrieved datasets, new results can be determined by altering the variables in a regression formula from the plotted data. This is particularly useful when there are small effects between the variables and assumed values can be devised to predict similar distributions.

The non-parametric analysis follows the same criteria of the standard covariance and its relationships between a set of dependent variables. This data analysis is better suited to smaller samples and datasets as it makes no assumption about the distribution of the data. In this case Spearman's (rho) rank correlation is used to assess the relationship between two variables that have a monotonic function (neither increasing nor decreasing). While Pearson (R & R^2) correlation measures linear relationships between variables, Spearman's (rho) tends to analyse the strength and direction of association between two ranked variables (Field, 2009).

The retrieved data in this research is small, therefore a non-parametric analysis is preferred performing an analysis on the median of the values, however the mean of values is also a good analysis and one that is better suited, regardless of the sample size and datasets available. For this reason and to have two perspectives on the data analysis, both parametric and non-parametric correlation methods are applied to the descriptive data analysis which help to select variables that could be analysed further in other sections and chapters.

3.5.3. Defining heat loss by dwelling performance factor

This study seeks to use a variety of quantitative and qualitative results and identifiers that can be used to extend the observed trends of energy use and building envelope performance to seek out the dilapidation of the dwellings over time. In this research the retrieved energy demand for space heating and its associated environmental impact has been used both to evaluate the dwellings against its design compliance calculations and to devise future projections.

Steady state calculations in compliance models provide an energy balance considering heat loss and heat gains to determine the additional energy requirements to keep set point temperatures and internal thermal comfort (Kelly et al., 2012; SBS, 2013). An important factor of the heat loss calculation is the determination of all the sources of heat loss including; ventilation heat loss, envelope heat loss and infiltration heat loss. These are calculated using steady state formulas that determine the monthly total heat loss considering; external weather conditions, thermal mass parameters, efficiencies of equipment and heat transfer coefficients (W/K). Often the quoted values in compliance model results (SAP2009) is the heat loss parameter (HLP) which simply normalises the monthly heat transfer coefficient (HTC) by its treated floor area.

In this research a quasi-steady-state approach is used by combining steady state and measured values to determine new heat transfer coefficients or dwelling performance factors (DPF's). Original steady state values are used in combination with the retrieved values after monitoring the dwellings in this research. Of interest is the impact the fabric heat loss has to the overall heat loss of the dwelling. Table 3-4 below indicates the values that were dependent from measured sources and controlled from the SAP as-designed values. Keeping the controlled variables as a constant value and changing the measured values for a given year provides a new DPF which can be associated as an as-built result which influences overall energy requirements for space heating. This calculation process is used throughout this research to indicate dilapidation of the building envelope over varying time periods.

Table 3-4: Dependent and controlled variables - measured and steady state

Dependent variable (measured)	Controlled variable (Constant, SAP)
Wall U-value (W/m^2K)	Ventilation heat loss (open vents)
Infiltration heat loss air permeability ($m^3/h.m^2$@50Pa) converted into ACH	Theoretical U-value for other opaque elements
	Thermal bridging coefficient
	Heat recovery efficiency (if MVHR), pumps & fans
	Thermal Mass parameter (TMP)

The steady state calculation in the compliance models use the following equations to derive a heat loss trough the dwellings envelope:

$$\sum Q: A \times U \times (\Delta T) \qquad \text{Equation 27}$$

Where:

$\sum Q$: heat loss of each component (wall, Floor, roof, etc.) (W/K)

A: Area of each component in dwelling (m^2)

U: Measured or as-designed U-value of given component (W/m^2K)

ΔT: Difference between Internal and external temperature (°C)

To account for thermal mass and the heat capacity of each component Equation 28 is used. However, for this research the as-designed values has been kept.

$$Cm = \sum (A \times \kappa) \qquad \text{Equation 28}$$

Where:

Cm = Heat capacity of each component (kJ/K)

A = Area of each component in dwelling (m^2)

κ = Kappa value or heat capacity per unit area of material (kJ/m^{2}K)

Thermal bridging, although dependent on individual Psi values calculated of each junction and relevant detail where thermal bridging is an issue, used Equation 29 below:

$$\sum (L \, x \, \Psi) \qquad \text{Equation 29}$$

Where:

L = Length of linear thermal bridges (m)

$\Psi =$ Psi value derived from a thermal bridge calculation

To determine the total thermal bridging the combined thermal bridge result from individual calculations is multiplied by the total area of external elements (m^2). This then concludes with the total envelope heat loss adding total thermal bridging value and the result in Equation 27.

Finally ventilation heat loss considers both equipment ventilation (pumps, fans and mechanical systems) and infiltration ventilation heat loss derived by Equation 30.

$$Qv\text{: } \eta x V x 0.33(\Delta T) \qquad \text{Equation 30}$$

Where:

Qv: Ventilation heat loss (W/K)

η: monitored air permeability converted to air changes per hour * (ACH)

V: Volume of dwelling (m^3)

ΔT: Difference between Internal and external temperature (°C)

0.33: density of air (ρ) is 1.205 kg/m^3 at 20˚ C and specific heat capacity (C) is 1000 J/kg K.

* Note that infiltration rate was modified for monthly monitored wind speed creating an adjusted infiltration rate.

A total heat loss coefficient is obtained by combining the monthly ventilation heat losses and the envelope heat loss as shown in Equation 31.

Total heat loss:

$$Q_{total} = Q_V + Q_{envelope} \qquad \text{Equation 31}$$

Where:

Q_{total}: Total heat loss also known as heat transfer coefficient or DPF in this research (W/K).

Q_V : Total heat loss from ventilation (equipment heat loss and infiltration) (W/K)

$Q_{envelope}$: Total envelope heat loss (W/K)

3.5.4. Heating and cooling demand by HDD and CDD

To estimate future impact of weather in the statistical analysis of this research, heating degree days (HDD's) and cooling degree days (CDD) were used. As a first approach they were used to test the delivered energy consumption that was monitored and to validate it to estimate subsequent months or years of space heating energy demand. Additionally for further longitudinal analysis and projections, the use of external dry-bulb probabilistic future weather data provided by DEFRA and their UKCP09 programme was used to estimate heat loss and energy for space heating and cooling using set timelines into the 2030's, 2050's and 2080's, under the set probabilistic percentiles and CO_2 emission scenarios (Jenkins et al., 2009; Jones et al., 2009; Murphy et al., 2009). Stage 3 of this methodology explains further.

3.5.5. Degree day baseline temperature calculation

HDD and CDD data are used to estimate energy use for space heating and cooling respectively and to normalise against weather shifts. Differences between the normalised and actual energy will help to understand any discrepancies not caused by differences in weather such as occupant behaviour and thermal comfort (Belcher et al., 2005). HDD's in the UK are calculated considering a base line internal temperature of 15.5˚C. However, this base line figure is obtained considering two factors; the use of constant internal heating set point temperature of 19˚C and an estimation of internal and external gains contributing 3.5˚C (BRECSU, 1993 & CIBSE, 2015). Another determining component is the use of external temperature which often uses the mean twenty year weather data of the closest weather station which can be different to those experienced in the actual location of the building. The most recent source of observed mean values are between 1983 and 2004 of 14 UK selected locations by the Chartered Institute of Building Services Engineers (CIBSE) (CIBSE, 2015 & DECC, 2015). The files include two sourced data, a test reference years (TRY's) that are mean weather data over the 20 year period considered appropriate for energy performance predictions, and design summer years (DSY's) that are years of observed mean weather data of extreme hot summers, considering the third hottest summer in a 20-year baseline mainly used for overheating risk assessments (Mylona, 2012). CIBSE also publish monthly HDD data of every month past for 18 UK locations, however these are all based on the 15.5˚C baseline which is appropriate for simple estimations, but not when performing more in-depth calibration and future projections such as in this research (CIBSE, 2006b).

This research proposes the use of a new baseline set point, as opposed to the standard UK value of 15.5˚C. It is based on the recorded mean daily indoor temperature obtained from the analysed sample of dwellings and the use of two internal gains contribution temperatures; the standard 3.5˚C and a new proposed value of 6.5˚C which considers shifts in solar gains and a greater consideration in latent heat sources (BRECSU, 1993). The internal gains values have not been calculated for each dwelling as proposed by CIBSE (2006b) as this required estimations and further dwelling monitoring which was beyond the scope of the research.

The calculation of degree days in this research uses mean daily temperatures only. As explained in Chapter 2 there are other methods, however they require more data and an extensive calculation process. The calculated daily degree data is often presented as a sum of all the days in a month that resulting in an annual or seasonal value when heating or cooling is in operation, normally October to April in the UK. As a first step the baseline is calculated using recorded mean hourly internal temperature as a set point temperature and applying the gains temperature as shown Chapter 2 and Appendix 2a.

Once daily degree day data is available for each dwelling, monthly and yearly totals are summed which in turn can be used to calculate the energy consumption of the calculated degree days. The calculations used in this research respond to the dwelling location, its weather conditions and also measured internal set point temperatures, thus providing data relevant to the dwellings considering as occupied and built conditions.

3.5.6. Estimated energy consumption for heating and cooling

The calculation of the dwelling specific daily baseline for heating and cooling followed by the corresponding HDD and CDD leads to Equations 9 and 10 as explained in Chapter 2 section 2.3.3.2. These equations are used to calculate the corresponding energy demand for heating and cooling for daily, monthly and yearly totals.

3.5.7. Validation of monitored data

For validations purposes and to be confident that the HDD data can be used for future projections; the HDD energy demand yearly totals were compared against the retrieved energy totals of all dwellings in the research. To perform this an analysis using Pearson (R^2) regression analysis in a x–y scatter plot of measured space heating energy for years 1 to 3 against corresponding yearly energy demand using HDD energy demand was performed. This analysis resulted in a best-fit straight-line equation using least squares regression analysis. Subsequently to test the HDD data, a fourth year of energy data was estimated using the equation to then compare against the recorded actual fourth year energy demand data. This method allowed for a validation of the HDD methodology and the confidence to use it to predict energy demand in subsequent years.

3.5.8. Future weather data HDD and CDD

Simple energy demand estimates of subsequent occupied years can be applied once the regression analysis in a x–y scatter plot is validated, however for deeper analysis over longer timelines two important elements need to be considered; actual sensible gains, a true internal set point temperature and actual external temperatures. These elements can be difficult to estimate over time and if constants are used the assumptions are less credible (Belcher et al., 2005; CIBSE, 2006b). Despite these concerns, this research has proposed to overcome this by implementing a dynamic indoor and outdoor temperature method using a more credible estimate of baseline and external temperatures.

Implementing probabilistic climate change future weather files and dilapidated dwelling performance factor (DPF), this research proposes to calculate a dynamic baseline for heating and cooling energy demand based on changing external conditions. External temperature provided by the UKCP2009 future weather tool, expanded further in Section 3 of this chapter, would allow for estimated future energy demand over extended timelines, primarily for the 2030’s, 2050’s and 2080’s considering two CO_2 emission factors; high and medium, under three probabilistic percentiles; 10%, 50% and 90%. The weather files and the use of external dry-bulb temperature as the main component to implement into the HDD and CDD analysis provided many scenarios and considerations into future energy demand of the analysed dwellings.

Conditions internally to propose a new baseline can be more difficult to obtain. Despite having a threshold internal set point temperature, the baseline is dependent on the sensible gains impacting on the dwelling. These can be partially calculated using future probabilistic solar radiation as this is available in such weather files. Additionally, thermal inertia can be considered constant from the as-built envelope specifications. However, the elements that cannot be estimated over time are the gains from plugged appliances and the efficiency of the heating and cooling technology which can diminish based on many factors but cannot be fully accounted for at this level of analysis (de Wilde et al., 2011).

3.6. Dynamic thermal modelling & Resilience study

To analyse the relationship between envelope performance and space heating demand, this research has opted to use dynamic building energy simulation (DBES) software on a sample of dwellings, forming part of Stage 3 of this methodology. The literature review has highlighted the lack of longitudinal operational energy demand of buildings, particularly in the residential sector with complex occupancy patterns and dysfunctional tenure periods. Most studies do not consider the changes over the lifetime of the dwellings, let alone the environmental impact over the years.

Thermal modelling in the building design sector has become not only a compliance tool in its steady-state format but also, for more complex studies, in its dynamic format a tool that accurately investigates the assumed performance at the design stage; considering occupancy profiles, actual location and weather patterns, pre-designed heating, ventilation and air conditioning (HVAC) services.

For this research, DBES has been chosen not as a design tool to obtain optimum performance but also to model the as-built and occupied performance. This has been achieved in combination with recorded data building performance results which further refined or calibrated the model replicating actual occupied energy demand. By having these refined base models, optimum control simulation scenarios are made which can show measurable savings in energy and reduced environmental impact. Also useful in such simulations is to predict future patterns and unaccountable changes, for example impacts of climate change in future years. Such projections impact on the resilience of the building envelope, services and operation of the dwellings against changing weather patterns and exposure to outside elements. This research seeks to explore through DBES and climate change weather patterns, how dwellings dilapidate over time impacting on energy use and the environment.

This stage of the methodology begins by explaining the choice of modelling software used and the sample size modelled for such research. It then describes the methodology adopted for creating base models, calibration, validation and climate change weather files. Finally, a description of the method adopted for comparing results over time against actual measured performance.

The selection of a software that can simulate accurately the energy demand of a building was determined by the availability and training of the software and also whether it was capable to have modifiable building envelope and dynamic parameters (occupancy and weather) as well as a user friendly interface for the addition of input data and the interpretation of simulation results. Important in the selection was how well it aligned with the imposed British, European and International standards, in particular BS ES ISO_13790, (2008) for the thermal calculation process of the simulations and the EPBD requirements. Also important is the processing of historical weather data and its capacity to run simultaneous simulations considering future climate conditions considering climate change scenarios and time periods (Jarić et al., 2013).

A software solution which meets the required metrics above is the Integrated Environmental Solutions, Virtual Environment (IES-VE) software. It is a widely-used DBES software tool which comprises building analysis tools used to predict the performance of a building at design or post construction stages. IES-VE is considered a “black box” piece of software which does not require the user to codify or have any knowledge of computer programming to generate a simulation. The user-friendly software has been built to simulate on the basis of the software specific input data through a graphical user interface (GUI) linked to building specific parameters (envelope, services, location and occupancy). Selection of such parameters and the interpretation of its results after simulation, do require some knowledge of building physics however it’s understanding and use in this research application requires considerable insight and skill. The DBES software uses different model modules; the first being the *ModelIT* module to construct a geometric volume, representing the heated (or cooled) zones of the building, followed by the *Radiance* module which simulates Its alignment between orientation, fenestration location and size with required day-lighting; also *MacroFlo* which analyses the volumes considering the effectiveness of natural ventilation and finally the thermal analysis module called *Apache*, which considers HVAC systems, envelope performance values and occupant profiles.

IES-VE is capable of calibrating the models based on actual measurements, either from the building envelope or the energy demand during occupation. This process of calibration or fine-tuning in accordance with real life situations, as defined by Reddy and Maor (2006) & de Wilde et al. (2011) where monitored data acts as a determining factor between the simulations and the recorded energy demand data. Within its possibilities is the inclusion of newly generated or up-to-date weather files, either from actual locations not included in the software weather database or the future weather files affected by climate change.

3.6.1. Dwellings selected

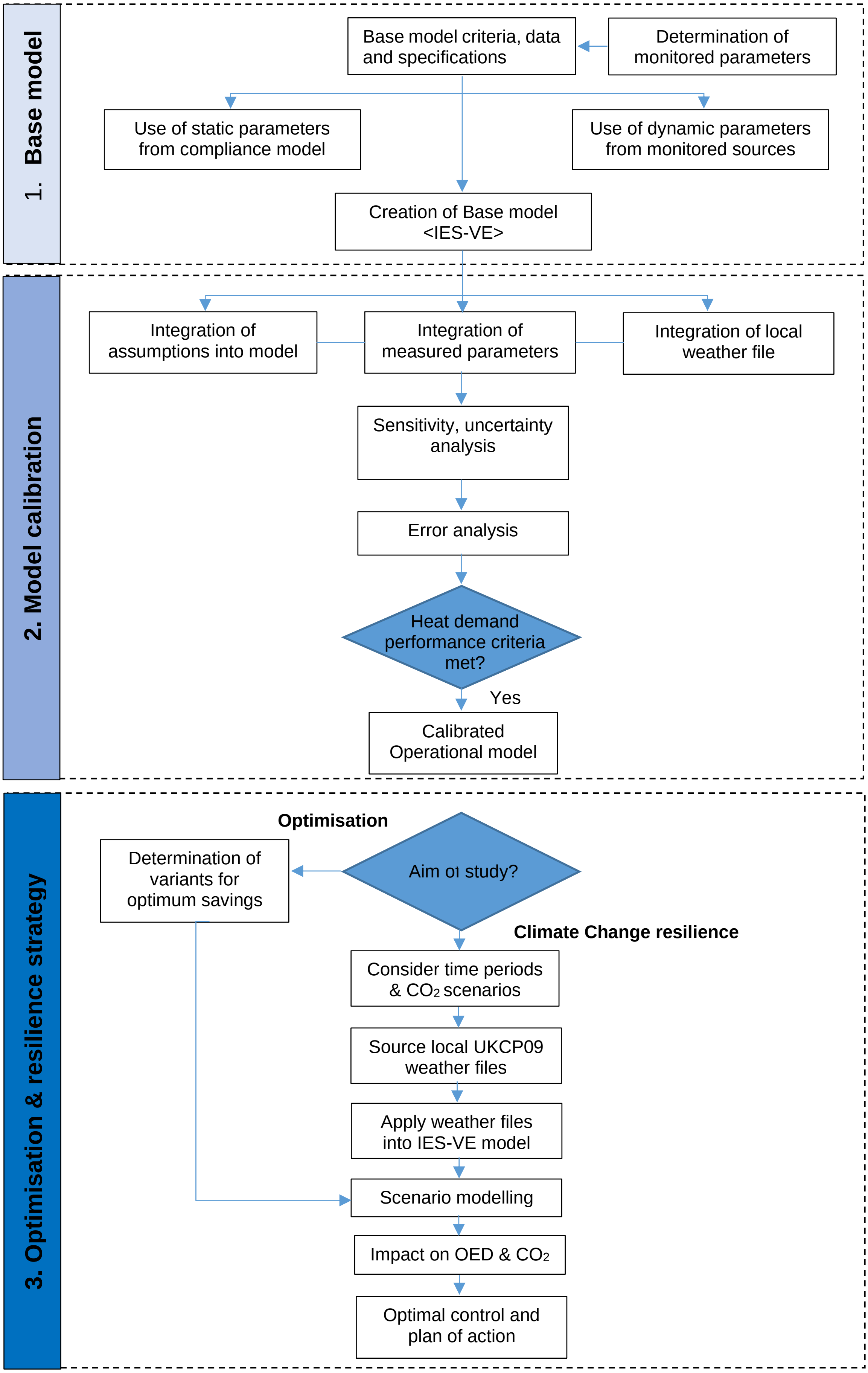
For the detailed analysis of the performance of dwellings in this research, three of the thirteen monitored dwellings were modelled using the IES-VE software.

Referring to Appendix 1a, the selected dwellings and their codes were; SD.6.17, SD.6.18 and T.7.19. Dwelling T.7.19 defined as the *Section 7 Gold* design and SD.6.18 referred as the *Passivhaus* design were selected for their different high energy efficient methods of construction and different heating technology (electric & natural gas), whilst SD.6.17 referred to as the *control house* epitomised the typical dwelling design by the housing developer. The dwellings, during the monitoring period, experienced un-interrupted monitoring which facilitated the calibration stages of the models. They also represent high aspirational standards against typical house designs in Scotland.

3.6.2. Adopted modelling methodology

Figure 3-7 below graphically explains the different steps to creating a calibrated base model to conduct the resilience study relevant to this research. Step 4 of this methodology is of importance as it defines the direction of the research. Most work related to DBES is performed to propose optimisation and improvements to a new design or if modelled for retrofit purposes, improvements that can be implemented. However, in this research optimisation is not modelled and rather focuses on longitudinal climate change energy demand scenarios.

Figure 3-7: Dynamic thermal model and resilience methodology flowchart



3.6.3. Base model creation

The base model creation is an important stage in the analysis of the building as it is the first stage of a decision-making process of balancing the actual performance of the dwelling with the static design parameters that were used for compliance purposes.

The process involves creating a three-dimensional model using the design drawings and basic geometry of the dwelling. The as-built drawings were used in this process but later verified on-site to corroborate dimensions and specifications. The dwellings were not geometrically modelled in detail, in fact IES-VE requires that the model comprises of basic shapes of the heated or cooled rooms and zones in the building, including circulation areas. Data for the creation of the base model included a mixture of specifications and assumptions used in the compliance SAP model, and the first year building performance results and early occupation survey data. These monitored results were useful as it began to calibrate the model with actual as-built data. Table 3-5 below shows the base model parameters used; steady-state as-designed parameters used throughout the model creation and the more dynamic data parameters that would be further changed while monitored data was obtained.

Table 3-5: Base model parameters

Steady state as-designed parameters	Dynamic parameters (measured)
Dwelling geometry	Air permeability/ air infiltration rate
Orientation	Envelope U-values
HVAC specification	Occupant profiles & numbers
Window & door location & dimensions	Set point temperatures
Internal gains from appliances	Weather file

3.6.4. Uncertainty analysis of models

With a base model created in IES-VE it was then possible to continue onto the calibration phase. There are three sources of information which assisted the creation of the model. The first included assumptions which are un-known parameters that the software requires before simulation. Examples of this are appliances ratings and occupancy schedules during weekend activity. The second criteria used are the actual monitored data sets from the longitudinal fabric performance tests, primarily air permeability and wall U-value. Although already used in the base model, at this stage the dwellings were monitored over four years and a more accurate account to the buildings performance was obtained. This stage also included occupant survey results used to create accurate as-occupied profiles. The last stage included the creation of a compatible weather file (.fwt or .epw) for use in the model. Weather data from the installed weather station was added into an IES-VE Visual Basic weather file creator, later inserted into the base models for accurate weather considerations.

Implementation of these three data sets completed the model creation and uncertainty analysis. It follows a comparison with the delivered energy demand of each dwelling, focusing primarily on the space heating requirements over the last two years of occupation as these were deemed to be the more accurate figures representative of the homes performance (Bros-Williamson et al., 2017). If energy figures were very different, a subsequent sensitivity analysis, is performed refining the models by considering a sensitivity analysis and error analyse that would further calibrate the models.

3.6.5. Calibration using sensitivity analysis and error analysis

Performing an uncertainty analysis and a sensitivity analysis relate to each other as they both aim to achieve the best fit using model parameters. This study has relied on the metered energy for space heating to calibrate the models. The sensitivity analysis determines a step-by-step model adjustment which is followed by an error analysis to determine the best approach and closes fit to the recorded energy figures. Chapter 2 determined the calculation process of each of the uncertainty, sensitivity and error analysis. The analysis was performed using parameters that were related to the variances and impact on space heating demand; followed by a model calibration once an error analysis is performed.

The step changes applied in the uncertainty analysis were based on the results from the descriptive statistics and a further correlation analysis to select appropriate parameters that most impacted space heating energy demand. Based on as-designed and as-built space heating energy demand, parametric and non-parametric correlation analysis determined the best parameters.

Error analysis played an important part in the calibration process. Monthly aggregated energy consumption was used to observe the similarities between the recorded and the modelled energy rather than twelve-month total demand. This allowed a good alignment to the seasons and actual energy use per month. Descriptive statistical analysis such as standard deviation, mean and coefficient of variation (CV%) were used to evaluate each data set. Also adopted as an error analysis method was coefficient of determination through linear regression and the Pearson (R^2) methods to determine the proportion of variation between the variables. Additionally, determination of root mean squared error (RMSE) of the predicted mean and the coefficient of variation of root mean square root error (CVRMSE), were used to measure the uncertainty of the model and variability of the errors between measured and simulated values. For a good statistical indices to evaluate simulations against actual measured data, mean bias error (MBE) are used in combination with Normalized Mean Bias Error (NMBE) as a percentage magnitude of the error (Burman et al., 2014). Lastly the goodness of fit (GoF) measures how well the simulated values fit the measured ones.

The proposed error analysis validated the sensitivity analysis step-changes and giving an indication of the best parameters and consideration to apply, finalising with a calibrated model ready for subsequent simulations.

3.6.6. Climate change considerations and resilience method

At this stage of the building evaluation, the model has been created to simulate as close as possible the as-built real-life conditions responding to similar energy demand profiles. Generally, there are two paths to take with the model, a building optimisation direction which will create scenarios to enhance building performance and demonstrate savings and improved conditions, and a resilience pathway that studies the current conditions and how the building could operate over longer periods of occupation. The purpose of using DBES in this research was to use the model for the latter path, resilience over time.

The first stage of the resilience study requires to analyse the buildings under future weather conditions by creating future weather files based on future weather data. This requires proposing three boundary points derived by CIBSE’s UKCP09 climate projections methodology also known as probabilistic climate profiles

(ProClip) that will be applied to generate future weather files in the form of Test Reference Years (TRY's) which are used in most thermal modelling studies. These are as follows:

- **Time periods:** These are likely projections compared with a baseline weather file, which in most DBES software takes average weather file taken from 1961 to 1990 or 1990 and 2002. Three over lapping time periods were selected as part of the UKCP09 methodology that included three equally spaced time dates: 1) 2030's between 2020 & 2039, 2) 2050's between 2040 & 2059 and 3) 2080's 2060 & 2089.
- **Carbon emission scenarios:** Each of the above time periods were analysed under different carbon emission scenarios in order to test the effect of the future weather. For this research a probabilistic future weather method was used proposed by the UKCP2009 Weather Generator. Two International Panel on Climate Change (IPCC) emission scenarios were used impacting on environmental impact for the 2100's; a medium impact (a1b) and high impact (a1fi).
- **Probability level:** The probability levels used by UKCP2009 and the IPCC projections include levels of 10%, 33%, 50%, 67% and 90%. These projections based on frequency distribution functions allowing the uncertainty in projections to be quantified by giving the relative probability of different climate change outcomes (Cubasch et al., 2001). For this study, three levels have been chosen to analyse the future weather files, a 10%, 50% and 90% probability showing the two extremes or tails of the distribution function and a medium probability.

3.6.7. Creating future climatic data

Sourcing climate change future weather files has been developed under the above time series and carbon scenarios using the probabilistic climate change projections method. The on-site weather station created the buildings actual baseline weather file compared with the historical averages used by (CIBSE, 2015). Data from the weather station for a full year was taken and converted into a comma separated value (CSV) text value that was easily converted into a usable weather file in the IES-VE software such as the. epw or .fwt file extension for simulation purposes.

The conversion from CSV text file to .epw file was performed using a weather file conversion tool called Elements (Big Ladder Software, 2016) that required a full year of monitored weather variables logged by the weather station. The created weather file was implemented into the IES-VE weather database to re-calibrate the model and have a realistic account of actual performance, later used for the projected simulation under future climate change weather conditions.

Future weather datasets were obtained by selecting the nearest location relevant to the studied dwellings within a 25Km grid spacing of probabilistic future weather files under the UKCP2009 guidelines. In this research an open source data base of .epw files using baseline datasets of historical averages for the nearest location were used; in this case data related to Edinburgh. These probabilistic future weather files were created as part of the Prometheus EPSRC funded project developed by The University of Exeter (Eames et al., 2010).

The .epw files were manually added into the model to run batched simulations in the IES-VE *Vista Pro* function based on the timelines, CO_2 emission scenarios and the probabilistic percentiles selected. By doing this, each modelled dwelling can display simulations of probabilistic space heating energy, internal temperatures and other thermal conditions; vitally important in the longitudinal performance and environmental impact of the building’s life.

3.6.8. Cooling estimates using hours above thresholds

The DBES model did not account for simulations for direct energy space cooling therefore two methods were tested; the use of cooling degree days as mentioned in §3.5 and the calculation of electrical energy from a cooling device that occupants could easily install in their dwelling. These were based on thresholds set by CIBSE Guide A, (2015) of the number of occupied hours above 25˚C where occupants felt uncomfortably warm and even further above 28˚C threshold where overheating became an issue. These thresholds generally represented as the percentage of occupied hours above the threshold during a whole year or non-heating season are provided by an internal ambient analysis of DBES simulations in IES-VE of the whole dwelling or selected rooms. This analysis is influenced by the trends in external temperatures generated from future weather UKCP2009 weather files. In this study, such weather patterns and files were helpful to predict not only the internal temperature conditions, but also the requirements of energy demand for space cooling by external means (Wang et al., 2010).

The calculation for cooling energy considered the total hours occupied in each dwelling to be in the region of 5110 hrs/year assuming 14 hrs mean daily occupied hours (Yun and Steemers, 2011). Considering the results of the simulations stipulating an annual percentage of hours above the 25˚C threshold of each dwelling, a total number of hours requiring cooling can be obtained (Jankovic and Huws, 2012). To overcome the increase in indoor temperatures and to lower the risk, cooling technology is proposed in the form of a wall mounted air source cooling unit with a nominal cooling capacity of 2.0 kW, typically positioned in the living room area. The proposed is a warranty installed system and not another appliance purchased by the occupant. Considered an easily retrofitted device into the dwelling, it is also known as a “Mini-Split” system, with an indoor unit and an outdoor heat pump fan condenser. It is also assumed the system would operate with an installed mechanical ventilation unit as a recirculation system, where sensible and latent heat is recovered in proportion to the amount of room air mixing with the fresh air. Manufacturer’s typical nominal efficiency or seasonal coefficient of performance (SCOP) can range from 3.5 to 4.5. However, for the purposes of this study a SCOP of 3.0 has been used considering that in real life and installed device does not perform as manufacturers predict. The total energy for cooling can be calculated for every DBES simulation produced using Equation 32.

$$F_{chiller} = \frac{\sum_{i-0}^{12} (Q_p t_{>25^{\circ}C})}{SCOP} \qquad \text{Equation 32}$$

Where:

$F_{chiller}$: Annual fuel energy of the cooling device (kWh)

Q_p: Installed plant output capacity (kW)

t: Total annual occupied hours >25˚C indoor temperature threshold

$SCOP$: Seasonal coefficient of performance of cooling device

The above calculation is based on the DBES simulations provided an estimated cooling energy demand under the stated thresholds. Furthermore, considering climate change and future weather patterns using the UKCP09 timelines, CO_2 emission scenarios and probabilistic percentiles; a longitudinal energy demand of space cooling and heating demand can be estimated alongside the associated operational environmental impact of each dwelling.

3.7. Chapter conclusions

The methodology used is a mixed and balanced approach blending qualitative and quantitative techniques of research that together have complemented each other to provide a triangulation method study (Nau, 1995). This approach rests on the premise that weak information and results from limited access to resources for extended monitoring or data from single methods can be compensated by counter-balancing strengths of each other (Amaratunga et al., 2002). This was useful in this particular research as some data was not available from purely testing buildings and the use of qualitative methods gave a refined and more accurate account to the real performance over time.

The implemented quantitative methods have derived from prescribed and standardised procedures, in order to maintain accuracy and align to industry accepted benchmarks and comparisons. This is the case of the methods described for air permeability and thermal transmission testing. The procedures in place have remained the same, however it's the repeatability and use of data that has been proposed as part of this methodology. The qualitative methods complement the quantitative, results that are later implemented in to refine the analysis tools used – statistical and DBES.

For the purposes of longitudinal analysis, two analysis methods are used both using similar independent variables. Use of degree day data and regression analysis and the DBES extending the building performance after calibration with the effects of climate change.

Stage 4 of the methodology compares the results from the two analysis tools and observes the trends over a longitudinal study. The results from this analysis will begin to demonstrate the decline of dwellings efficiency, which will be linked to the life cycle and service life calculations which will further argue the need for resilient housing through increased impact from the built environment. Referring to Figure 3-1, both methods will seek to use the data retrieved over the four years of occupation and extended to evaluate possible future energy trends and impacts over the environment. This extension of occupancy will be compared against CO_2 emission standards, the as-designed compliance aspirations and Scottish Government targets to assess the real impact over time and ways in which it can be remediated. The methodology discussed in this chapter is a precursor to the subsequent chapters where the results from monitoring, statistical analysis and modelling can show the impacts of dwellings over longer periods, different to targets imposed by policy and design stages.

Chapter 4

Data collection & Results

4.0. Chapter introduction

This chapter will begin by applying the described methodology to generate quantitative and qualitative data from the field tests and monitoring from pre-occupation periods to the fourth year of occupation. The data is analysed independently but applied statistically and then into the dynamic simulation (DBES) models to calibrate and create baseline models. The quantitative data collection and analysis will generate envelope and energy performance data as well as data retrieved from deployed monitoring equipment such as meteorological and internal sensors. A summary of retrieved energy demand and environmental impact; CO_2 emissions, over the years of occupation also forms part of the quantitative data analysis. This data was also compared against design theoretical calculations both as delivered energy consistent with the fuel used for heating in the dwelling. The qualitative data will be obtained from the annual surveys issued to the residents and analysed to extract occupant characteristics, perceptions of comfort and use of dwelling. Following the data collection stages, an analysis to summarise the dwellings results created a mix mode ranking of performance by re-running steady state calculations and non-monitored information with monitored data, easily comparable with design performance factors. This chapter also presents the future weather data acquired nearest to the location of the three dwellings, explaining the timeline and CO_2 projections used to show the buildings resilience over time.

4.1. Quantitative and qualitative data collection

This section follows Stage 1, of the methodology (Chapter 3, Figure 3-1). This first stage in the chapter seeks to present and describe the mixed mode data retrieval obtained throughout the periods of monitoring. The dwellings were continuously monitored to obtain quantitative and qualitative data which involved repeated visits and interaction with the residents and RSL staff. Stage 1 informs Stage 2 and Stage 3 of this research as well as other subsequent chapters. It provides information on the dwelling fabric testing; primarily air permeability and thermal transmission (U-value). Of importance were also the results of total heat energy and the segregation of water and space heating. Following this, a conversion of such heating demand into CO_2 emissions provided an environmental impact figure of each dwelling. Also presented are results of indoor and outdoor conditions that have a direct relation with the dwellings performance and occupant comfort. This information was presented as meteorological data using nearby and on-site weather stations and from loggers inside dwellings recording temperature and relative humidity. Pertinent were also the results of the survey issued, providing an occupant profile and perception of comfort during the monitored years.

4.1.1. Building performance evaluation results

Longitudinal envelope performance tests at set periods of pre and post occupation and the internal/ external environment conditions formed the basis of the quantitative data analysis. In this sub section, data analysis of dwelling wall thermal transmission (U-value) and the air permeability to measure the rate of air infiltration was compared against as-designed theoretical values and subsequently against each year of tests. These results will be analysed statistically and later used to refine the dynamic simulations. Also presented are internal temperature conditions and the results from a full year of external weather conditions. For the analysis of the data, each dwelling was given a distinctive code followed throughout this thesis and described fully in Appendix 1a.

4.1.2. Thermal transmission of walls

Walls form a large part of a building envelope and one that if not addressed adequately can contribute a large part of envelope heat loss. Given the limitations of time, dwelling access and availability of monitoring equipment, this research measured longitudinal U-value performance of walls in the dwellings. Another determining factor were the ten-wall design and specifications, representative in each block of the development.

Table 4-1 shows the differences between the predicted values calculated at the design stage against the results from the in-situ monitoring. The results show a performance gap and considerable effects to the building fabric. Figure 4-1 supports this by comparing measured between interval tests and as-designed predicted values.

Table 4 - 1: Measured In-situ U-value results against predicted at design

	U-value (W/m²K)							
Dwelling code	Design	Year 1 (2012)	Uncertainty (±)	Year 2 (2014)	Uncertainty (±)	Year 3 (2016)	Uncertainty (±)	Mean
F.1.4	0.11	0.21	0.08	0.22	0.05	0.17	0.06	0.20
F.2.5	0.19	0.30	0.08	0.35	0.07	0.35	0.07	0.33
F.3.12	0.15	0.2	0.08	0.27	0.05	0.2	0.07	0.22
B.4.14	0.15	0.44	0.11	0.39	0.08	0.38	0.07	0.40
B.5.16	0.14	0.24	0.07	0.2	0.03	0.21	0.07	0.22
SD.6.17	0.23	0.25	0.06	0.39	0.08	0.38	0.08	0.34
SD.6.18	0.10	0.13	0.08	0.11	0.02	0.14	0.09	0.13
T.7.19	0.15	0.16	0.06	0.14	0.03	0.14	0.06	0.15
T.7.20	0.15	0.18	0.08	0.22	0.03	0.2	0.06	0.20
T.7.21	0.15	0.18	0.07	0.15	0.02	0.17	0.07	0.17
SD.8.23 - BW	0.19	0.13	0.07	0.26	0.04	0.33	0.07	0.24
SD.8.23	0.10	0.14	0.07	0.14	0.03	0.23	0.07	0.17
SD.9.24	0.18	0.23	0.07	0.24	0.03	0.25	0.08	0.24
SD.10.33	0.19	0.28	0.1	0.21	0.04	0.22	0.07	0.24

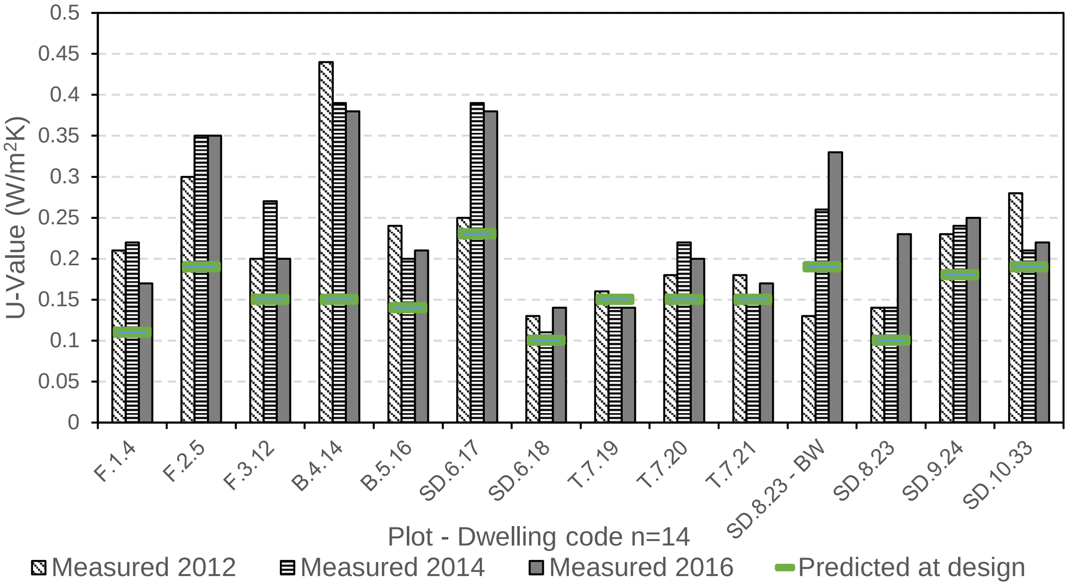


Figure 4 - 1: Measured U-value results against the predicted

To demonstrate the results and their proximity to the predicted, a percentage difference calculation between design and actual mean figures was calculated. As shown in Figure 4-2, results closer to the predicted have a lower percentage difference. Across the development, a mean percentage difference of 47% is obtained, the lowest difference of 2% from a timber closed panel system (T.7.19), whilst 170% difference from an insulated clay brick wall (B.4.14). Dwelling SD.8.23 shows two U-value results and this is due to the varying insulation methods applied. The breathing wall system (SD.8.23 – BW) consisted of expanded polystyrene (EPS) insulation located on the southernly orientation of the dwelling in line with dominant winds and exposure to solar radiation. The other orientations applied the non-breathing wall method (SD.8.23) with mineral wool inside a closed timber panel.

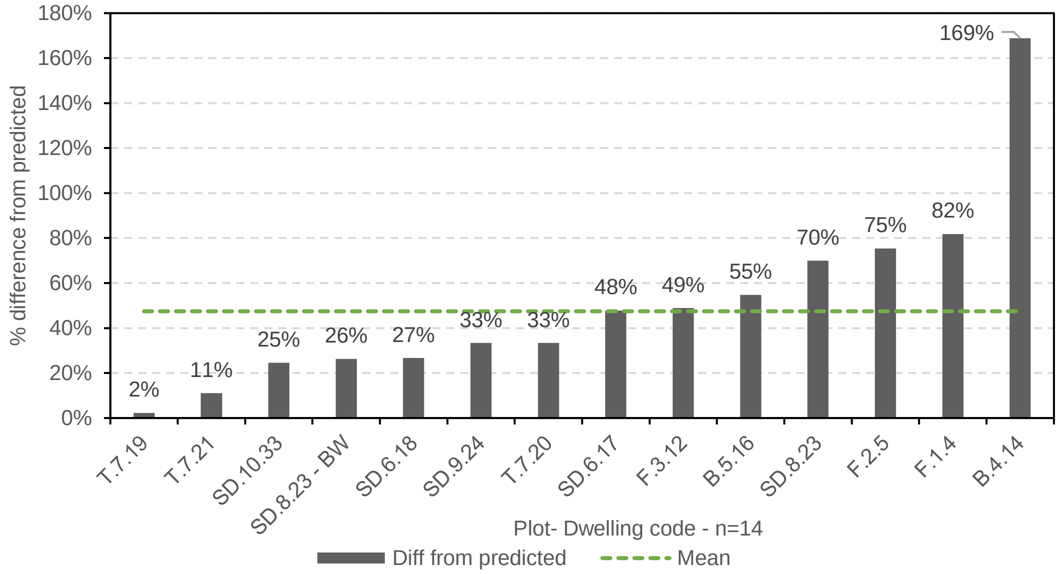


Figure 4 - 2: % difference of mean measured results against predicted values

4.1.3. Air permeability

To account for envelope ventilation heat loss over time, each dwelling was tested prior to hand over and then on a biannual basis. Table 4-2 shows the measured values with a downwards trend in air permeability and an increase in air leakage. A distinct change appears between the pre-handover results and the second-year post-handover. The measurements obtained in the third interval after four years of occupation increases also, however not at the same rate as before.

Table 4 - 2: Measured air permeability

(TFA) Treated floor area					Air permeability - q50 ($m^3/h.m^2$ @50Pa)				
Dwelling code	TFA (m2)	Volume (m3)	Envelope area	Ratio Vol/TFA	q50 (Design)	q50 (2012)	q50 (2014)	q50 (2016)	Mean
F.1.4	77.6	186	240	1.29	2.18	3.07	3.76	3.98	3.60
F.2.5	78.1	180	231	1.28	2.5	2.4	4.39	6.11	4.30
F.3.12	77.9	187	240	1.28	2.00	2.16	2.79	2.79	2.58
B.4.14	78.8	189	243	1.28	2.50	2.00	5.25	5.40	4.22
B.5.16	78.7	188	242	1.29	3.00	2.38	4.50	5.50	4.13
SD.6.17	96.9	247	238	0.96	5.00	3.66	4.00	3.26	3.64
SD.6.18	94.0	232	224	0.97	0.60	0.55	2.10	2.35	1.67
T.7.19	83.2	212	222	1.05	3.00	3.87	5.60	5.78	5.08
T.7.20	83.2	212	222	1.05	3.00	4.80	5.55	6.77	5.71
T.7.21	83.2	212	222	1.05	5.00	4.71	6.15	6.14	5.67
SD.8.23	95.7	239	241	1.01	3.00	2.87	3.37	3.61	3.28
SD.9.24	95.8	247	247	1.00	3.00	3.11	4.30	4.70	4.04
SD.10.33	83.4	239	241	1.01	3.00	2.18	4.47	4.85	3.83

Analysing the results in detail over the period of testing showed that the envelope air leakage increases during occupation, see Figure 4-3. Results show a decline in performance (larger air leakage) except for dwelling SD.6.17 that improved. Most dwellings reached the design expectations during first tests, however the second and third intervals recorded higher values (less airtight).

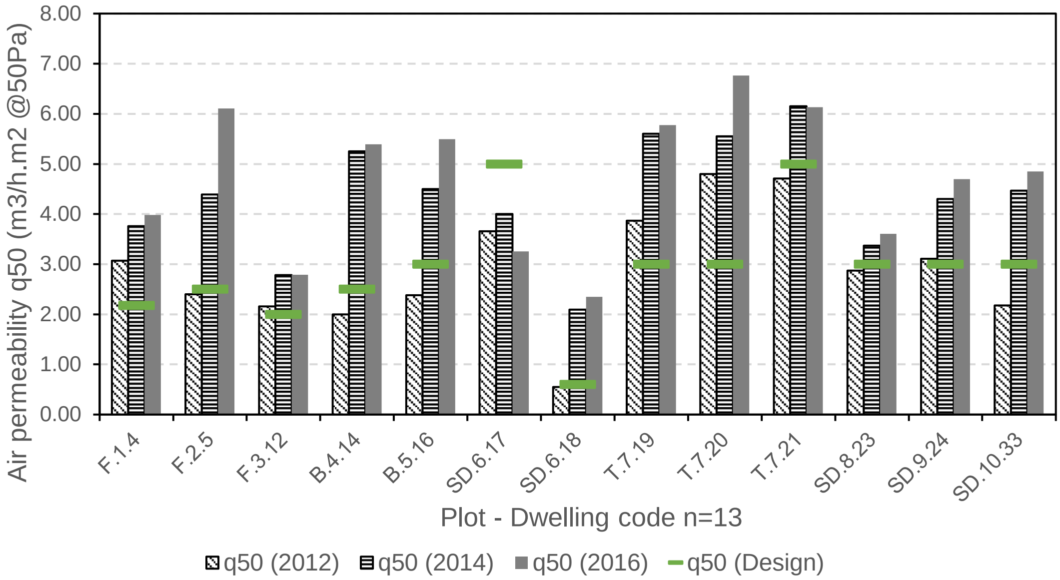


Figure 4 - 3: Air permeability results over time against the predicted

Figure 4-4 shows a percentage difference over the mean values during the three intervals. Dwelling SD.6.17 outperformed the predicted value, in contrast dwelling SD.6.18 obtained a difference of 178% above the predicted.

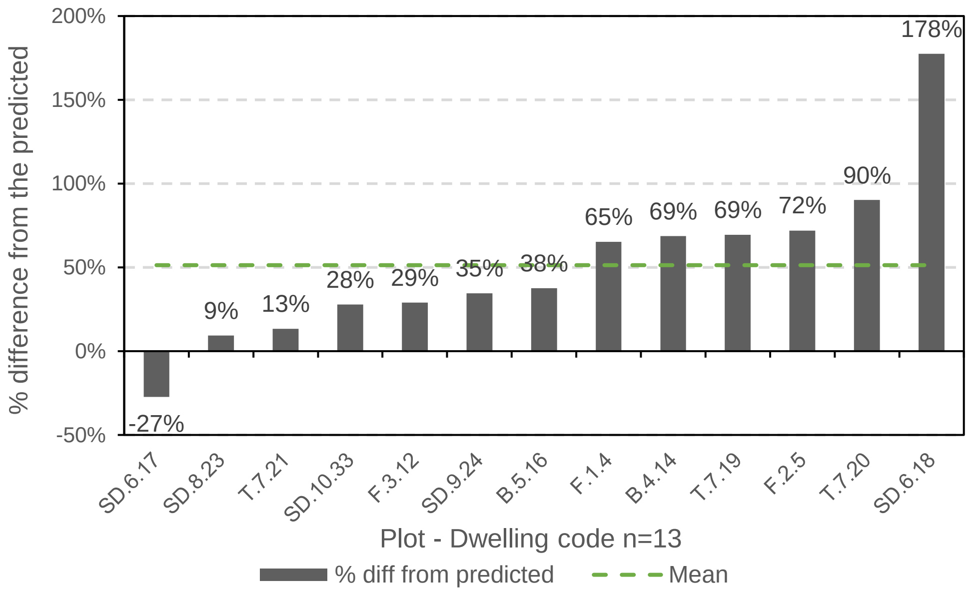


Figure 4 - 4: Mean % difference from the predicted – air permeability

4.1.4. Internal dry bulb temperature and Relative Humidity

Between the heating period of 2015 and 2016-2017, dwelling living room indoor ambient temperature was monitored to obtain dwelling thermal comfort conditions and set point temperatures; later compared with compliance modelling. Additionally indoor relative humidity levels relevant to the indoor comfort conditions of occupied dwellings were monitored; a concern arises if levels drop or increase from recommended levels (<40RH% & >70RH%) (Baker et al., 2015; Refaee and Altan, 2012). As a means of measuring comfort levels, the CIBSE Guide A, table 1.5 (CIBSE, 2015) benchmark and recommended criteria for comfort was used. The guidance recommends that living rooms in dwellings maintain a comfort temperature between 22˚C and 23˚C, while relative humidity levels can range between 40% and 70%. Table 4-3 shows the results over the periods of testing in all 13 dwellings. Nine of the thirteen dwellings managed to monitor two heating periods between 2015 and 2017, the remaining four dwellings only recorded data over a summer and early winter period in 2014.

Table 4 - 3: Analysis of temperature and relative humidity in living rooms

	Temperature (˚C)					Relative Humidity (%RH)					
Dwelling code	Max	Min	Mean	% Hours <22˚C	% Hours >23˚C	Max	Min	Mean	% Hours <40%	% Hours >70%	Δt (˚C)
F.1.4	27.1	17.1	21.9	55%	18%	79.8	42.2	57.5	0%	0%	7.1
F.2.5	27.7	13.3	22.4	36%	30%	81.3	32.2	50.7	15%	1.5%	12.6
F.3.12	25.9	12.3	20.3	80%	8%	81.5	33.4	52.7	1%	0.3%	10.9
B.4.14	27.5	14.7	22.3	40%	37%	65.5	25.0	44.0	34%	0%	12.6
B.5.16	28.7	15.9	22.0	50%	31%	75.7	20.6	44.1	36%	0.1%	12.3
SD.6.17	25.4	18.1	21.1	74%	8%	68.1	37.8	55.5	0%	0%	6.3
SD.6.18	27.0	9.8	21.9	52%	27%	66.0	19.5	40.8	45%	0%	12.2
T.7.19	34.2	12.9	21.2	82%	3%	72.9	20.4	49.5	24%	0.03%	11.8
T.7.20	32.4	16.9	23.4	24%	57%	70.7	22.6	45.6	15%	0.02%	13.7
T.7.21	25.9	12.6	20.1	96%	1%	100.0	26.2	47.7	16%	0.2%	10.7
SD.8.23	27.9	17.2	22.4	42%	35%	70.0	33.7	49.2	2%	0%	7.6
SD.9.24	26.1	12.1	18.9	94%	2%	77.2	25.8	51.0	10%	2%	9.2
SD.10.33	26.6	19.2	21.9	54%	17%	78.2	33.9	52.2	1%	0%	7.1

The percentage of hours above and below the benchmarks and comfort criteria has been calculated to give an indication of how much time the living room is outside and between these boundary points. However, there are periods in which space heating and set point temperatures were set below the criteria, most being during unoccupied periods and night-time. Yearlong temperature and humidity recorded data tested for normal distribution (bell curves) against a histogram are shown in Figures 4-5 and 4-6, and humidity in Figures 4-7 and 4-8. Such data was recorded over two periods; thus, shown separately. One curve shows the data against the measured mean while the other curve shows its distribution using a mean of CIBSE recommended criteria values. The graphs show the mean across all the dwellings and the frequency of readings. Such observations are important across the monitored dwellings as they provide an indication of thermal comfort, directly related to heating patterns and energy demand. Figure 4-5 shows a frequency range between 21.5 and 22.5 ˚C, similarly, Figure 4-6 between a range of 20.5 and 22 ˚C. The first set of dwellings in Figure 4-5 have a distribution skewed to the left using the mean of the recorded data, however a better alignment is shown using the CIBSE best practice mean.

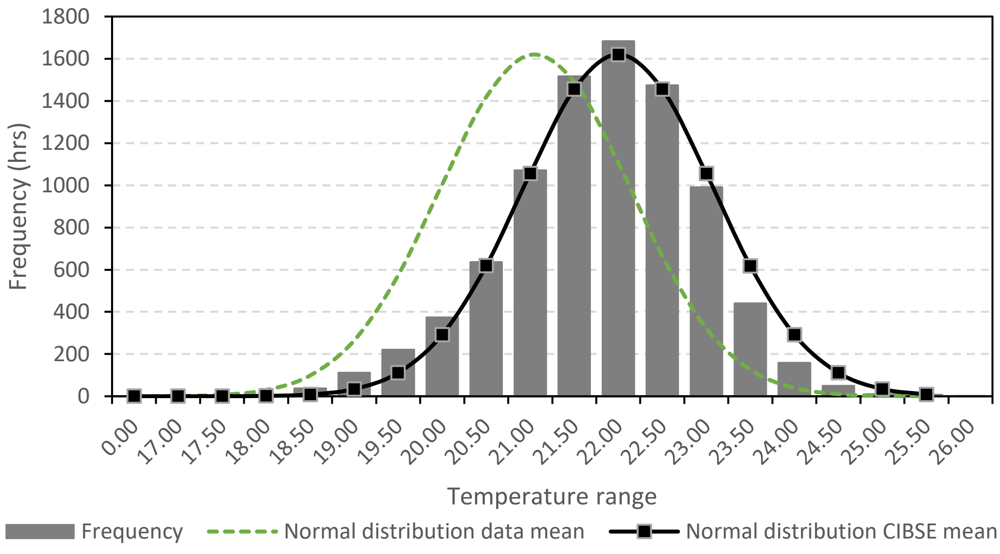


Figure 4 - 5: Temperature histogram of normal distribution with Data & CIBSE mean – Living room in dwellings: B.4.14, SD.9.24, T.7.20, F.2.5 & T.7.19

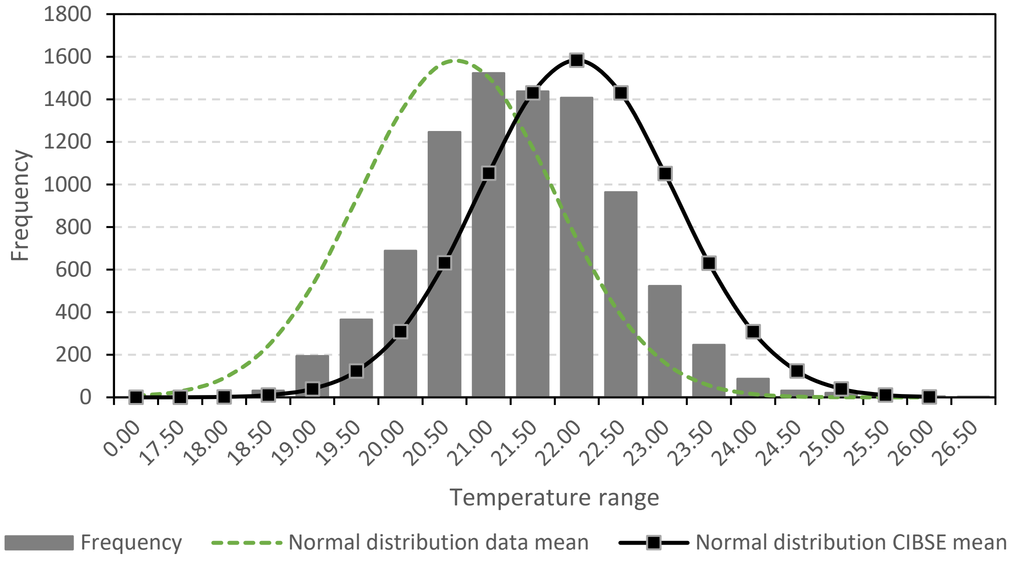


Figure 4 - 6: Temperature histogram of normal distribution with Data & CIBSE mean – Living room in dwellings: B.5.16, T.7.21, F.3.12 & SD.6.18.

Other dwellings in Figure 4-6 show data is between the two normal distribution bell curves but doesn't fully align to them, despite covering wider temperatures.

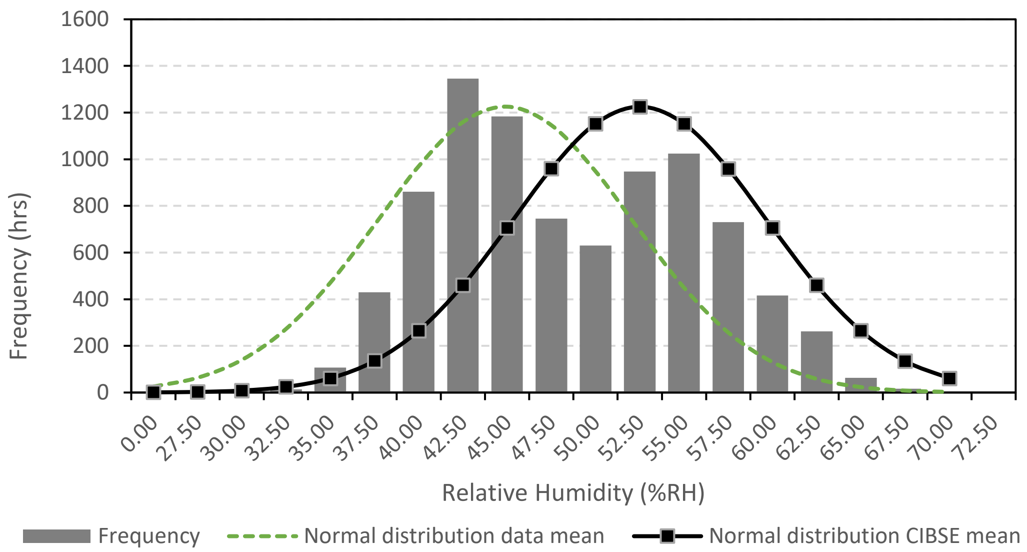


Figure 4 - 7: Humidity histogram of normal distribution with Data & CIBSE mean – Living room in dwellings: B.4.14, SD.9.24, T.7.20, F.2.5 & T.7.19

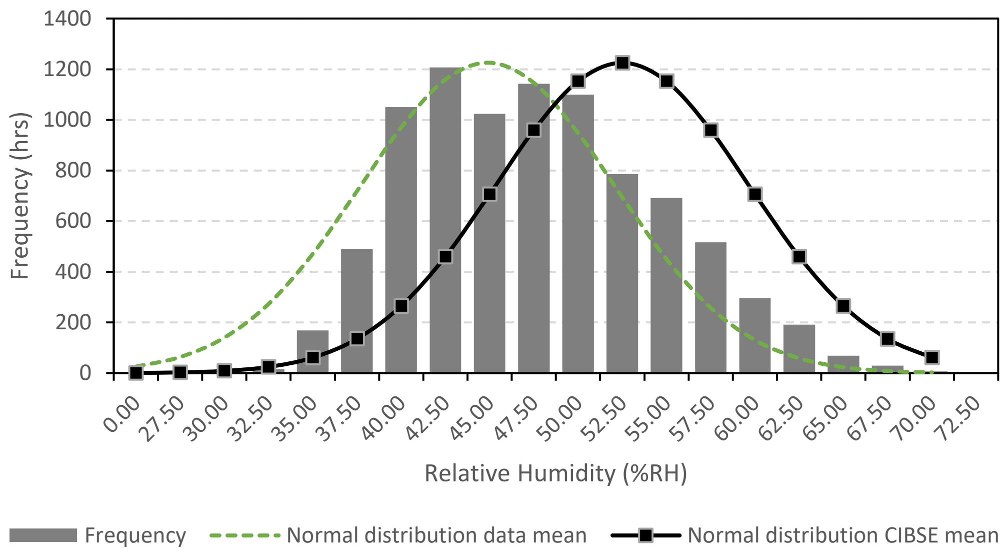


Figure 4 - 8: Humidity histogram of normal distribution with Data & CIBSE mean – Living room in dwellings: B.5.16, T.7.21, F.3.12 & SD.6.18.

Recorded relative humidity over the same periods of occupation show that the mean in all dwellings is between 40 and 45 %RH, as shown in Figures 4-7 and 4-8. In both frequency charts, the normal distribution aligns best to the mean of the data as the CIBSE benchmark is skewed to the right in the upper range of readings.

4.1.5. External weather conditions

Over the course of the monitoring period, external weather conditions were obtained from two sources; local weather stations and deployed site weather station. Data has been recovered which will form the basis of analysing the dwellings under actual meteorological conditions both from a perspective of weather exposure and performance under changing weather patterns. Table 4-4 below summarises the recorded meteorological weather from the two sources as mean yearly values from 2013 to 2016, with full monthly data available in Appendix 4a. For the purposes of DBES to calibrate and increase the approximations between what has been modelled and the actual energy use, a weather file over a twelve-month period closely aligned to year three of occupation was used. This period was preferred as it aligned with a true representation of the dwellings energy demand analysis (Bros-Williamson et al., 2017) while also providing a full data set to be used in the modelling software.

Table 4 - 4: Mean yearly recorded meteorological data – weather stations

	Year 1 2013	Year 2 2014	Year 3 2015	Year 4 2016
Mean Temperature (°C)	8.78	9.98	9.73	9.74
Mean Humidity (%RH)	70.65	71.90	81.35	81.44
Mean Pressure (mBar)	1013	1007	1016	1011
Mean Solar Radiation (W/m^2)	-	-	114.21	108.71
Mean Wind Direction (degrees)	-	-	191	169
Mean Wind Speed (m/s)	2.20	2.15	2.30	1.98

4.1.6. Longitudinal delivered energy demand

The assessment of total delivered energy consumption resulted in the separation of water and space heating. Meter readings were collected after full twelve-month periods of occupation, however essential to this study is space heating energy demand converted into kWh's for a direct comparison with as-designed calculations and best practice benchmarks. Many dwellings were fitted with renewable technology that would alleviate the energy used for water and space heating. However, this energy data was not always accurate and available as it was used by the RSL to claim feed-in-tariff incentives.

This section describes the best normalisation factor used in the research to compare data against benchmarks and other years of occupation. It follows the total heat energy for each dwelling and the separation between space and water heating using compliance model equations in combination with qualitative and quantitative data results. Finally, environmental impact of the consumed energy is compared against Scottish Government targets and standards.

4.1.7. Identifying the best normalisation factor

Analysis between dwellings within a sample size or larger regional or national data sets often use a normalisation factor that acts as an equal unit to compare against. Most studies tend to compare energy calculated or delivered over the heated floor space (kWh/m^2) however that factor may not be appropriate across the whole sample making the comparison inaccurate and difficult to interpret. To define the best factor to implement in the research, the coefficient of variation (CV%) was used as a percentage using design and delivered space heating of all dwellings across the four years of occupation.

Table 4 - 5: Normalisation of data under coefficient of variation (CV%)

	Year				
	2012-13	2013-14	2014-15	2015-16	Mean 4 years
kWh	50%	49%	60%	55%	51%
kWh/m^2	51%	50%	58%	55%	51%
kWh/ppl	62%	60%	61%	64%	60%
kWh/m^3	52%	51%	58%	52%	51%
kWh/kWh	56%	56%	58%	68%	58%

Results in Table 4-5 show that lower the CV%, the closer each individual data point is to the group mean, suggesting that the mean is a good representation of the whole data set. These results show that by normalising the space heat consumption data against the design calculation obtained from the SAP2009 compliance model (kWh/kWh), a high CV of 58% is obtained. Normalising by number of people (ppl) obtains the highest CV of 60%. In the case of normalising by people, perhaps weighting of people on a 1 to 1 ratio is insufficient to account for the complexities of heat consumption behaviour by households with very young and/or elderly occupants. However, a lower CV is found when space heating energy consumption is normalised by the heated volume (m^3), floor area (m^2) and on its own without any normalisation (kWh) meaning these normalisation factors are appropriate for this research. This exercise was useful as it gave a higher confidence over the varied normalisation factors used in similar studies and provides confidence over the use of energy over treated floor area in this study.

4.1.8. Total delivered energy for heating

Each dwelling was monitored for its delivered heat and electric energy demand for four consecutive years from the residents first and last monitored heating periods from 2012 until 2016 and early 2017. This research focused on heating energy demand, particularly energy for delivered space heating, where natural gas was the dominant fuel used, except for two dwellings where air source heat pumps (ASHP) were powered by electricity. Such dwellings were fitted with heat meters to distinguish energy for heating. Total delivered heat energy converted into annual kWh's using the formulas and criteria explained in Chapter 3 are shown in Table 4-6. Due to a heat meter malfunction and pulse factor calibration, dwelling F.2.5 could not provide an accurate reading of their delivered heating demand following the first year of occupation.

Figure 4-9 shows the percentage difference (% diff) between the calculations of total heating energy at the design stage and the mean over the four years of occupation. This data shows all sources of heat such as water, space and even cooking energy demand, thus is dependent on many factors that could answer the displacement between the designed. This research uses space heating to define the envelope performance. The lowest displacement is shown by SD.6.17 of just 5% whilst dwelling T.7.19 showed a large displacement of 227% more than twofold its design calculations. The mean across the twelve dwellings was 106% difference, which is above double the design calculations. Important to point out is the need for these results to be segregated to recognise and compare energy for cooking, space and water heating separately.

Table 4 - 6: Total delivered heat energy compared with design calculations

	Total heat energy demand (kWh/ year)					
Dwelling Code	Design total	Year 1	Year 2	Year 3	Year 4	Mean all years
F.1.4	3,799	8,014	7,972	8,207	8,090	8,071
F.3.12	5,132	6,250	5,608	6,149	5,523	5,882
B.4.14	3,476	11,084	9,108	8,205	8,486	9,221
B.5.16	3,811	8,796	8,357	9,750	7,970	8,718
SD.6.17	6,359	8,266	5,884	6,173	6,410	6,683
SD.6.18	4,821	5,875	6,739	6,226	6,365	6,302
T.7.19	2,078	6,937	6,485	6,625	7,103	6,787
T.7.20	2,749	6,192	6,371	5,382	6,013	5,990
T.7.21	4,418	7,217	7,096	7,418	7,942	7,418
SD.8.23	5,942	12,250	10,523	14,257	11,987	12,254
SD.9.24	3,957	9,568	9,251	8,163	9,176	9,040
SD.10.33	4,598	11,577	11,305	12,916	14,494	12,573

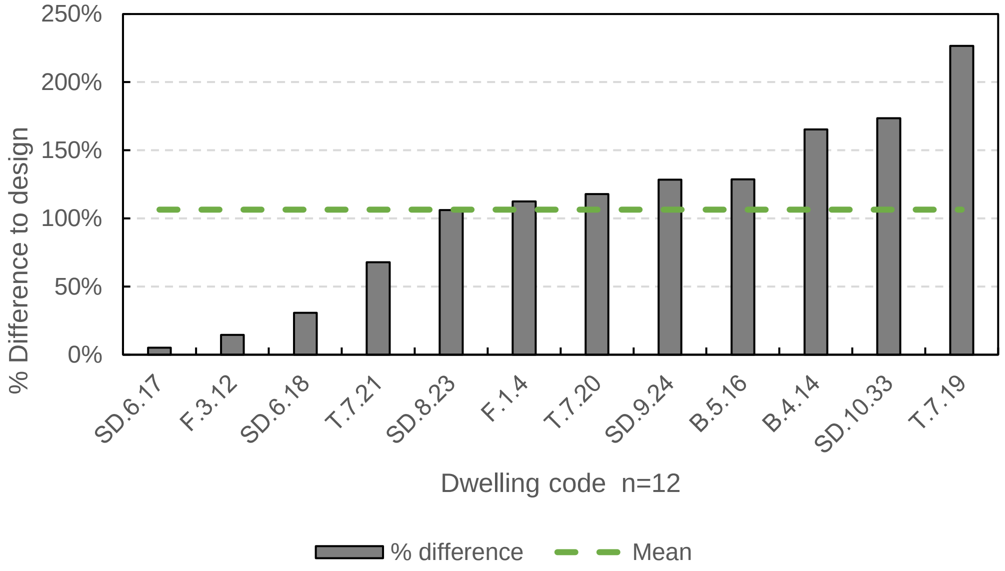


Figure 4 - 9: % difference of mean recorded heat energy against the design calculations

4.1.9. Delivered energy for water heating

Using the results of the qualitative yearly survey data from each household and the guidance and formulas explained in Chapter 3, it was possible to calculate the new hot water heating requirements in relation to the actual number of occupants, as shown in Appendix 4b and summarised in Table 4-7. The new calculation has considered water heating by accounting for the number of baths, showers and the mix per household of fuel used for kitchen hot water use. Also considered was the type of cooking fuel used in each household. This actual amount calculated was subtracted from the total delivered energy to obtain an actual energy distribution between water and space heating.

Table 4-7 summarises the calculations between the revised dwelling occupant numbers and the use of actual hot water demand through the qualitative surveys. Although individually some dwellings had a smaller occupancy than predicted, on average there was an increase against the design predictions. This coupled with the actual calculation of showering, bathing and kitchen water use impacted on the new hot water demand.

Table 4 - 7: Actual number of occupants and household surveys for actual water heating

Dwelling code	TFA* (m²)	No. of occupants		Water heating (kWh/ yr)				Cooking	
		Design	Actual (mean)	Design stage	Actual calculated	Diff	% Diff	Fuel type	kWh/yr
F.1.4	77.62	2.42	2	2,175	2,786	611	28%	gas	674
F.2.5	78.14	2.43	2	1,156	1,379	223	19%	gas	674
F.3.12	77.9	2.42	2.25	2,517	3,239	722	29%	gas	698
B.4.14	78.8	2.44	2	1,044	1,354	310	30%	gas	674
B.5.16	78.67	2.44	2	1,737	2,067	330	19%	electric	385
SD.6.17	96.92	2.71	3.75	2,535	3,298	763	30%	gas	842
SD.6.18	93.96	2.68	4	2,792	3,728	936	34%	electric	495
T.7.19	83.2	2.52	2	1,719	1,738	19	1%	electric	385
T.7.20	83.2	2.52	4	2,099	2,792	693	33%	gas	866
T.7.21	83.2	2.52	2	2,334	2,392	57	2%	electric	385
SD.8.23	95.76	2.70	3	2,755	3,327	572	21%	gas	770
SD.9.24	95.8	2.70	3.5	1,541	2,070	529	34%	electric	468
SD.10.33	95.76	2.70	5	3,192	4,079	888	28%	gas	963
Mean		2.55	2.88						
SD		0.12	1.05						

* Treated floor area

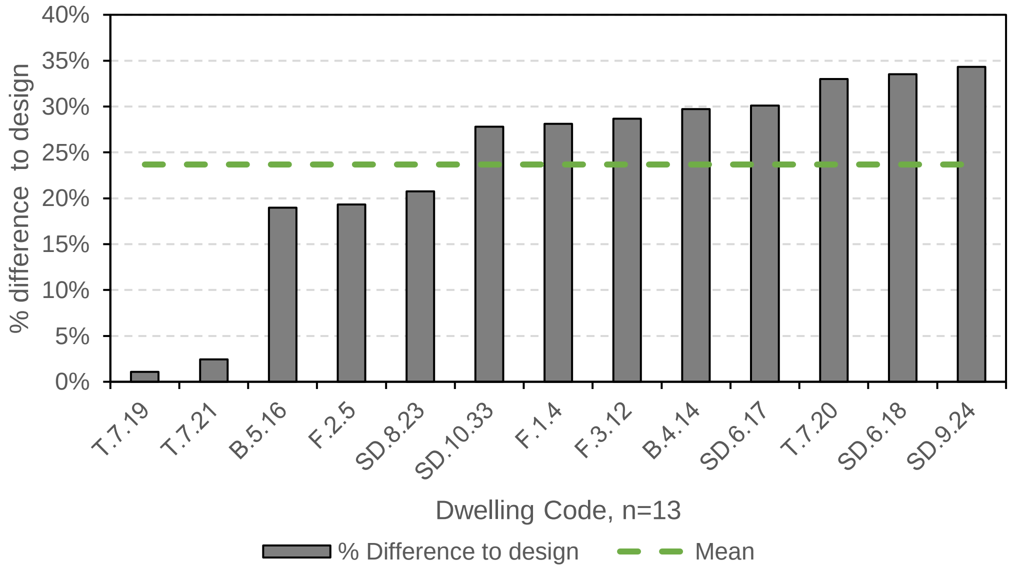


Figure 4 - 10: Energy for hot water percentage difference to the design calculations

The average percentage difference against the predicted was 24% more hot water demand with highs of 34% and some small differences of 2%, as shown in Figure 4-10.

4.1.10. Delivered energy for space heating

By subtracting the revised hot water heating and cooking demand, a new actual space heating demand is obtained over the four years of occupation, as shown in Table 4-8. The separation of the water heating and cooking has provided a comparable space heating demand responding to the actual number of occupants in the dwellings and the re-calculation of actual energy for water heating. Data recorded over the four years of monitoring shows for most dwellings that the first year of occupation experienced the largest displacement from the as-designed calculations. The consumption then begins to stabilise as occupants adjust to their new dwelling and energy demand is adjusted. A clear comparable set of demand data in years 3 and 4 confirms that the adjustment period has been passed and that the totals are more presentative of the occupant's energy demand for space heating.

Table 4 - 8: Summary of revised space and water heating demand after energy segregation

	Predicted design heating (kWh/yr)		Actual energy for heating (kWh/yr)					
Dwelling Code	Design water heating	Design Space heating	Actual Water heating	Actual Cooking	Actual space heating demand			
					Year 1	Year 2	Year 3	Year 4
F.1.4	2,175	1,624	2,786	674	4,554	4,513	4,748	4,630
F.3.12	2,517	2,615	3,239	698	2,313	1,671	2,212	1,586
B.4.14	1,044	2,432	1,354	674	9,056	7,080	6,178	6,458
B.5.16	1,737	2,074	2,067	385	6,345	5,905	7,298	5,518
SD.6.17	2,535	3,823	3,298	842	4,126	1,744	2,032	2,270
SD.6.18	2,792	2,029	3,728	495	1,653	2,516	2,003	2,142
T.7.19	1,719	359	1,738	385	4,814	4,363	4,502	4,980
T.7.20	2,099	587	2,792	866	2,534	2,713	1,724	2,355
T.7.21	2,334	1,880	2,392	385	4,440	4,320	4,642	5,165
SD.8.23	2,755	3,186	3,327	770	8,153	6,426	10,160	7,890
SD.9.24	1,541	2,416	2,070	468	7,030	6,714	5,626	6,638
SD.10.33	3,192	1,406	4,079	963	6,536	6,263	7,874	9,452

Using the normalisation factor of annual kWh over dwellings floor space (kWh/m^2/yr), results are compared with design standards and benchmarks.

Table 4 - 9: Revised space heating demand compared with benchmarks

Dwelling Code	TFA* (m^2)	Space heating demand ($kWh/m^2/yr$) Design	Actual mean all years	Actual mean year 3 & 4	Silver SBS	Gold SBS	Passiv haus	% difference
F.1.4	77.62	20.93	55.42	60.41	30	20	15	165%
F.3.12	78.8	33.19	23.38	24.10	30	20	15	-30%
B.4.14	78.67	30.92	86.46	80.31	35	25	15	180%
B.5.16	96.92	21.40	75.32	66.12	35	25	15	186%
SD.6.17	93.96	40.69	30.56	22.89	35	25	15	-23%
SD.6.18	83.2	24.38	24.98	24.91	35	25	15	16%
T.7.19	83.2	4.31	56.07	56.99	35	25	15	1199%
T.7.20	83.2	7.06	28.03	24.52	35	25	15	297%
T.7.21	95.76	19.63	55.79	51.20	35	25	15	147%
SD.8.23	95.8	33.26	98.04	94.21	35	25	15	195%
SD.9.24	95.76	25.23	78.15	64.03	35	25	15	210%
SD.10.33	95.76	14.68	90.52	90.47	35	25	15	516%
* Treated floor area							Mean	264%

Table 4-9 shows the comparison which is useful to recognise gaps in performance over longer periods of occupation but also the variance between industry standards. The use of the SBS Section 7 criteria for Silver level dwellings of this type, where flats are expected to consume 30 $kWh/m^2/yr$ and detached or semidetached dwellings 35 $kWh/m^2/yr$ provides a comparison between them (SBS, 2011).

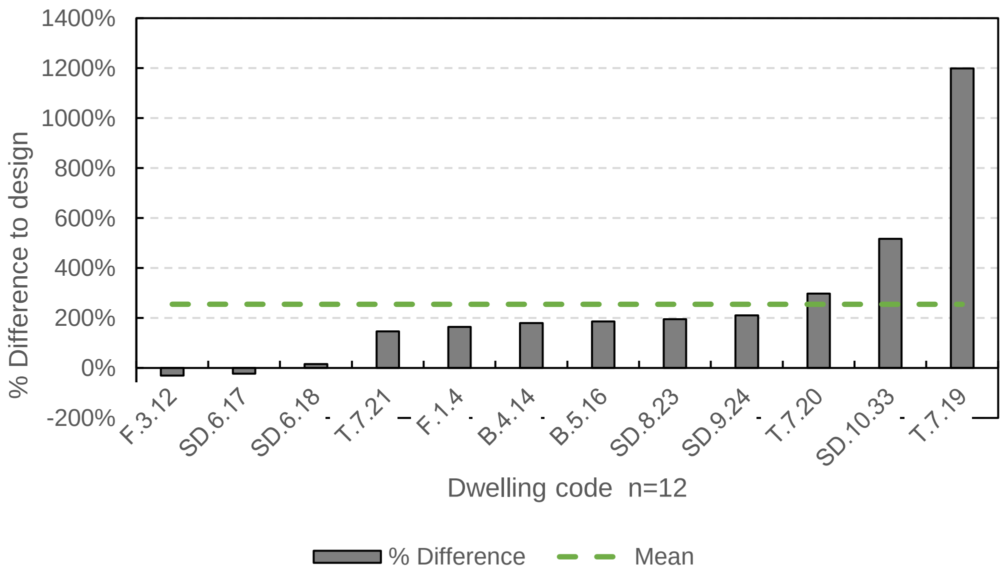


Figure 4 - 11: % difference between design and actual over years 4 & 5 of occupation

Only four dwellings out of the twelve analysed achieved the Silver standard and only one dwelling achieved the Gold level where flats are required to achieve 20 kWh/m^2/yr and dwellings 25 kWh/m^2/yr. Likewise the more stringent *Passivhaus* standard requiring 15 kWh/m^2/yr of normalised space heating demand. Dwelling SD.6.18 designed to the *Passivhaus* standard did not achieve this level of performance. Not all properties have been designed to these standards, however they do align to sustainable energy efficient dwelling energy demand which was the motivation in this housing development.

Figure 4-11 displays the displacement between the design and the actual mean value over the last two years of occupation. Only three dwellings achieved a 30% or less displacement than the design with the remaining consuming more than double its predicted demand and close to the samples mean displacement of 264%. Dwelling SD.20.33 reached five times more energy use than the design. Another designed to the SBS Gold level of energy use; dwelling T.7.19 exceeded the design figure by 1200%, partly due to its very ambitious energy calculation at design stage. As evidenced in the fabric performance results, dwellings SD.6.17 and F.3.12 have consumed less than its prediction, -23% and -30% respectively.

4.1.11. Environmental impact of delivered space heating energy

Following the analysis of space heating recorded and calculated over the four years of occupation, an analysis of the impact of fuel used on the environment against design predictions took place. The analysis is made using Environmental Reporting Guidelines set by DEFRA, (2013) and yearly UK Government Conversion Factors for greenhouse gas (GHG). The change in factors have been applied accordingly to the monitored data of each dwelling fuel for space heating. Table 4-10 shows the impact of energy used for space heating where eleven out of the twelve dwellings use natural gas whilst one uses electricity (T.7.19). The rate of displacement between the design operational CO_2 emissions of the analysed years of occupancy are like the delivered energy, although dwelling T.7.19 will have a larger impact as the CO_2 emission equivalent factor for electricity is higher than that of natural gas.

Table 4 - 10: Environmental impact of space heating over the four years of monitoring

Dwelling code	CO_2 emissions ($kgCO_2e/m^2/yr$)						
	Design	Year 1	Year 2	Year 3	Year 4	Actual mean all years	Mean years 3 & 4
F.1.4	4.14	10.80	10.75	11.28	10.98	10.95	11.13
F.3.12	6.65	5.40	3.92	5.18	3.70	4.55	4.44
B.4.14	6.11	21.19	16.65	14.49	15.11	16.86	14.80
B.5.16	5.22	12.05	11.27	13.89	10.48	11.92	12.18
SD.6.17	7.81	8.08	3.43	3.99	4.44	4.99	4.22
SD.6.18	4.28	3.66	5.59	4.44	4.74	4.61	4.59
T.7.19	2.23	12.23	10.89	10.96	12.14	11.55	11.55
T.7.20	1.40	5.60	6.03	3.82	5.21	5.17	4.52
T.7.21	4.47	8.53	8.34	8.94	9.92	8.94	9.43
SD.8.23	6.59	15.66	12.41	19.56	15.15	15.70	17.36
SD.9.24	4.99	13.51	12.97	10.84	12.75	12.52	11.80
SD.10.33	2.91	12.56	12.10	15.17	18.16	14.50	16.66

Table 4-10 shows normalised operational CO_2 emissions over the four years of occupation, Figure 4-12 shows how different these are against design calculations. The control house, SD.6.17, dwelling F.3.12 and SD.6.18 have all emitted less CO_2 than predicted, however most dwelling have emitted close to the sample mean of 150% above the design calculations and only three dwellings emit above it; dwelling T.7.20 nearly three times the estimated (275%) and dwellings SD.10.33 and T.7.19 by four-fold.

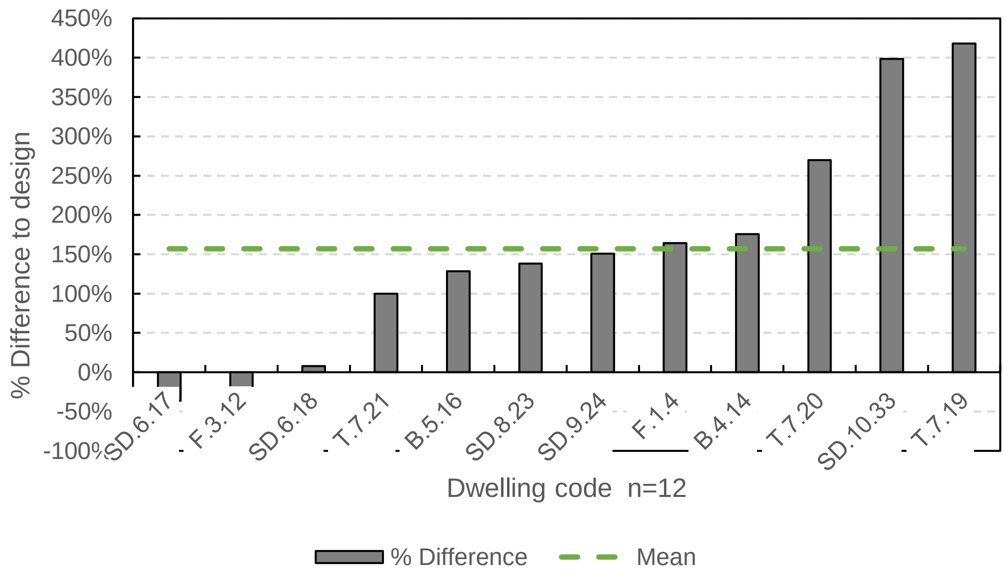


Figure 4 - 12: % difference of CO_2 emission against design calculations for space heating

4.1.12. Occupant profiling and perceptions of comfort

As described in the methodology section, dwelling occupant visits included a yearly qualitative evaluation in the form of a survey. The purpose of such assessments was to obtain data on dwelling use and occupant characteristics with perceptions of occupant's comfort levels. The first survey took place between November and December 2013, a full year with both a winter and summer period after occupation. The subsequent surveys in 2014, 2015 and 2016 replicated the same questions to the same households giving a clear longitudinal appreciation of the occupant's demographics and thermal comfort levels. This section is split between the occupant household profiling and the evaluation of the occupant comfort. Both sets of data were useful to further evaluate the dwellings as-built occupancy patterns and merge occupant indoor comfort conditions with the quantitative data retrieved for energy demand and recorded indoor temperatures.

4.1.13. Occupant profiling

Household occupancy profiles (OP's) were defined from the analysis of the survey responses which concerned occupant type, their activity and dwelling use. The results were used to understand the analysis of energy demand and also serve as occupant schedules in the calibration of the dwelling models.

Important for defining these OP's is the occupant's employment and daily activity in order to understand how often they were in the home using services such as space and water heating that can later be compared with the dwelling space heating demand. Occupants that are in the dwelling most of the time during the working week have been classified into the OP 1 category; those out of the dwelling most of the working week belong to classification OP 2 and a third category, OP 3 was created depicting occupants that use the dwelling half of the time most of the working week, including those in part time employment and with children attending nursery. Figure 4-13 shows the percentage split of the sample demographic, based on employment and daily activity over the surveyed years.

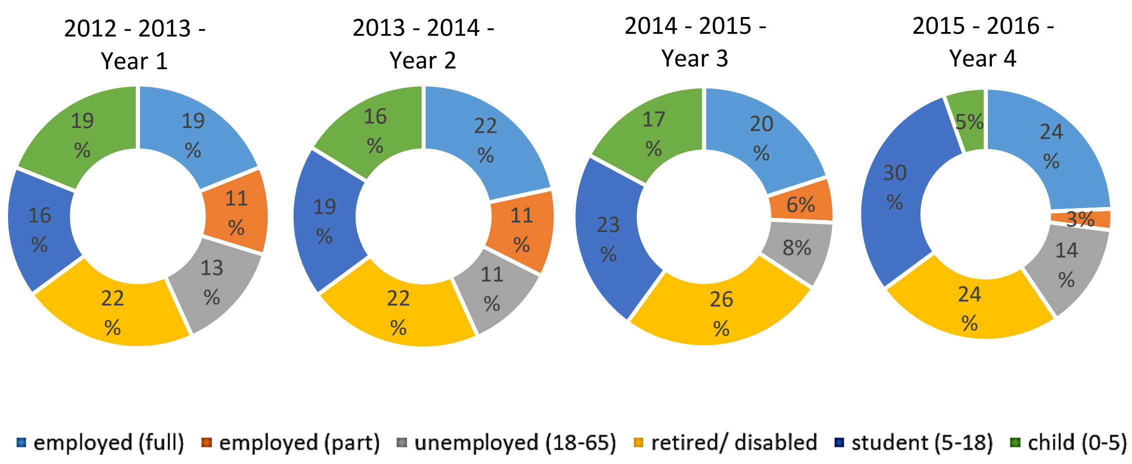


Figure 4 - 13: Years 1, 2, 3 and 4 employment status

Figure 4-13 above shows that occupant profiles are based on their day-to-day activity, employment status and occupants that are studying. Six activities and employment modes were identified. A mean percentage of 21% of occupants fell under the fully employed status; similarly, the retired or disabled occupants that occupied 24% of occupants. Likewise, were the full-time students who are represented by 22% of the population. These three modes present opposite occupancy time periods; the fully employed and the students are absent most of the time and the retired are mostly in the dwelling most of the time. A logical chronological observation can be made of the percentage of small children during the first three years of the study (18%), whereby in year four, these children have moved on to full time education or longer hours at nursery, thus less hours in the home.

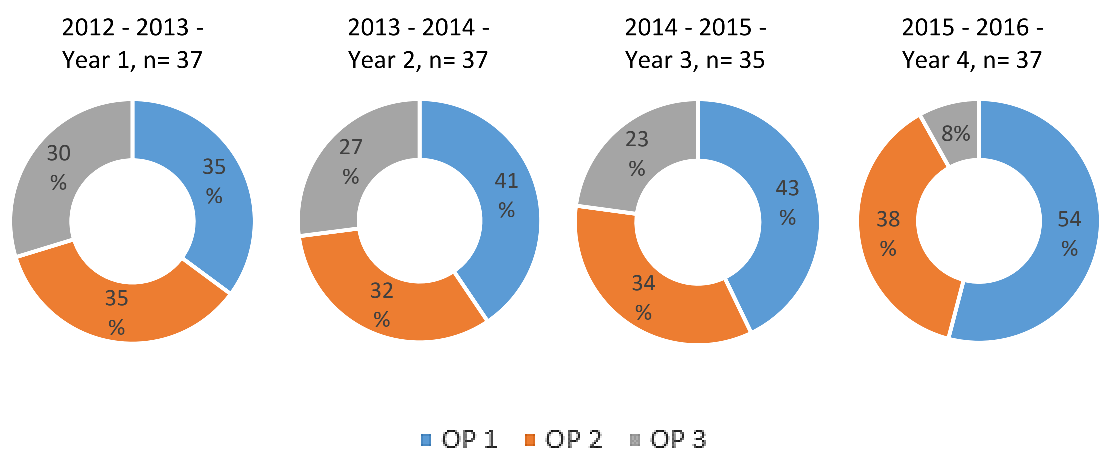


Figure 4 - 14: Years 1, 2, 3 and 4 occupancy profile

Figure 4-14 shows that a variety of occupancy profiles have emerged from the survey and the analysis of Figure 4-13. Although individually the majority can be placed in OP1 representing a mean 43 of the population out most of the day, a second predominant profile of occupants (mean 34%) is OP 2 in and partly in the property most of the day means that that dwellings have occupants at all times in the week which in winter months may increase heating and lighting demands. Occupants in OP 3 are strongly represented in the first three years of occupancy (mean 27%), but sharply fall to 8% in year four. The occupant profiles in years one, two and three do not differ much, however in year four there is shift from part time to full time occupancy. Results from the occupant profiling of the analysed sample indicate that each dwelling should be analysed separately using its predicted and actual energy during the analysed years.

4.1.14. Differences between design and actual occupancy

The surveys were also useful to account for the actual number of occupants living in the dwellings, compared with the number of occupants used for the compliance energy consumption calculations. The real occupant numbers used in this research can been seen in Table 4-11, however for calculation purposes the mean from the four years of data was used to simplify the analysis.

Table 4 - 11: Comparison of design and actual occupant numbers

	Number of occupants					
Dwelling code	Design SAP	Year 1	Year 2	Year 3	Year 4	Actual (mean)
F.1.4	2.42	2	2	2	2	2
F.2.5	2.43	2	2	2	2	2
F.3.12	2.42	2	2	2	3	2.25
B.4.14	2.44	2	2	2	2	2
B.5.16	2.44	2	2	2	2	2
SD.6.17	2.71	3	3	4	5	3.75
SD.6.18	2.68	4	4	4	4	4
T.7.19	2.52	2	2	2	2	2
T.7.20	2.52	4	4	4	4	4
T.7.21	2.52	2	2	2	2	2
SD.8.23	2.70	3	3	4	2	3
SD.9.24	2.70	4	4	3	3	3.5
SD.10.33	2.70	5	5	5	5	5
Mean	2.55	2.85	2.85	2.92	2.92	2.88
SD	0.12	1.07	1.07	1.12	1.19	1.05

On average, all the dwellings present a small difference between the calculated occupant values in the compliance predictions; 2.55 occupants as designed and 2.88 mean of all years and all dwellings. However, comparing dwellings individually between them shows a significant difference, such is the case of dwelling SD.10.33 which had 2.30 more occupancy numbers than the predicted. These distinct increases of occupancy numbers can be seen in 6 out of the 13 dwellings surveyed. There are also decreasing occupant numbers, the majority by small differences. The changes in occupant numbers together with the profiles identified above have a large impact on energy use and contribute to the discrepancies between predicted and actual energy demand.

4.1.15. Dwelling occupant comfort

As part of the surveys issued to each head of family, there were a set of questions focusing on comfort within the dwelling. The occupants were asked to answer according to their comfort levels experienced in the year past, combining summer and winter periods. Three main categories were included:

- Perception of temperature (Temperature)
- Perception of ventilation (Air movement)
- Perception of natural and artificial light (Illuminance)

All three aspects were integrated into the survey with two Likert scale options each, addressing comfort conditions aligned to the perceptions of the dwelling over a whole year of occupation. Chapter 3 explains the methodology behind the survey and Appendix 3g includes a sample questionnaire used with all participants.

In order to explain and evaluate the comfort and reaction to the dwellings, survey answers were displayed in Figures 4-15 to 4-18 in line with the three comfort perceptions and the year of the survey results. The results were placed in acceptance bands where green signifies an area of comfort and satisfaction. The red band has a negative reaction and discomfort, whilst the white band is a moderate perception of the dwellings.

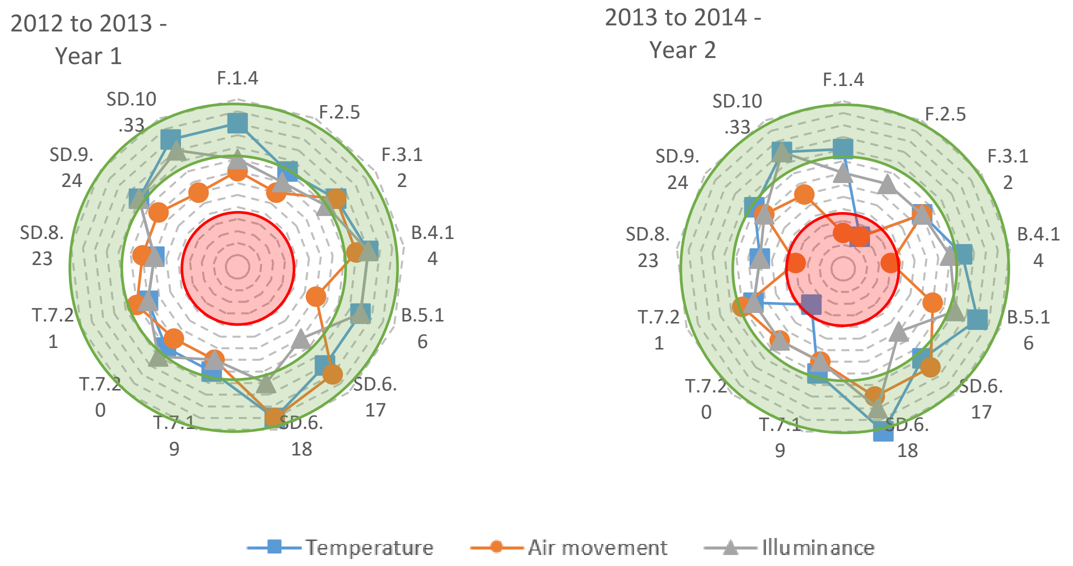


Figure 4 - 15: Results of comfort during year 1

Figure 4 - 16: Results of comfort during year 2

Figure 4-15 which displays the results for year one, regarded as an adjustment year, where most people are learning how to operate the building and are generally content with the home they have been given, in some instances much better to what they previously had. Year two shown in Figure 4-16 is regarded as a realisation year where the occupants are much more aware of the good and bad aspects of the dwelling.

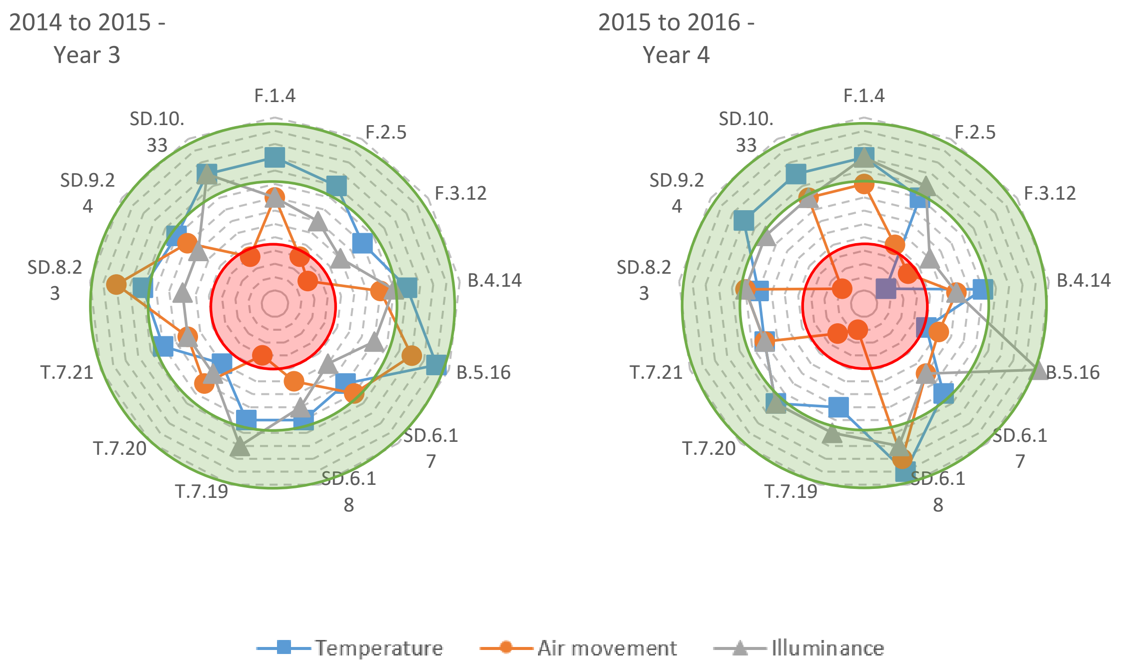


Figure 4 - 17: Results of comfort during year 3

Figure 4 - 18: Results of comfort during year 4

Years three and four in Figure 4-17 and 4-18 respectively, are considered as depicting a more realistic interpretation of the dwellings where most occupants fully engage with the dwellings and at times are more frugal in their use of it, including energy use. Distinctively year one differs from the rest of the years as it tends to be a more positive year as occupants are happy with their new home. Subsequent years are evaluated more stringently.

4.1.16. Overall occupant comfort

The perceived comfort of the sample dwellings across the four years of occupation is analysed in Figure 4-19. Rather than analysing each dwelling individually and comparing against each other, an overall mean value of all the dwellings is used to summarise each of the aspects of comfort for the years in which the surveys were issued. This results in a perception banding of high, medium and low comfort that shows occupant's levels of comfort as the buildings are being used. Year one shows that the response to the three comfort categories were close to the high comfort level. Year two shows a decrease in comfort, particularly in air movement with a declining negative perception to air movement. Year three sees a dispersion of the three categories but just as year two, within the medium comfort level. Year four shows a tendency to decline the perception of the buildings with a downwards decline in the scores and comfort level. Trends and relationships with other independent variables in this research can be used to further understand dependent variables such as demand of space heating. However, this overall comfort should be used with caution as there are other unaccountable variables which could influence the values and that are beyond the scope of this research (energy cost, past housing conditions and occupant cultural and ethnic background).

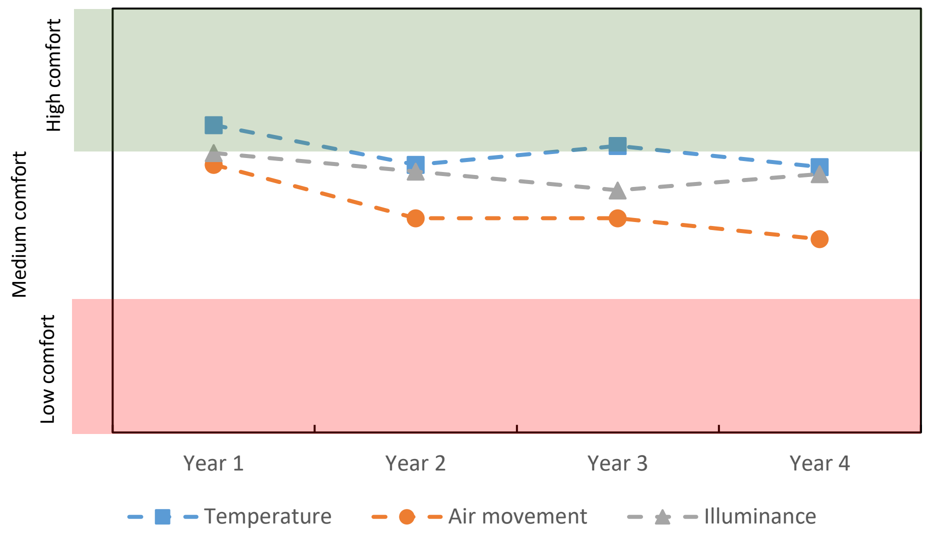


Figure 4 - 19: Perceived mean comfort results over the four years of study

4.2. Descriptive statistics and steady state calculations

4.2.1. Introduction

This section of the chapter presents a first glimpse of a statistical analysis with the data collected over the monitoring period. It forms part of Stage 2 mentioned in Chapter 3, Figure 3-1 that includes the use of results to obtain performance ranking, normalisation of data and descriptive statistical analysis as a means of showing the patterns and trends observed with the retrieved data. It also serves as a first stage approach to the interferential statistics applied in subsequent Chapters that describe the main output of the proposed research.

4.2.2. Descriptive statistics and summary of data

Descriptive statistical analysis of the data obtained is particularly useful at this stage of the study as it serves as a summary of the data and provides an understanding of any trends and observations against variables. In this study, the mean normalised energy for space heating (kWh/m^2/yr) of the dwellings over the four years of occupation has been compared against the design calculations and the difference between design and actual (DBDA) energy use. A list of dwelling variables as shown in Table 4-12 and Appendix 4c show the wide range of dwelling characteristics and parameters under a correlation and error analysis.

Table 4 - 12: Summary of dwelling variables

Dwelling variables	
Building standard	SBS 2010
	SBS 2010 & Section 7
	SBS 2010 & *Passivhaus*
Construction type	Off-site
	On-site
Dwelling type	Flats
	Bungalows
	Terrace
	Semi-Detached
Heating type	Combi gas boiler
	Gas boiler η ≥90%
	Gas boiler η ≤90%
	ASHP/ electric
Ventilation type	MVHR
	ME only
Household composition	With children
	Without children
Occupancy	Mostly occupied
	Early mornings/ evenings
	Mixed

The first characteristic analysed was the building standard used in the dwelling sample size. Although all were built complying to 2010 Scottish Buildings Standards using the Standard Assessment Procedure 2009 (SAP2009); four dwellings brought additional enhancements to the design. Three dwellings were designed to the Scottish Building Standards Technical Handbooks Section 7, Sustainability (SBS, 2013). Also implemented at design stage was the *Passivhaus* standard, only applied in one dwelling of this sample. Figure 4-20 clearly shows the results as per standard with the dwellings designed only to the SBS 2010 standard resulted in a larger difference of +35 kWh/m^2/yr between design and actual (DBDA) energy for space heating. This was followed by the dwellings designed to meet Section 7 sustainability criteria, with a displacement of DBDA of 23 kWh/m^2/yr. The *Passivhaus* dwelling had the smallest DBDA with <5 kWh/m^2/yr displacement. The graph also shows that SBS 2010 dwellings consumed, without any additional standard, the most energy over the four years (>60 kWh/m^2/yr) whilst the *Passivhaus* and Section 7 dwellings halved such amount. This analysis shows how additional and enhanced sustainability and energy criteria at the design stage can have an impact on energy reductions.

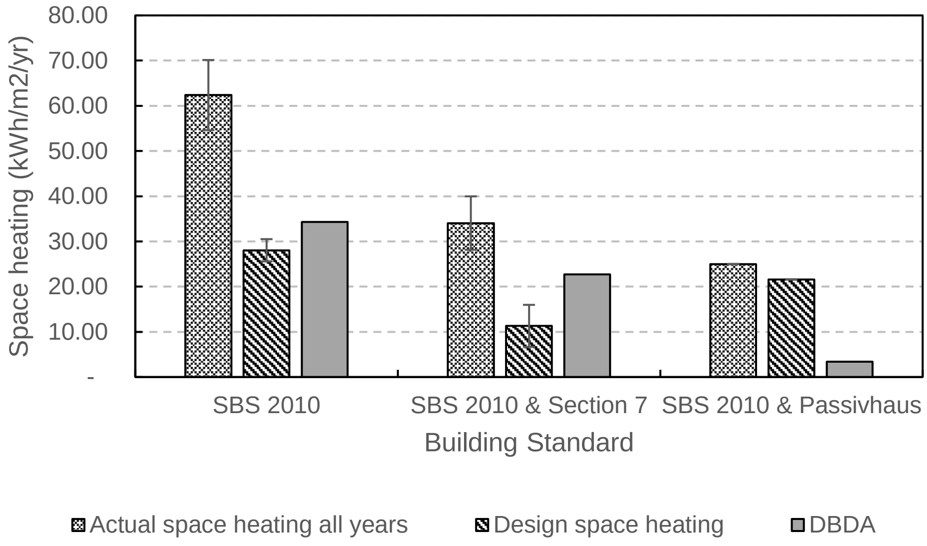


Figure 4 - 20: Space heating demand analysed as per design standard

Likewise, is the analysis of the construction type and system employed at design and construction shown in Figure 4-21. Eight dwellings were built using off-site fabricated systems; seven using timber closed panels and one using an insulated steel volumetric pod method. Four dwellings were assembled and built on-site; two dwellings using timber open panel systems, one insulated concrete formed system and one honeycomb insulated clay block.

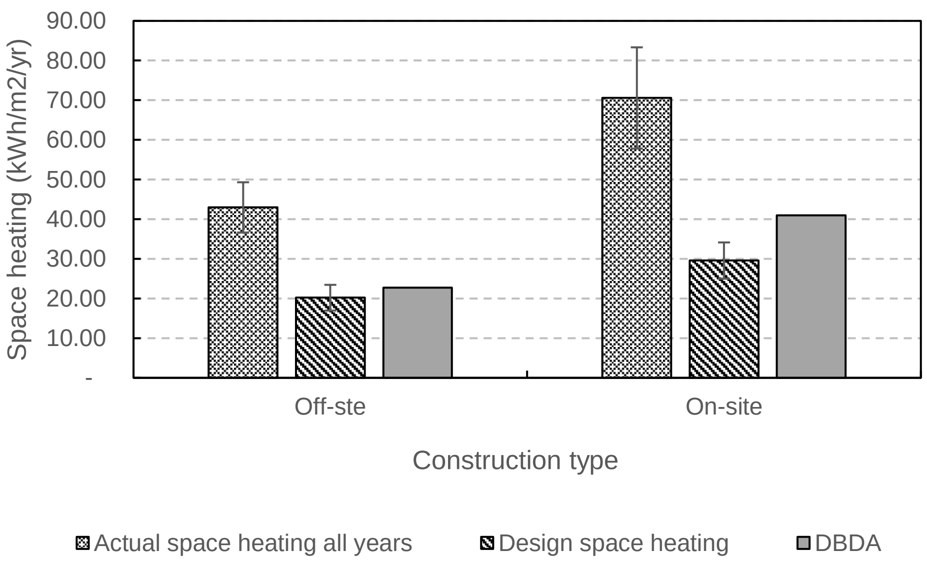


Figure 4 - 21: Space heating demand analysed as per different construction type

A comparison between the off-site and the on-site dwellings can be observed in Figure 4-21. At design stage there are differences; off-site dwellings achieved a theoretical 20kWh/m^2/yr whilst on-site dwellings were expected to consume 30kWh/m^2/yr. The DBDA between the off-site and on-site dwellings was double, 22 kWh/m^2/yr and 40 kWh/m^2/yr respectively. Figure 4-22 shows the total energy used for space heating for each individual construction system for each year of occupation.

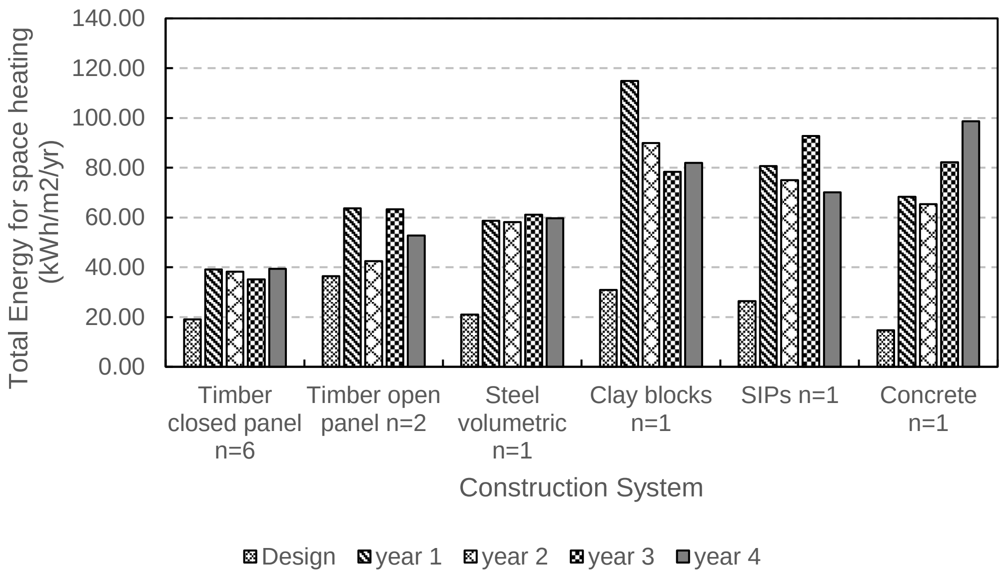


Figure 4 - 22: Space heating demand analysed as per construction system

The best performing dwellings were the closed timber panel systems manufactured off-site under controlled conditions. Both the timber closed panel and steel volumetric dwelling show little variation of yearly consumption patterns. The latter one however shows a two-fold increase between the design and actual consumption. Other dwellings have a distinct variation between years which could be aligned to occupancy patterns and number of people living in such dwellings.

Pertinent to this study were the type of dwellings; flats in a 4-in-a-block configuration (n=2), one storey semi-detached bungalows (n=2), terraced two storey dwellings (n=3) and semi-detached two storey dwellings (n=5). Figure 4-23 below shows that the least DBDA occurs in flats and terraced dwellings, with 15kWh/m^2/yr and 23kWh/m^2/yr respectively. Terraced dwellings presented small as-designed heat energy demand but the actual resulted being two-fold, despite it being below the 40kWh/m^2/yr. The dwellings that consumed the most were the bungalows, with large DBDA of 50kWh/m^2/yr. This might however be linked to the large number of occupied hours.

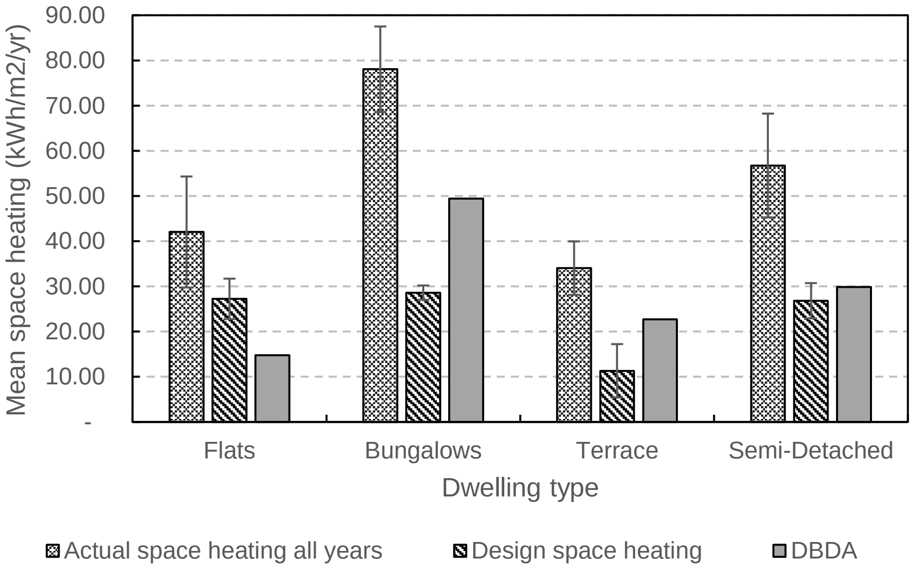


Figure 4 - 23: Space heating demand analysed as per dwelling type

Likewise, analysed in this descriptive statistics section were the influence of different heating and ventilation types installed in the dwellings. Figure 4-24 below shows results for the heating type where dwellings were fitted with natural gas condensing boilers (n=11) and an air source heat pump using electricity (n=1). The combi gas boiler dwellings consumed large amounts of energy in comparison with the single ASHP dwelling; 54.6kWh/m2/yr and 25.7kWh/m2/yr respectively. The DBDA was large in dwellings with both systems with a near three-fold difference for the gas boilers and a two-fold difference for the ASHP. However, if analysing the fuel expenditure of dwellings; the larger expenditure was from the electric ASHP where the £/kWh is larger than the gas equivalent. The impact of boiler efficiency on consumption of energy for space heating is also shown in Figure 4-24. Boilers with efficiency <90% calculated a larger space heating consumption than the dwellings >90% efficiency; 29 kWh/m^2/yr & 22 kWh/m^2/yr respectively. However, similarities are found between the overall mean consumption of these dwellings with various boiler efficiencies which leads to believe that at an early occupation stage (< 5 years) the efficiency doesn't impact demand. The DBDA is larger in the gas boilers with >90% efficiency than those of a <90% efficiency technology. This may be due to the calculation at design stage where more efficient boilers underestimate energy demand.

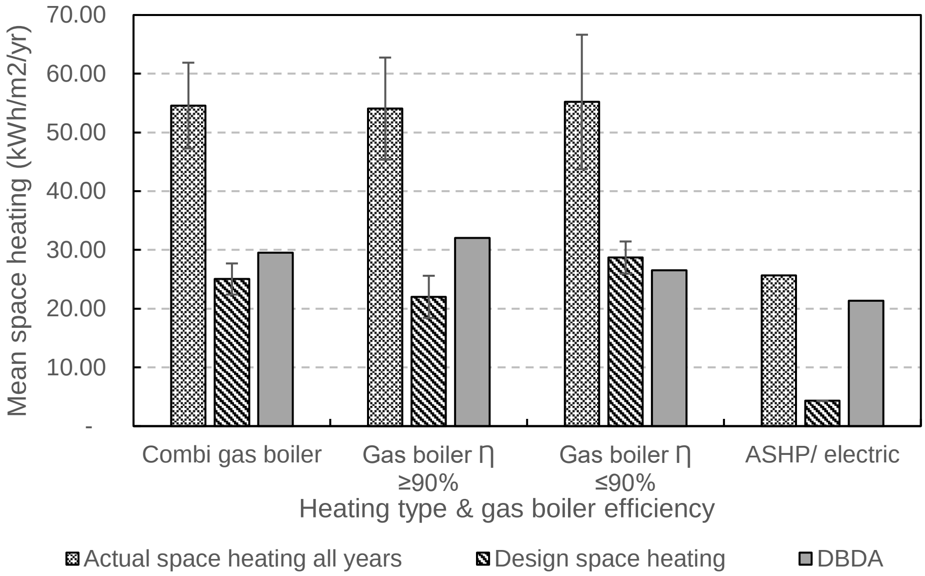


Figure 4 - 24: Space heating demand analysed as per heating type and efficiency

Figure 4-25 shows the differences between dwellings with a mechanical ventilation with heat recovery (MVHR) system and dwellings with a mechanical extract (ME) in bathrooms and kitchens. The MVHR dwellings were found to consume the most compared with the ME dwellings which leads to assume that the heat recovery of the MVHR's do not contribute to the comfort temperatures in each dwelling hence reducing space heating requirements.

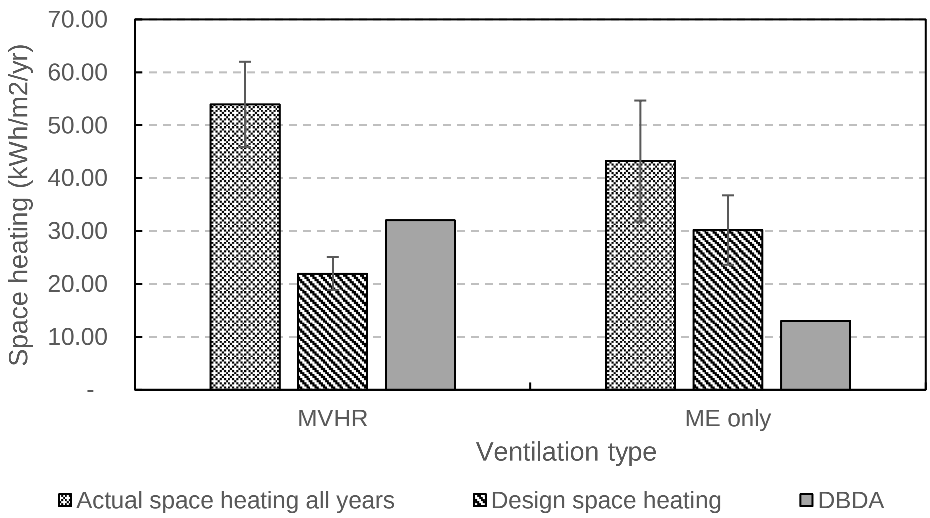


Figure 4 - 25: Space heating demand analysed as per ventilation strategy

The DBDA in the MVHR dwellings are also much higher that the ME dwellings; 32 kWh/m^2/yr and 13kWh/m^2/yr respectively, partly due to the differences in design energy calculations.

Although beyond the scope of this study, it was important to show the results with the occupants and household composition differences. Figure 4-26 below shows how occupants with children younger than 16 years of age (n=6) consumed more with a DBDA of 31kWh/m^2/yr.

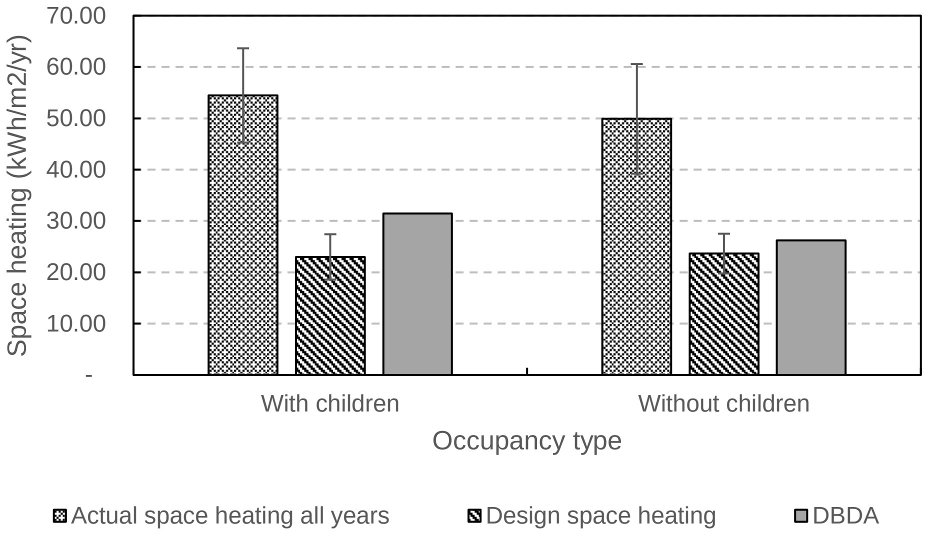


Figure 4 - 26: Space heating demand analysed as per different occupancy type

However, the actual space heating consumption of dwellings without children was not far from those with children, 54.5 and 50 kWh/m^2/yr respectively. The differences may be linked with the number of hours in the dwellings, where most occupants without children were retired or living with a disability.

This can be also observed in Figure 4-27 below showing heating energy demand according to the occupancy pattern linked to their employment and number of hours in and out of the property. Both these dwelling occupancy patterns consumed between 62-67 kWh/m^2/yr with a similar DBDA of 43 kWh/m^2/yr. Dwellings with a mixed mode of dwelling occupancy, i.e. with residents that were equally in and out most of the time due to their employment status and hours of work consumed the least reached 34.5 kWh/m^2/yr; whilst the DBDA was only 9 kWh/m^2/yr.

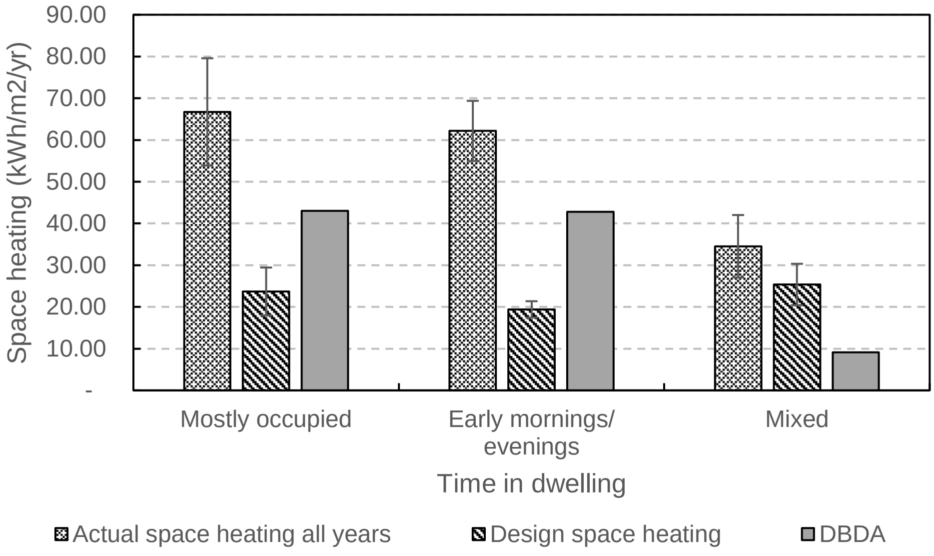


Figure 4 - 27: Space heating demand analysed as per time in the dwelling

4.2.3. Dwelling performance factor (DPF)

The dwelling performance factor (DPF) also known as the heat loss coefficient, is derived from a combination of dependently measured variables obtained from the bi-annual tests of wall U-value and air permeability, and controlled variables from the design compliance calculations (SAP2009). The heat loss calculations focused on fabric (dwelling envelope), ventilation (ventilations system) and infiltration (air permeability). The calculations performed in line with the measurements give a measure of the efficiency over time which if compared with the design factors are a good indicator of a change in performance over the occupied periods.

By calculating the DPF for each dwelling over the three periods in which measurements were taken, as shown in Table 4-13; a comparison between the design and the measured years shows a performance gap, it also outlines changes over the course of occupation. The table also shows how the measurements impact the performance factor over the years with most dwellings above the theoretical design factor. The largest shift in results is observed in dwellings F.1.4 and B.4.14 where a large difference between design and actual is present in the first year and gradually increasing in subsequent years. The effects of this will impact energy use which over the years are expected to grow regardless of the occupant led changes to the dwelling use.

Table 4 - 13: DPF of design and subsequent years using measured data

Dwelling code	Design	Year 1 (2012)	Year 2 (2014)	Year 3 (2016)	Mean
	Dwelling performance factor (W/K)				
F.1.4	55.89	72.96	73.74	72.19	72.96
F.2.5	57.04	59.39	67.98	72.67	66.68
F.3.12	49.86	52.97	59.20	55.31	55.83
B.4.14	85.89	97.71	105.59	105.59	102.97
B.5.16	69.23	70.80	75.52	78.67	75.00
SD.6.17	109.52	109.52	122.12	120.18	117.27
SD.6.18	56.38	58.26	62.95	65.77	62.33
T.7.19	58.24	61.57	66.56	67.39	65.17
T.7.20	49.92	57.41	60.74	64.90	61.01
T.7.21	68.22	69.06	72.38	73.22	71.55
SD.8.23	98.63	98.63	106.29	113.00	105.97
SD.9.24	80.47	84.30	91.01	93.88	89.73
SD.10.33	61.73	65.90	67.57	70.07	67.85
Mean	69.31	73.73	79.36	80.99	78.03

4.2.4. Heating Degree Days (HDD)

Heating degree days have been adopted in this research as a mechanism of estimating energy demand over longer periods of occupation. The process involves the validation of measured energy demand over three years of occupation and by linear regression extend the consumption calculated by HDD over a fourth year; this in turn is then compared against the measured fourth year.

The best degree day data to perform this comparison is dependent on the accuracy of the baseline temperature used. Typically, the UK uses 15.5˚C as a baseline, however the analysis made in this research argues that more refined baselines are needed to extend HDD equivalent space heating energy demand. Figure 4-28 shows the impact of different baselines using recorded indoor and outdoor temperatures and different sensible gains temperatures.

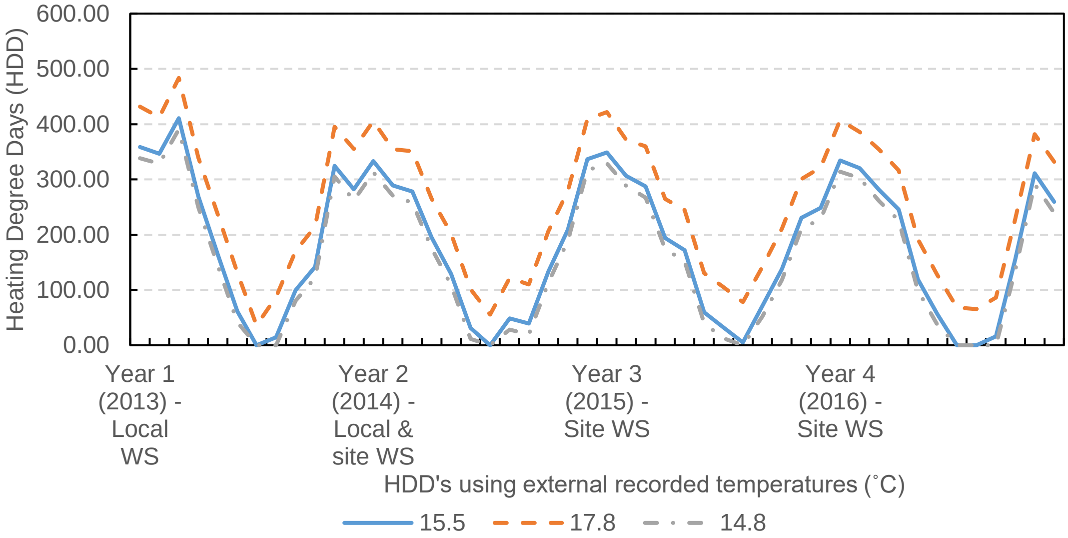


Figure 4 - 28: HDD’s using different external recorded temperatures and baselines

As a result, two new baseline temperature were determined; 17.8˚C and 14.8˚C respectively. Figure 4-28 shows the HDD’s during the four years of occupation against different baselines. The recorded internal temperatures have averages between 19 and 23˚C, however daily this changes so new baselines also shift accordingly. This makes the new baseline temperatures directly related to the dwellings thus more accurate future predictions. Different gains impacting temperatures can produce some discrepancies, despite the standard and extreme internal gains are similar despite different internal set point temperatures and external recorded data, as shown in Figure 4-29.

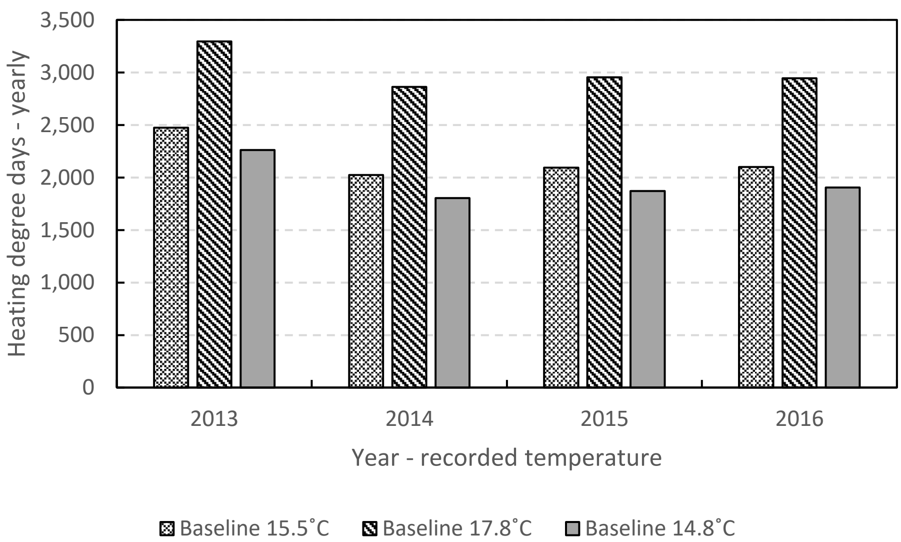


Figure 4 - 29: Yearly HDD’s using the different baselines

Figure 4-29 above shows the changes in heating degree days using the three baseline temperatures with the monitored data over the four years of the study. It shows similar HDD’s for the 15.5˚C and the 14.8˚C baselines. Baseline 17.8 ˚C however shows that more HDD are calculated given the low gain’s temperature applied. The first year (2012-2013) was a distinctively colder year with a mean external temperature of 8.8 ˚C, hence more HDD’s were required than the following three years experiencing external temperatures of near 10˚C.

4.2.5. Normalising energy demand using HDD data

Having determined the three baselines, a further analysis required the normalisation of consumption data collected from the dwellings. The process involves the use of a HDD’s factor to weather correct the data against each year and account for external variations making it feasible to compare against benchmarks and locations. The analysis involves the separation of weather and non-weather dependent energy i.e. energy for water and space heating. Appendix 4d has corrected the HDD results against the actual energy for space heating of all thirteen dwellings using the three baselines. This is summarised in Table 4-14 with mean of all years and the mean normalised energy (kWh/m^2).

Table 4 - 14: Normalised space heating energy using the different baselines

	Mean normalisation (kWh/m^{2}/yr)			
Dwelling code	Mean actual energy (all years)	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C
F.1.4	59.41	67.78	65.69	71.75
F.2.5	24.98	28.24	27.44	29.89
F.3.12	91.29	103.05	100.21	108.98
B.4.14	79.66	90.78	87.99	96.13
B.5.16	26.24	29.11	28.45	30.71
SD.6.17	22.12	25.49	24.63	27.01
SD.6.18	25.66	29.15	28.29	30.83
T.7.19	28.03	31.91	30.95	33.76
T.7.20	55.79	63.70	61.72	67.41
T.7.21	85.18	96.98	94.02	102.66
SD.8.23	67.87	77.19	74.89	81.67
SD.9.24	78.65	90.03	87.15	95.26
SD	25.75	29.33	28.43	31.04
Mean	53.74	61.12	59.29	64.67
Median	57.60	65.74	63.70	69.58

The results in Table 4-15 show the weather correction using HDD's of each dwellings mean energy demand over the four years of monitoring. The three baseline temperatures have been used to observe the differences in weather correction; the 17.8˚C baseline shows a closer set of results with the mean recorded space heating values for the four years of monitoring. However, analysing each individual dwelling shows that some values are still higher than the mean recorded. This may indicate that a better sensible gains calculation may be required for each dwelling, demonstrating that HDD's should be building specific with more emphasis on accurate indoor/ outdoor conditions monitoring.

4.2.6. Testing the demand data against the baseline temperature

To determine the most appropriate baseline temperature to use for subsequent analysis and assumptions, a correlation analysis and a test of the degree of scatter is shown in Table 4-15.

Table 4 - 15: Coefficient of determination of the HDD baseline against recorded energy data

	Correlation R^2 HDD with actual data - years 1,2 & 3			% difference of calculated and actual year 4		
Dwelling Code	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C
F.1.4	0.95	0.90	0.96	-4%	-0.22%	-10%
F.3.12	0.014	0.18	0.00005	24%	23%	25%
B.4.14	0.31	0.47	0.22	7%	7%	9%
B.5.16	0.48	0.29	0.54	19%	18%	19%
SD.6.17	0.99	0.99	0.99	-8%	-8%	-3%
SD.6.18	0.87	0.87	0.87	4%	4%	3%
T.7.19	0.016	0.88	0.23	-21%	-21%	-20%
T.7.20	0.076	0.034	0.09	-3%	-2.4%	-2%
T.7.21	0.89	0.79	0.92	-13%	-13.5%	-13%
SD.8.23	0.09	0.02	0.13	3%	2.9%	4%
SD.9.24	0.18	0.03	0.25	-5%	-4.90%	-4%
SD.10.33	0.51	0.34	0.55	-26%	-26.42%	-26%
Mean	0.448	0.482	0.479	-2.0%	-1.7%	-1.5%

The HDD and recorded space heating energy data presents a best-fit straight line plotted for every analysed year under the three baselines using least squares regression analysis. This produced a performance line equation which is used to calculate subsequent years of recorded data. This exercise and its methodology are explained in Chapter 3 and an example of a dwelling correlation exercise is in Appendix 4e.

Table 4-15 shows a summary of results obtained on correlation coefficient (R^2) and % difference of the fourth year on energy calculated and recorded. Results show that not all dwellings are better suited to one baseline temperature, in fact when there is a high correlation shown in red, such as F.1.4, T.7.21, SD.6.17 and SD.6.18 with an R^2 >.79 all three baselines are suitable and closer to the line of "best fit". Many dwellings have a low and medium correlation to the three baselines shown in green and orange respectively. Taking the mean of all dwelling's correlation with the baseline temperatures all three present a medium correlation close to 0.5; with baseline temperature 17.8˚C being the highest. With the understanding that this analysis has been done with three years' worth of data and a larger sample size and number of years would increase accuracy in results; the scatter on the line of best fit is useful as it provides some clues and assumptions on the reasons a high, medium and low correlation is obtained. A low and medium correlation can be a sign that the consumption data requires more investigation. In most cases this can be done through the controls and operation of the heating system or a refinement in the use of the baseload temperatures and the calculation of the HDD's is required. One assumption is that the gains temperature used to calculate the baseline may require some more detailed analysis and calculation, and that each dwelling will have a figure and resultant yearly or monthly HDD's value. This is the case of particularly solar gains, internal equipment gains, and occupation linked to the dwelling's orientation, type of equipment in dwellings and quantity and utilisation factors, which leads to variable monthly base temperatures and an inherited error influencing all calculations.

Obtained through the correlation analysis is the line equation which was used to obtain a new fourth year of energy demand (y) using the HDD's value for that year (x). To measure its alignment to the actual fourth year energy data, a percentage differential calculation gave an approximation measure where values (±) closer to 0 indicated a more accurate calculated assumption. Values of ±10%

qualified as a good match for subsequent analysis. However, higher % values out-with this boundary didn't favour in subsequent regression analysis as the accuracy and reliability would decline despite its high correlation in previous stages. Nevertheless, an approximation to 0 is present in many of the dwellings which can be used for the subsequent regression's analysis of future occupation years. Mean values in the three baseline temperatures show that Baseline 14.8˚C and 17.8˚C are closer to the recorded, -1.5% and -1.7% respectively.

4.2.7. Concluding remarks

Descriptive statistics is particularly useful in this study, as it shows the data against different variables which can explain a variety of trends in the measured energy data. Of interest was the construction type analysis where off-site and on-site dwellings were compared followed by a yearly analysis of all the individual systems throughout the period of testing. The analysis strongly favours the off-site systems, particularly the timber closed panel systems that have a greater attention to detail under factory conditions. Also, of importance is the heating and ventilation technology, which in this sample of dwellings has taken away the myths and benefits of MVHR systems. Although in principle the technology is beneficial, a lot more needs to be done to inform occupiers in the correct operation and controls of each system, but equally inform manufacturers and installers of the reasons such technology is not used properly (noise, supply temperatures & calibration and maintenance). Occupancy and household composition although beyond the scope of this study; have been included as it relates strongly with the patterns of energy use. The mean results from the analysis and the Figures above show little difference between the variables of occupancy. This may be due to the wide variety of occupant patterns or the small sample size in the study.

Following this, a more in-depth statistical approach will be taken, combining the above results with other tools that can give a longitudinal approach to dwelling analysis.

4.3. Dynamic thermal modelling

4.3.1. Introduction

This section presents the work performed to create a dynamic model and the data collection and results once dynamic building energy simulations (DBES) were obtained. It forms part of Stage 3a of the proposed methodology in Chapter 3, Figure 3-1. The models were calibrated; first using design data to replicate the conditions first assumed, followed by a second stage that will include fabric performance results and occupant schedules from surveys. Important in this calibration process is weather station meteorological data to further refine the models for Stage 3b undergoing a longitudinal climate change study.

4.3.2. Baseline modelling

The IES-VE software was used in this research to produce a first stage un-calibrated geometry and thermal model using design stage parameters and specifications in combination with the measured values. The selected dwellings to model were considered the best representative dwellings for further developing this research, these are: dwelling SD.6.17 also known as the “Control house”, Dwelling SD.6.18; built to the *Passivhaus* German standard and dwelling T.7.19, built to Scottish Building Regulations Section 7 Sustainability Gold label. The selected three dwellings are shown in Figures 4-30 and 4-31 and detailed in Appendix 1a.

Figure 4 - 30: Dwelling SD.6.17 and SD.6.18

Figure 4 - 31: End terrace dwelling SD.7.19

4.3.3. Modelling strategy and uncertainty analysis

Considering the base model parameters, a selection of the modelling data input and geometrical build-up took place. Often these are assumed at a design stage, however in this study a series of measurements were able to be used to calibrate the model and align to real-life energy demand, primarily space heating. To perform this, an uncertainty analysis is required to assess the impact of various parameters often associated with services efficiencies, meteorological data, and thermodynamic performance of the envelope, internal and external gains and the variability of occupant behaviour. All these are attributed to lack of actual as-installed data and accuracy in the input parameters. It is therefore necessary to calibrate the models and achieve low levels of error between the measured energy and the simulated in the model. The following input variables as described in the sections below are part of an uncertainty analysis to identify the key parameters which influence the energy demand of the modelled dwellings.

4.3.4. Steady state as-designed models

The modelling started by exporting the basic geometry of the dwellings footprint from digital versions of as-built drawings provided by architects and system providers. Dwelling footprint was traced considering the internal boundary line for external elements and middle line for party and separating elements. The volumes represent each heated room occupied by residents omitting un-heated areas with different conditions; in some instances, like external conditions. The models were completed by the placement of windows and doors including voids for stairs. This information was created in a three dimensional (3D) plain providing a geometrical shape of the building. Figures 4-32, 4-33 4-34 show the basic geometry modelled for the three dwellings.

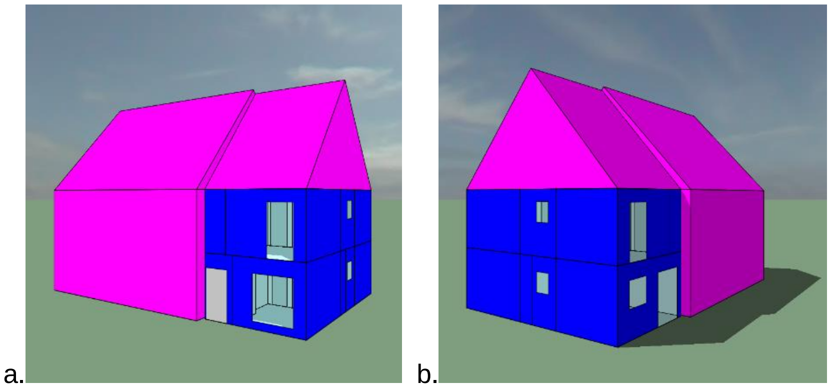


Figure 4 - 32: Dwelling T.7.19 a. Front & side, b. back & side with adjacent terraced dwellings

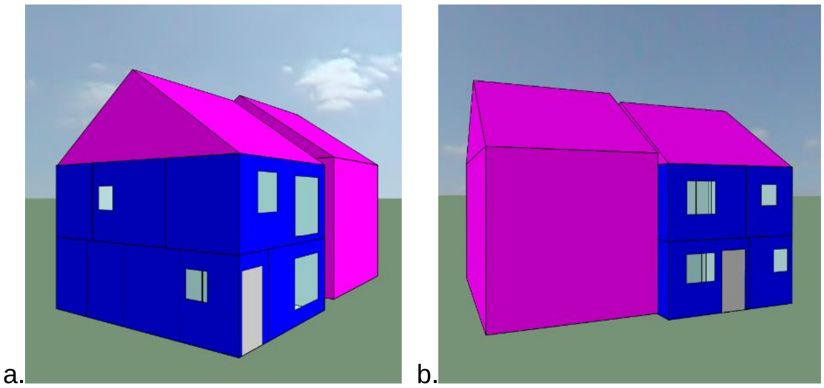


Figure 4 - 33: Dwelling SD.6.18 a. Front and side. b. Back & adjacent dwelling SD.6.17

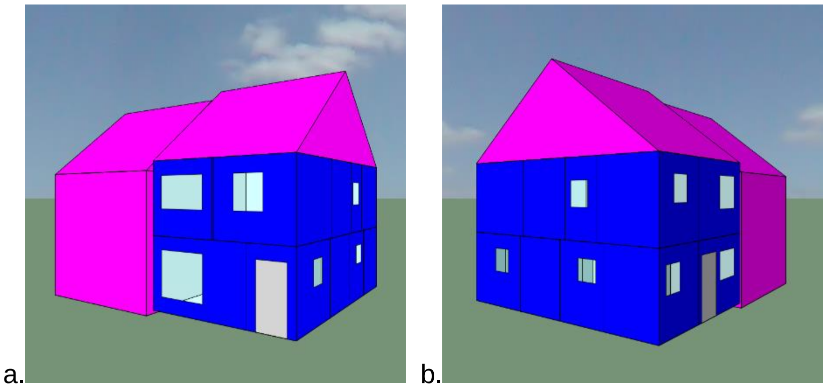


Figure 4 - 34: Dwelling SD.6.17, a. Front & side, b. Back & side

Following the creation of the geometric models, the dwellings azimuth was set in order to consider solar gains and the impact of shading in the thermal calculations. The model required a location and weather file to consider yearlong meteorological conditions influencing the internal thermal conditions. To finalise the base model, the selection of a heating and ventilation system provides the means for conditioning the dwellings, primarily for space heating and adequate ventilation, as shown in Table 4-16. Monitoring of installed heating and ventilation efficiencies were outside the scope of the research and therefore not monitored.

As a result, a general as per design specification was applied. The software uses system databases, however in these models, efficiencies and type of technology were manually added to the room conditions and main system input of each zone. The use and benefits of renewable energy were omitted from the study.

Table 4 - 16: Heating and ventilation system efficiencies applied to the models

Dwelling code	Heating type	η%*	Controls	Ventilation type	η%*
SD.6.17	Combi gas boiler, & one electric shower	88.8%	Time and temperature zone control and TRVs	Natural (trickle vents) & Mechanical extract in bathroom/ kitchen	-
SD.6.18	Combi gas boiler, & one electric shower	88.8%	7 day prog. thermostat and TRVs	Mechanical ventilation with heat recovery (MVHR)	93%
T.7.19	Air source heat pump – (ASHP) & 150Lt cylinder	COP 3 to 4	7 day prog. thermostat and TRVs	Mechanical ventilation with heat recovery (MVHR)	91%

* system efficiency

4.3.5. Uncertainty analysis using measured parameters

Dynamic measured parameters refer to the input data that was used in the model as summarised in § 4.2, 4.3 and 4.4 of this Chapter. They are as follows:

- Envelope performance values
- Occupant profiles and numbers
- Internal gains from appliances
- Weather file
- Measured internal temperature

The envelope performance values were split between three main interval measurements. To account for ventilation heat loss by infiltration the tests were converted from air permeability ($m^3/hr.m^2@50Pa$) to air changes per hour (ACH). This was easily done by using the total air flow in the test results and dividing it by the dwellings volume. Important to the data input stage was the envelope heat loss, best accounted for by stating the thermal transmission (U-value) of the dwelling's elements. As explained in § 4.3.1, only the wall U-value was recorded, thus other elements such as windows, roof and floor took the steady state calculation from the design compliance models. Table 4-17 below shows the envelope mean values used in each dwelling to create the base model.

Table 4 - 17: Envelope performance figures, as recorded

Dwelling code	Mean wall U-value (W/m^2K)	Predicted floor U-value (W/m^2K)	Predicted roof U-value (W/m^2K)	air permeability (q50)	ACH (n50)
SD.6.17	0.34	0.15	0.10	3.26	3.50
SD.6.18	0.13	0.15	0.10	2.35	1.67
T.7.19	0.15	0.15	0.09	5.78	5.07

Occupant profiles and number of occupants in the dwellings used a combination of standard schedules from results in the issued surveys and qualitative data taken during the dwelling visits. The profiles obtained from §4.5 were useful to further refine the model conditions and occupant patterns. Table 4-18 below summarises the occupant profile data used in the models.

The software predicted many schedules to various technology and services controls and occupancy actions, however for simplification, the models in this research have opted for focusing on space heating profiles during heating months i.e. October to May and turned off during non-heating months i.e. June to September. A determinant factor of the model's thermal performance are the allocation of internal gains from sensible and latent heat sources emitted within the internal space of a building. This heat contributes to the temperatures experienced by the occupants and are often an addition to the temperatures set for heating and cooling in buildings.

Table 4 - 18: Schedule of occupancy used in models

Dwelling code	No. of occupants	Occupancy Pattern	Weekly schedule	Weekend Schedule
SD.6.17	3.75	Unemployed with occasional part-time work, young children.	Outdoors on average 4hrs per day (20hrs)	Outdoors on average 5hrs per day. (10hrs)
SD.6.18	4.0	1 adult works night shifts and rests during day. 1 adult works part time. The other 2 adults study and work but out of the dwelling most of the time.	Mixed schedule. On average occupants out of the dwelling 8 to 10hrs per day.	Mostly indoors with occasional outings. Outdoors on average 4hrs per day. (8hrs)
T.7.19	2.0	Retired couple who use gym and go shopping	Outdoors on average 2 – 4 hrs each day. Mainly indoors	Outdoors on average 4 to 5 hrs with family and friends

As mentioned in §4.6.3 of this chapter, internal gains play a principal factor in setting the baseline temperature for calculating HDD's; and important to consider them when observing internal thermal comfort of dwellings. Whilst external gains can be obtained from global solar irradiance (W/m^2), internal gains come from a variety of sources such as; occupants, electrical appliances and latent sources such as boiling water, a kettle or a shower/ bath. In dwellings some gains come from the occupants (even pets), released as latent and sensible heat lost from their bodies according to metabolic activity. Their contribution ranges from 70 to 115W for sedentary activities to >500W if lifting heavy equipment or practicing some exercise. Internal gains from lighting also play a principal factor in the overall contribution to ambient temperatures. Lamps emit both radiant and conducted (including ballasts) heat to the interior of buildings. For this research a mixture of fluorescent and energy efficient lamps were used with a radiant percentage heat output of 45% and a conducted output of 55%. Although occupants and lighting contribute to the internal gains, the majority comes from plugged in appliances. With increased dependence on technology and new devices in dwellings for entertainment, home working and controls connected to Wi-Fi signals; dwellings are expected to increase their ambient indoor temperatures from high concentrations of heat generated from such devices. For the models in this research, an equivalent set of appliances were used, typically found in dwellings and their occupant category. Most appliances characteristics were taken from the latest CIBSE Guide A (CIBSE, 2015) and were applied equally across the three dwelling models.

Another principal factor considered in the creation of the models was the location and weather files used. The weather data in the IES-VE software relies on a location nearest to the building and the nearest corresponding weather file. These do not always coincide therefore there may be instances where the correct or approximate location (longitude, latitude and altitude) to the nearest weather file are different. For example, models using the Edinburgh location can only use the Dundee weather file as that is the nearest file available to the location. Undergoing a model with these limitations can begin to create uncertainties and increase the error between recorded and modelled of energy demand and internal temperatures. To alleviate this error and provide a more accurate approach to the simulations a weather file was created using hourly data results from actual weather station on-site meteorological recordings. In order to do this, the IES-VE software provides a spreadsheet for Microsoft Excel© using Visual Basic (VBA) macro to facilitate the creation of a compatible file extension (.fwt or .epw) from the recorded data. Such process further indicated the importance of localised weather recordings that provide actual weather conditions to the model to test real life conditions. This process makes the simulation more realistic and closer to the energy demand of each dwelling. An example of the spreadsheet prior to its conversion to as shown in Figure 4-35 below.

IES
Simulation weather data worksheet

Key:		
Mandatory field	Include one field from set	Include field where possible
	Include one field from set	Discretionary field (normally omitted)

	Simulation weather file name (up to 24 characters including extension .fwt)	Brief description (up to 16 characters)	Full description (3 lines of up to 32 characters each)	Year of last record	Site latitude (deg N)	Site longitude (deg E)	Time zone (hours ahead of GMT)	Solar radiation convention (1 = hour-centred, 2 = half-hour-centred
HEADER DATA	FNAME	BDESC	FDESC	YEAR	LAT	LON	TZ	SRC
Values:	Dunfermline.fwt	HIS site	Weather station at the HIS development in Dunfermline 28 Erict Drive.	2016	56.06	-3.41	0.00	1

	Hour	Day of month	Month	Dry-bulb temp. (°C)	Wet-bulb temp. (°C)	Relative humidity (%)	Humidity ratio (kg/kg)	Dew-point temp. (°C)	Wind speed (m/s)	Wind direction (° E of N)	Direct normal solar irrad (W/m²)	Direct horizontal solar irrad (W/m²)	Global horizontal solar irrad (W/m²)	Diffuse horizontal solar irrad. (W/m²)	Solar altitude (°)	Solar azimuth (° E of N)	Cloud cover (fraction)	Atmosph. pressure (Pa)
HOURLY DATA	H	DM	M	T	TW	RH	G	TDEW	WS	WD	IDIRN	IDIRH	IGLOB	IDIFF	ALT	AZ	CLD	PAT
Multiplier:	-	-	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Offset:	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Values:	1	1	3	7.158		86.324			9.215	242.6	0			0	0.0	18.1	0.375	970.221
	2	1	3	6.562		83.666			8.169	247.67	0			0	0.0	35.5	0.625	972.115
	3	1	3	5.506		84.658			6.811	252.81	0			0	0.0	51.3	0.500	974.126
	4	1	3	4.849		88.192			5.613	251.27	0			0	0.0	65.6	0.875	975.401

Figure 4 - 35: Visual Basic spreadsheet to generate weather file from recorded values

Furthermore, for indoor heating thresholds (set points) in the model two methods are employed; applying a constant value determined by the mean or median; and a dynamic method determined by actual twelve month recorded data considering heating and non-heating seasons. The dynamic approach used hourly recorded data into the model by using an extension to the software called ERGON which creates schedules and operating files used to replicate and calibrate models with real-life building use (Coakley et al., 2014).

Parameters with limited and small amount of data sets, such as the measured envelope performance, occupancy patterns, and internal gains were taken direct from the results. An exemption was made where results with mean values over the recorded years, such as air permeability and wall U-values.

4.3.6. Model sensitivity analysis, calibration and error analysis

A sensitivity analysis with an appropriate error analysis leading to a calibrated model can assure the building modeller to a certain level of confidence that results from simulations will be reliable and closely in-line with a real life situation once built. As a design tool, this process can be more complicated as it includes many assumptions and aspirational specifications. Once built it is different, as measured values and actual energy demand figures can help to model a building closely to the way it performs and with that proceed to optimisation scenarios for improvements, changes or even longitudinal projections. The calibrated model in this research were used to understand the longitudinal performance and to account for the influences of a dilapidated building envelope and climate change. The results obtained in this chapter section relate to the stated methodology in chapter 3 and were performed by combining actual retrieved data from monitoring and with results from the occupant surveys which revealed many actual parameters included in the models.

4.3.7. Sensitivity analysis of independent variables (parameters)

The sensitivity analysis refers to ranking the best independent variables that influenced the main dependent variable; energy for space heating. To determine the best parameter through the sensitivity analysis, and calibrate the model, each parameter is tested for correlation using regression coefficient applied to three inter-linked dependent variables; energy as measured, energy at design stage and the difference between design and actual energy (DBDA). The parameters chosen are from set conditions of the dwelling, household and comfort that relate to their performance. Data from measurements appeared to be normally and non-normal distributed, which led to apply both parametric tests using Pearson (R and R^2) and non-parametric tests such as Spearman (rho) to understand the correlations between variables, shown in Table 4-19 below.

Table 4 - 19: Evaluation of parameters for modelling – space heating in (kWh/m²/yr)

Parameters	Actual energy		Design energy		DBDA		Actual energy	Design energy	DBDA
Pearson	R	R^2	R	R^2	R	R^2	Spearman's rho		
Dwelling factor Difference between Design & actual									
q50 (m³/h.m²@ 50Pa)	-0.26	0.07	-0.47	0.22	-0.10	0.01	-0.21	-0.58	-0.12
Wall U-value (W/m²K)	0.53	0.28	0.44	0.19	0.22	0.05	0.32	0.51	0.11
Mean q50 (m³/h.m²@ 50Pa)	0.05	0.00	-0.50	0.25	0.21	0.04	0.20	-0.43	0.12
Mean wall U-value (W/m²K)	0.49	0.24	0.59	0.35	0.12	0.01	0.63	0.63	0.36
DPF (mean of actual)	0.58	0.34	0.62	0.39	0.23	0.05	0.70	0.53	0.44
DER (design)	0.19	0.04	0.99	0.97	-0.25	0.06	0.08	0.99	-0.13
DER (actual)	0.91	0.83	0.00	0.00	0.89	0.79	0.93	-0.04	0.90
Floor area	0.08	0.01	0.16	0.03	0.09	0.01	0.15	0.12	-0.05
S/V ratio	0.23	0.05	0.17	0.03	0.08	0.01	0.12	-0.10	0.28
Volume	0.01	0.00	0.07	0.00	0.05	0.00	0.15	0.12	-0.15
Household/ conditions									
Number of occupants (actual)	-0.06	0.00	-0.15	0.02	0.07	0.00	-0.11	-0.10	-0.16
Number of occupants (Design)	0.07	0.00	0.12	0.01	0.09	0.01	0.16	0.09	0.00
mean occupant age (actual)	0.21	0.04	-0.10	0.01	0.18	0.03	0.12	0.03	0.25
Mean set point temperature (measured)	0.14	0.02	-0.19	0.04	0.22	0.05	0.30	-0.12	0.30
Comfort									
Mean perception of temperature	0.23	0.05	-0.04	0.00	0.24	0.06	0.25	-0.25	0.34
Mean perception of ventilation	-0.13	0.02	0.49	0.24	-0.32	0.10	0.08	0.38	-0.05
Mean perception of light	0.03	0.00	-0.54	0.29	0.24	0.06	0.03	-0.60	0.19

Table 4-19 highlights a medium (orange shading) to high (red shading) correlation in the parametric and non-parametric tests applied to the parameters against the three dependent variables. High correlation coefficient relationship is found between the dwelling characteristics and the actual or design space heating; particularly parameters concerning the envelope performance and dwelling CO_2 emission rating (DER). The results of the wall thermal transmission, both as a mean value and a difference between the design and mean actual recorded, have a high Pearson (R) correlation coefficient ranging from -0.5 to 0.6. Spearman's rho analysis also shows a similar correlation coefficient closer to 0.6. The dwelling performance factor calculated from recorded and steady state values provides a similar correlation coefficient, however the non-parametric tests show results that are closer to the high correlation coefficient of >.75. The analysis shows that the non-parametric analysis using Spearman's rho shows a better relationship with the variables which denotes the suitability of the test for such datasets and the small sample.

Although other independent variables have a high correlation (closer to 1) with the dependent variables; only the ones that could be applied to the model clearly by creating step-changes have been used as input variables. This made the batch simulation in the model with the impact and alignment to the metered energy for calibration easier and less time consuming. A description of the step-changes undertaken as part of the sensitivity analysis are described below in Table 4-20 leading to the sensitivity analysis, error analysis and calibration to decide on the best-fit for subsequent stages in the model.

Table 4 - 20: Step one sensitivity analysis for calibration

	Envelope performance		Set point temperature	Weather file
	Wall U-value 1st measure	Air tightness q50 (n50) 1st measure	Living room (Rest of the dwelling) Assumed	Closest to location
SD.6.17	0.25	3.63 (3.66)	21 (18) °C	
SD.6.18	0.13	0.55 (0.53)	21 (18) °C	Dundee file
T.7.19	0.16	3.87 (4.05)	21(18) °C	

- Note: Set-point °C: Bedroom & Kitchen: 18°C; Circ & Wet rooms 18°C; Living room 21°C

Table 4-20 above shows the first step-change implemented as part of the sensitivity analysis leading to calibration. The first approach is to take the same figures used at the design and compliance model and to create the baseline model. The fabric performance at design stage for envelope thermal transmission (U-value) and air permeability have been used in all components, while also the design set point temperatures and the nearest location and weather file available, Edinburgh and Dundee respectively.

Step-change two in Table 4-21 below uses measured data from the envelope performance testing. In this stage the mean recorded values after three tests have been used in conjunction with the mean recorded indoor living room temperatures over a twelve-month period. This step-change also suggested keeping the Dundee weather file and observe the approximation to the measured energy demand.

Table 4 - 21: Step two sensitivity analysis for calibration

	Envelope performance		Set point temperature	Weather file
	Wall U-value mean	Air tightness q50 (n50) mean	Living room (Rest of the dwelling) Mean	Closest to location
SD.6.17	0.34	3.64 (3.50)	21.1 (18)˚C	
SD.6.18	0.13	1.67 (1.60)	22.0 (18)˚C	Dundee file
T.7.19	0.15	5.08 (5.31)	20.7 (18) ˚C	

- Note: Set-point °C: Bedroom & Kitchen: 18°C; Circ & Wet rooms 18°C; Living room (mean recorded) °C

A third stage, as seen in Table 4-22 below has suggested to keep the mean envelope performance values and include recorded values into the modelling software. This provided a genuine approach to calibrate the model against measured data sets. The set point temperature of each dwelling was included as input data by an ERGON generated file of actual hourly living room data added to the different zones in the dwelling. Also applied was a correct weather file from the weather station nearby.

Table 4 - 22: Step three sensitivity analysis for calibration

	Envelope performance		Set point temperature	Weather file
Dwelling Code	Wall U-value mean	Air tightness q50 (n50) mean	Living room (Rest of the dwelling) Mean	Closest to location
SD.6.17	0.34	3.64 (3.50)	IES-ERGON files (Free-form file .ffd)	IES-VE compatible file (.fwt) – Weather station
SD.6.18	0.13	1.67(1.60)		
T.7.19	0.15	5.08 (5.31)		

4.3.8. Error analysis and calibration of model

Following a sensitivity analysis by applying step changes in accordance with measured data, an error analysis provided the best assurance that a simulation is aligned to actual energy consumption. Descriptive statistical analysis such as standard deviation, mean and coefficient of variation (CV%) were used to evaluate each data set. The use of CV% was particularly important as it acted as a standardised measure of dispersion from the mean of the simulated data. Higher CV%, showed greater dispersion around the mean. Equally, as part of the error analysis between the measured and simulated data the coefficient of determination (R^2) through linear regression was used together with determination of root mean squared error (RMSE) of the predicted mean, goodness of fit (GoF) and mean bias error (MBE).

Results of such error analysis of each dwelling were obtained from Table 4-20 particularly those that impacted more on energy use. Many simulations were made of each dwelling that helped to calibrate and shape the model to similar energy demand figures using; geometry, orientation, location, baseline weather file and envelope performance. However, the four presented in this calibration process were the more defining ones where an error analysis was applied. In order to complete this, energy demand data from the last monitored twelve months (January to December) was analysed. Monthly totals were extracted from the energy monitors, followed by the separation of energy for water heating and energy for cooking, resulting in energy for space heating; used in the error analysis against simulated energy for space heating. The first simulation followed parameters in Table 4-20, whilst Simulation two followed Table 4-21 with mean results of fabric performance and recorded set point temperatures. Simulation three followed a more dynamic approach with year-round set point temperature in the living room and a baseline weather file. Simulation four took the same approach as Simulation three but changed the weather file to a new file from measured nearby weather station data. The four simulations provided a better approximation to the measured data, more importantly closer to the monthly consumption, responding to seasonal outside temperatures and space heating.

Table 4-23 shows the results of the error analysis for SD.6.17; the Control house. The dispersion of the probability distribution, shown as a coefficient of variation (CV%) signifies that the first simulations have less of a dispersion from the mean of the sample at 42%; compared with Simulation 4 of 65%. When compared with the measured monthly data, Goodness of Fit (GoF%) and coefficient of determination or Pearson (R^2) are better indicators. Simulation 4 shows a lower positive GoF% meaning less dispersion and better fit month-by-month shown by the high R^2. This alignment is also seen in the results of normalised mean bias error (NMBE), with just 2.6%. Figure 4-36 is a scatter graph showing the four simulations and the measured energy.

Table 4 - 23: Error analysis of simulations and recorded energy for space heating – SD.6.17

Month	Measured data	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Jan	496.28	717.3	676.8	640.7	511.6
Feb	493.40	684.5	646	612.2	515.5
Mar	330.25	506.2	465.9	451.1	345.1
Apr	143.55	368.1	328.8	325	156.2
May	101.30	149.4	117.3	114.3	100
Jun	0.00	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00	0.00
Oct	149.99	286.7	250.3	247.1	44.1
Nov	246.66	446.8	410.5	407.4	228.7
Dec	307.57	576	537.5	513.9	278.6
Descriptive statistics					
Total	2269.0	3735.0	3433.1	3311.7	2179.8
SD	153.09	195.28	193.13	180.35	176.83
Mean	283.62	466.88	429.14	413.96	272.48
CV	53.98%	41.83%	45.00%	43.57%	64.90%
Error analysis - Measured vs Simulated					
MSE	-	1,803.25	1,557.84	1,828.96	1,125.01
RMSE	-	42.46	39.47	42.77	33.54
CVRMSE (%)	-	14.97	13.92	15.08	11.83
NMBE (%)	-	-43.07	-34.20	-30.64	2.62
GoF (%)	-	32.25	26.11	24.14	8.57
R^2	-	0.91	0.91	0.90	0.96

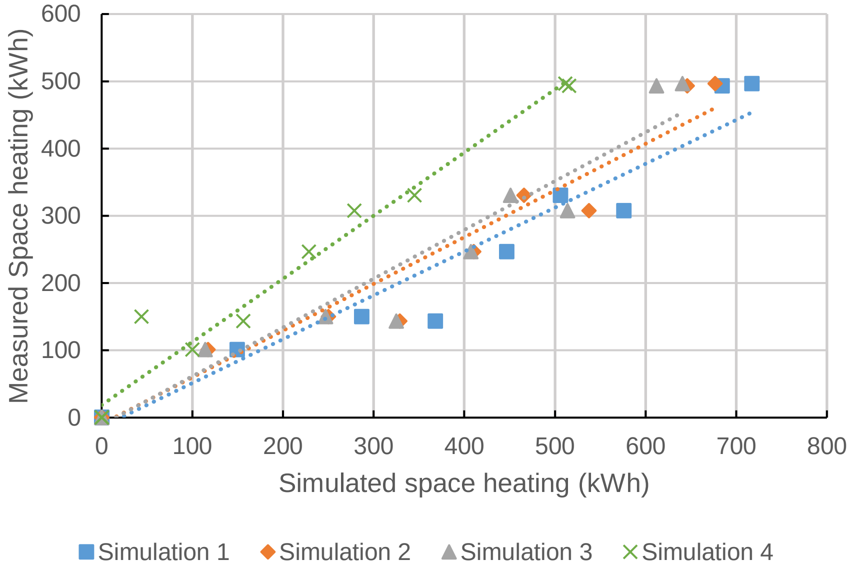


Figure 4 - 36: Scatter graph of simulations compared to measured data – SD.6.17

Table 4 - 24: Error analysis of simulations and recorded energy for space heating – SD.6.18

Month	Measured data	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Jan	344.64	424.3	765.2	722.9	447
Feb	336.34	304.2	623.5	559.6	434.2
Mar	306.91	206.9	469.4	460	344
Apr	232.83	56.4	223.5	214.3	125.1
May	105.10	20.7	91.1	95.2	113.1
Jun	0.00	0	0	0	0
Jul	0.00	0	0	0	0
Aug	0.00	0	0	0	0.5
Sep	44.87	12.9	44.1	50.4	8.5
Oct	167.00	88.8	248.6	247.4	29.6
Nov	267.66	188.5	424.1	392.9	225.7
Dec	337.03	384.8	682.9	649.9	279.8
Descriptive statistics					
Total	2142.4	1687.5	3572.4	3392.6	2007.5
SD	109.83	155.82	260.97	240.82	164.97
Mean	238.04	187.50	396.93	376.96	200.75
CV	46.14%	83.10%	65.75%	63.89%	82.18%
Error analysis - Measured vs Simulated					
MSE	-	4,429.39	1,985.17	1,929.61	3,683.89
RMSE	-	66.55	44.56	43.93	60.70
CVRMSE (%)	-	27.96	18.72	18.45	25.50
NMBE (%)	-	15.92	-50.06	-43.77	4.72
GoF (%)	-	22.75	37.79	33.59	18.34
R^2	-	0.78	0.89	0.88	0.79

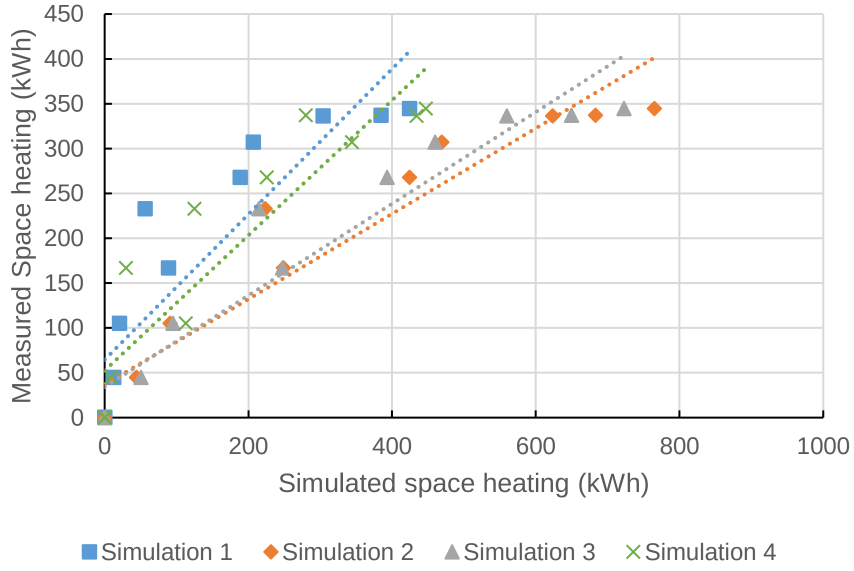


Figure 4 - 37: Scatter graph of simulations compared to measured data – SD.6.18

The second dwelling analysed and simulated in detail was SD.6.18 the *Passivhaus* dwelling. Results can be seen in Table 4-24 where a good approximation was obtained following the fourth simulation. Despite the CV% being high in all four simulations, the NMBE % for Simulation four resulting in a low magnitude of error with a low underprediction against the measured data. This was also strengthened by a low and positive GoF% of 18% and a good correlation using R^2 =.79.

Figure 4-37 shows the linear relationship in a scatter graph comparing simulation and measured data. Simulation 1 and 4 coincidently have similarities, however only by its correlation (R^2); the NMBE% as seen in Table 4-25 sets them apart with a better approximation and less scatter close to 0 (Zero) despite having just a medium coefficient of determination (R^2) of 0.77. Similarly, the lowest error is found in the goodness of fit % at 20.35%; not as low as Simulation 1 but with other error analysis calculations, stands out as being more consistent and reliable.

Table 4 - 25: Error analysis of simulations and recorded energy for space heating – T.7.19

Month	Measured data	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Jan	805.75	863.8	977.4	972.8	874.8
Feb	709.32	810	917.3	912.7	846.2
Mar	633.56	700	803.1	799.5	726.4
Apr	366.33	572.2	664.2	662.6	458.9
May	118.23	318.3	386.1	386.9	367.9
Jun	60.81	0	0	0	0
Jul	34.95	0	0	0	0
Aug	70.21	4.6	6.2	6.8	4.6
Sep	295.28	135.7	174.5	181.5	157.7
Oct	493.96	522.3	611.1	614.7	319.1
Nov	633.28	645.8	740.7	739.7	574.6
Dec	727.10	750.7	854.4	846.3	625.8
Descriptive statistics					
Total	4948.8	5323.4	6135.0	6123.5	4956.0
SD	291.05	290.39	325.01	321.76	288.14
Mean	412.40	532.34	613.50	612.35	495.60
CV	70.58%	54.55%	52.98%	52.55%	58.14%
Error analysis - Measured vs Simulated					
MSE	-	8,829.13	9,368.76	9,348.47	14,083.22
RMSE	-	93.96	96.79	96.69	118.67
CVRMSE (%)	-	22.78	23.47	23.45	28.78
NMBE (%)	-	-7.57	-23.97	-23.74	-0.15
GoF (%)	-	16.98	23.72	23.59	20.35
R^2	-	0.856	0.848	0.849	0.774

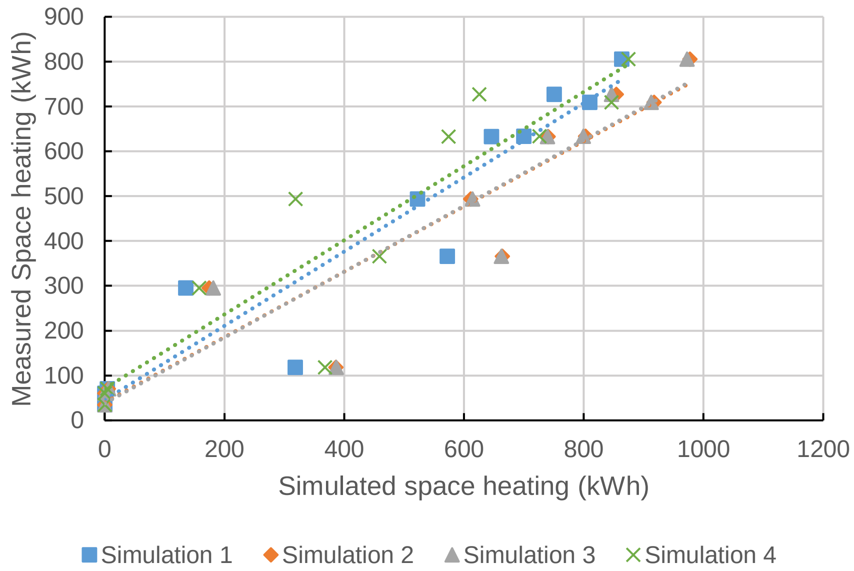


Figure 4 - 38: Scatter graph of simulations compared to measured data – T.7.19

The last dwelling simulated in detail was T.7.19 designed and built to the Scottish Building Standards Section 7 Gold label. It consumed a total of 4,950 kWh in space heating during the last year of measurements. The models were calibrated, and an error analysis performed for the last four simulations as shown in Table 4-25. An analysis of each simulation shows that Simulations 2 and 3 have the lowest CV%, despite them not being calibrated fully with the sensitivity analysis and the final conclusive step-changes in Simulation 4. However, the error analysis of these simulations shows a very similar GoF% in all four simulations and a decline in the coefficient of determination as seen in Figure 4-38 and Table 4-25, from R^2=.86 in Simulation 1 to R^2=.77 in Simulation four. Despite this, it's the NMBE% measuring the magnitude of error to the measured that distinguishes the simulations. The lowest magnitude is shown in Simulation 4 with a negative value (over predicting) of -0.15 compared with Simulation one of -7.6 and Simulations 2 and 3 similarly around -24.

Other error analysis calculations were included in the above tables which also measure the simulations approximations to the measured. This last approximation has shown that there can be a good alignment to the measured which can then be used in subsequent analysis in this research.

4.3.9. Generating future climate change weather files

Weather and climate shifts caused by climate change will be a determining factor in the performance of existing and new buildings. Existing buildings currently require withstanding the effects of weather shifts requiring adaptation strategies and mitigation to assure they are fit for purpose and perform adequately without affecting the users. New buildings planned and designed to meet current CO_2 emission criteria and targets require a more demanding role in the adaptation to climate change. There is scope to design for future changing scenarios in order to account for periods of high precipitation, increase and decrease of temperatures and larger periods of solar exposure affecting building envelope and causing overheating. This section in the chapter applies the methodology of generating and acquiring the climate change future weather files that correspond to the location of the dwellings analysed. Such weather files follow the methodology implemented by Eames et al. (2010), de Wilde and Tian (2010) and

Tian and de Wilde (2010) but most importantly has provided the information to apply future weather scenarios.

4.3.10. Outline of climate projection parameters and weather files

In order to propose climate change future weather files, it is important to understand the sources of data and required settings to undertake a resilience study using DBES models. In the literature review and methodology chapters a description of the sources of future weather files is made. Climate change files are based on this century (up to the year 2100) UK climate projections of overlapping periods of 30 years of a given location i.e., 2030’s, 2050’s and 2080’s. They are also based on the International panel on Climate Change (IPCC) global CO_2 emission scenarios labelled as low emission scenario B1, medium A1B and high A1F1 respectively. UKCP09 is the first in proposing climate projections using probabilistic statistical variables as cumulative distribution function (CDF) – 10%, 33%. 50%. 66% and 90%, probability levels defined according to mean air temperature (Hacker et al., 2009).

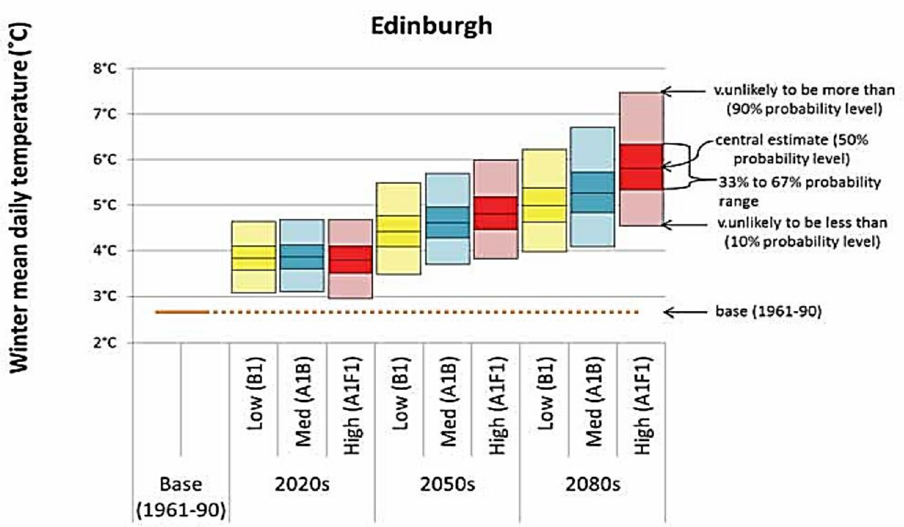
Although this study acquired actual weather data over a period of 3 years, it was difficult to use that data as a basis to generating future weather files directly in the simulation software. In this research the Edinburgh grid weather files were used as they were the nearest 25 km grid site location (<15 km from Dunfermline) conforming of baseline weather files originating from the Meteorological (Met) Office Hadley Centre’s (HadRM3) regional climate models, adopted by DEFRA’s Weather Generator (Jones et al., 2009). This grid proximity was enough of a spatial resolution reflecting impacts and adaptation assessment.

4.3.11. Probabilistic climate projections for Edinburgh

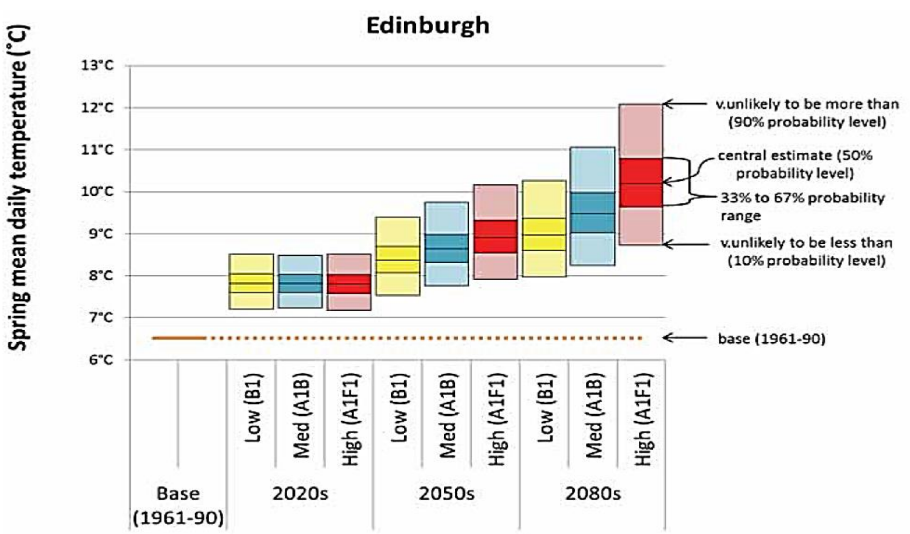
Following the ProCliP’s framework and suggested methodology, UKCP09 climate projections for Edinburgh were obtained to gain a better understanding of the changing climate over the projected periods (Shamash et al., 2012a) (Shamash et al., 2012b). Figures 4-39,a,b,c,d show the probabilistic seasonal temperatures for Edinburgh against its baseline during the three 30 year time periods and the emission scenarios (B1, A1B and A1F1) (Shamash et al., 2014). Winter mean daily temperatures shown in Figure 4-39 (a.), indicate the central estimate of 50%

probability level, at the high (A1F1) and medium (A1B) CO_2 scenario during the 2050's. It shows that there is a temperature difference (Δt) of 1.9 and 1.8°C respectively against the historical mean baseline. In the 2080's that difference (Δt) increases even further to 3.1 °C in the high CO_2 scenario and 2.6°C in the medium scenario. In the summer months (Figure 4-39 c.); the 2050's high and medium scenario temperatures increase by 3°C and 2.7°C respectively whilst in the 2080's a high and medium scenario they increase by 4.9°C and 3.9°C respectively. In the 2080's summer, under a very unlikely 90% probability, external temperatures could reach 20.5°C that will impact any buildings internal temperatures with added internal gains and solar exposure.

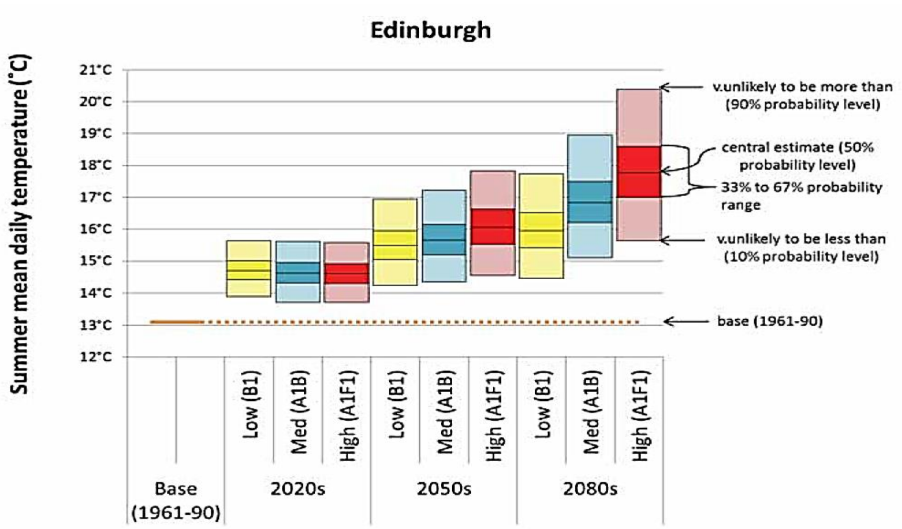
Figure 4 - 39 (below): Probabilistic climate profile (ProCliP) graph from UKCP09 data - Edinburgh mean daily temperature (°C) for; a. winter, b. spring, c. summer & d. autumn.



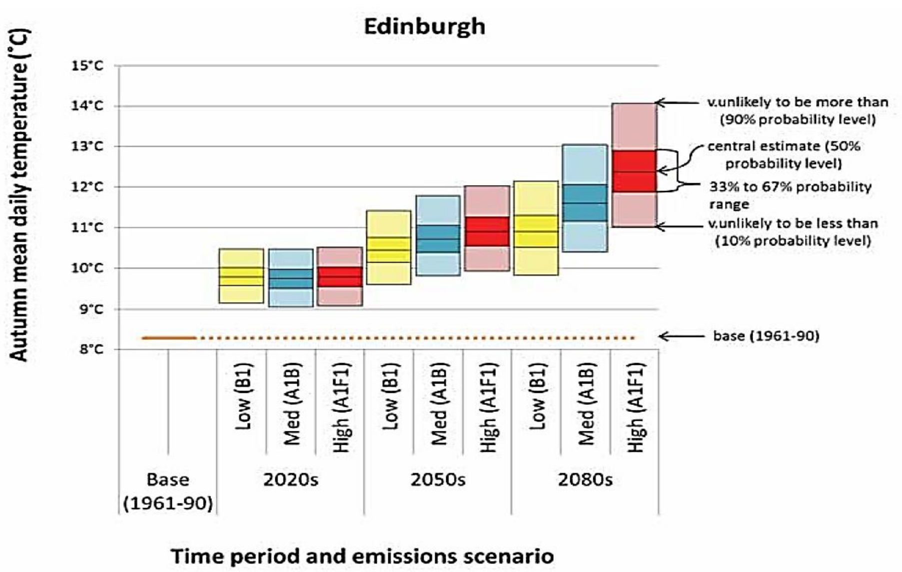
a.



b.



c.



d.

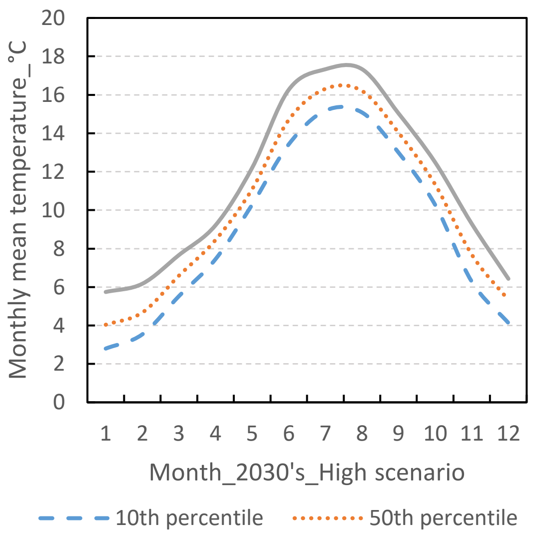
4.3.12. Integration and use of future weather files

The probabilistic climate data obtained from UKCP09 Weather Generator through the PROMETHEUS project files provides different applications into the resilience of buildings. Emulating the impacts and testing for alternatives into the adaptability of buildings caused by climate change provides projections into the internal conditions and the demand of energy of buildings. Seen as impacts to building users, they are based on reaching certain set thresholds with consequences on thermal comfort, affordability and environmental impact. These are set by benchmarks or compared against set baselines and targets, such as those for overheating in buildings when indoor air temperature conditions reach a percentage of hours above ≥28°C, causing occupants to feel thermally uncomfortable resulting in cooling requirements. This leads to energy demand for cooling in a response to more extreme weather from climate change for longer periods than expected, as well as space heating demand during winter periods with extreme cold weather shifts (Jenkins et al., 2015 & CIBSE, 2015). The impacts and resilience to such changes and extremes is rarely considered in new building design and construction, let alone existing buildings. For that reason, accounting for it at the calculation stage for energy demand is important.

Through the probabilistic weather files, a building simulation can produce a simplified output of results reporting on interior temperature and the resulting energy to maintain occupant thermal needs. This research has examined the distribution of outputs in two forms; one directly into the building simulation to obtain the changes in energy for cooling and heating throughout the year by using TRY weather files. Similarly using the above ProCliP's, exterior temperature changes and their impact on internal conditions during the 2030's, 2050's and 2080's respectively as shown in Table 4-26 and Figures 4-40 and Figure 4-41.

Table 4 - 26: Edinburgh - TRY 2030's High CO_2 scenario, external dry bulb temperature

Temperature °C/ probability	Minimum	Maximum	Mean	Std. Deviation
10th percentile	-7.60	24.40	8.95	5.7
50th percentile	-5.40	26.50	10.10	5.8
90th percentile	-7.10	30.30	11.30	5.8



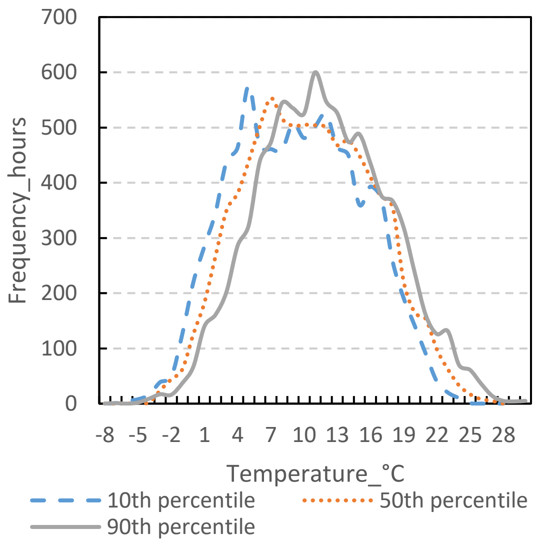


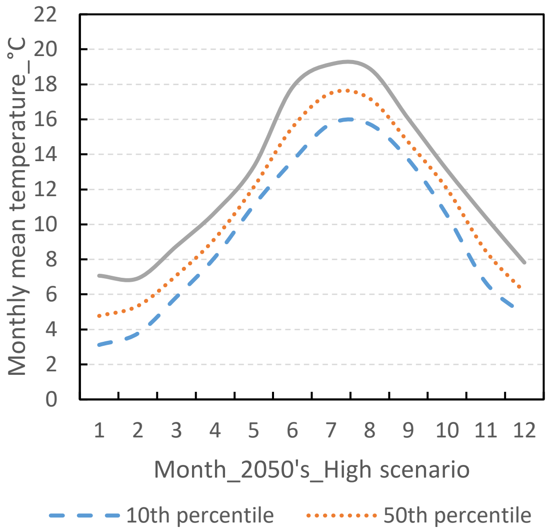
Figure 4 - 40: (left), Probabilistic monthly mean temperature, 2030's, Edinburgh

Figure 4 - 41: (right), Histogram of hours a temperature is expected, 2030's, Edinburgh

The above data corresponds to a probabilistic dry bulb exterior ambient temperature in a high CO_2 scenario during the 2030's time period. Figure 4-42 shows that there are differences in the mean values in each month over a twelve-month period under the three proposed probabilistic percentiles. Between a 10 % and 90% probability a difference of 2˚C to 3˚C is expected. Figure 4-43 has plotted this same data in a histogram showing the frequency in hours of temperatures; a shift from a 10%, 50% and 90% probability is apparent with a tendency to increase the percentage of occupied hours with >25 ˚C. The changes in temperature play a big role in the behaviour of buildings thus, it is important to show low and high probabilities.

Table 4 - 27: Edinburgh - TRY 2050's High CO_2 scenario, external dry bulb temperature

Temperature °C/ probability	Minimum	Maximum	Mean	Std. Deviation
10th percentile	-6.1	27.3	9.43	5.91
50th percentile	-5.4	26.8	10.87	5.95
90th percentile	-3.6	31.7	12.53	6.00



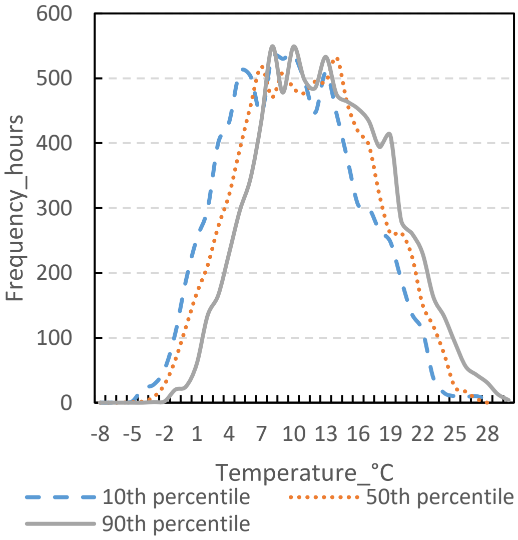


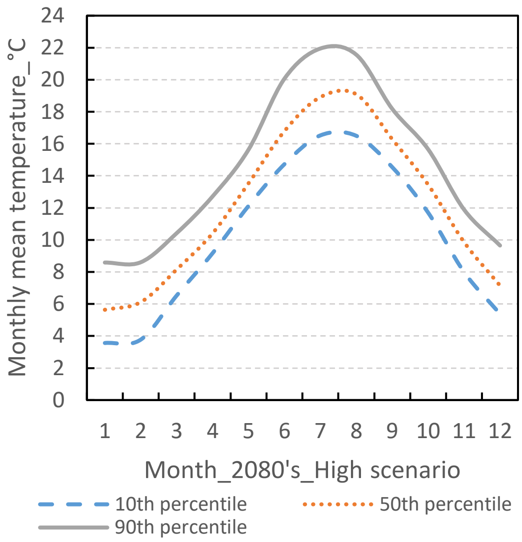
Figure 4 - 42: (left), Probabilistic monthly mean temperature for the 2050's – Edinburgh

Figure 4 - 43: (right), Histogram of hours a temperature is expected, 2050's, Edinburgh

Table 4-27 and Figure 4-42 and Figure 4-43 provide probabilistic data over dry bulb temperatures during the 2050's. Comparing the 2030's with the 2050's data there is a clear tendency of increased temperetaures even in the 10th percentile maximum value, 24.4 ˚C and 27.3 ˚C respectively. The 90th percentile has shifted considerably as shown in Figure 4-43 with lower frequency of hours below freezing in winter months and many more hours above 25 ˚C.

Table 4 - 28: Edinburgh - TRY 2080's High CO_2 scenario, external dry bulb temperature

Temperature °C/ probability	Minimum	Maximum	Mean	Std. Deviation
10th percentile	-5.20	26.80	10.25	6.11
50th percentile	-4.50	32.70	12.15	6.17
90th percentile	-0.80	35.70	14.61	6.11



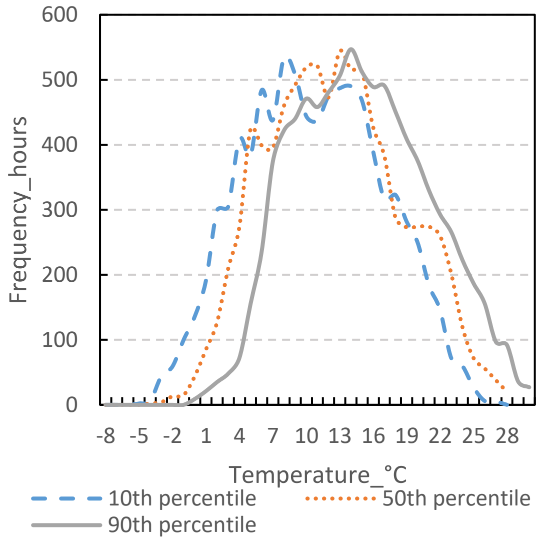


Figure 4 - 44: (left), Probabilistic monthly mean temperature for the 2080’s – Edinburgh

Figure 4 - 45: (right), Histogram of hours a temperature is expected, 2080’s, Edinburgh

The 2080’s time period data, shown in Table 4-28, for dry bulb temperatures show a higher tendency to extreme temperatures ranging from maximum values of 27 to 36 ˚C respectively, and minimum values from -5 to -0.8 ˚C respectively. The mean monthly data shown in Figure 4-44 has identified large displacements between the probabilistic data with a 10th and a 90th percentile. This is also evident in the histograms in Figure 4-45, where a significant shift is shown between the probabilities with lower number of hours below freezing and more above 25 ˚C. The 10th and 50th percentile show some similarities, with little shifting between them, however the 90th less probable assumption presents a larger number of hours with high temperatures.

4.3.13. Concluding remarks

This section of the results and data collection was split into two stages. Stage 3a has explained the different steps to modelling and emulating the space heating energy demand of three of the dwellings chosen. These sections explain how models were conceived by creating a base line model followed by a first stage of calibration using assumptions and measured in-situ data. A more in-depth calibration through a sensitivity analysis and step-changes of independent variables gave way to creating a refined approximation of actual measured energy use in each modelled dwelling. To achieve this, an error analysis was done that evaluated the step-changes taken by quantifying the dispersion between measured and modelled. This then defined three calibrated models to use for the subsequent resilience study, further testing the models during extended time periods with variable conditions.

Section 3b explains and presents the process of selecting and identifying the appropriate probabilistic future weather. This was done by proposing three time periods, two CO_2 scenarios and three probabilistic percentile projections. This section clarifies the source of data and the assumptions made for the best weather files, considering their suitability for thermal modelling.

Although the data presented only shows external dry bulb temperatures, it is clear that in order to generate a weather file with probabilistic climate change weather changes, a lot of background data processing is required for other variables (humidity, wind speed, pressure, dew point, etc.). For this reason, the weather files used have opted for adopting sources which have explored and generated files for the nearest location to the dwellings, in this case Edinburgh. The data from the UKCP09 implemented by the PROMETHEUS outputs for certain locations in the UK have been a valuable source that has saved time and further calculations.

4.4. Chapter conclusion

This chapter compiles and presents the results from various critical aspects of this research using a top-down approach. A mix-mode method combining quantitative and qualitative data was applied to parametric and non-parametric statistical methods facilitating the selection of parameters and settings for subsequent building modelling.

The in-situ building envelope tests and energy monitoring results provided vital evidence of the actual performance of the dwellings under study. Different levels of assessment provided the essential data to further analyse the dwellings in a longitudinal manner using longitudinal climate change parameters. Further test and results show that the difference between the compliance modelling envelope performance and the monitored in-situ tests can differ by 2 or 3 times.

Significant correlations between dwellings have also been presented. This shows how energy consumption can be interpreted differently according to different parameters. The best correlation with energy demand, according to its thermal envelope, construction method or occupation was identified. These correlations also provided vital evidence of the variables that make a larger impact to energy use, later used for further analysis. Results also showed that the retrieved building envelope, internal and external conditions that surround the dwellings are essential for the correct calibration of dynamic thermal models. This data was used in models to conduct an uncertainty, sensitivity and error analysis.

It was found that dilapidation of the building envelope in this short period of time has impacted more through fabric infiltration heat loss than thermal transmission (U-value) changes. The air permeability of the dwellings declined on average 40% (n=13) between the interval testing conducted over the period of study, compared to the thermal transmittance which declined on average by 8% (n=13). Despite this, all dwelling performance was re-calculated again to obtain a dwelling performance factor (DPF). The dwellings showed a persistent decline in performance with an increase in heat loss over the analysed years. However subsequent years of monitoring show a steady decline but not as high as the early occupation stages.

The next chapter of this thesis covers Stage 4 of the methodology flow chart as explained in Chapter 3 Figure 3-1. It will seek to statistically define the decline in performance using the DPF and applying it to the heating degree day statistical analysis and the longitudinal projections of climate change and the impact on the environment.

Chapter 5

Analysis & Interpretation

5.0. Chapter introduction

This chapter follows Stage 4 of the methodology in Chapter 3. Its aim is to use the results retrieved over the monitoring period to perform an analysis of the impacts on energy demand and indoor comfort levels. The focus is to show estimated longitudinal trajectories of environmental impacts using future weather data sets.

A selection of results from measurements and calculations gained at Stage 3a and 3b which included the envelope performance evaluation in Chapter 4 are presented to clarify a proposed dilapidation impact in the dwellings. The analysis follows two evaluation techniques; the first uses heating degree days, and the second; a dynamic simulation, both calculating future energy demand by implementing envelope dilapidation over time, gap in performance in the early occupation as a displaced CO_2 (energy) standpoint and climate change future weather patterns. Also relevant to the analysis over time as a result of shifting weather patterns are indoor comfort conditions; mentioned in Chapter 4, where overheating resulted in higher energy for cooling.

The chapter is split into four sections that cover the analysis of data and interpretation in a longitudinal manner. The first (5.1) explains how the results decline over the measurement intervals and analyses the dilapidation factor in all dwellings in this research. Section 5.2, 5.3 and 5.4 stretch the energy demand and interior conditions over time. Section 5.5 discusses the impact of tipping points of environmental performance against targets, indicating an estimated year in which they happen. This chapter will also propose baseline envelope performance figures to establish interventions and retrofit scenarios. Finally, Section 5.6 concludes and summarise the work, whilst introduces the final chapter.

5.1. Stating the recorded dilapidation

Chapter 4 outlined the difference between the as-designed and as-built, evidencing an envelope and energy demand performance gap. Three measurements were made of fabric performance resulting in a mean displacement of results for the thirteen observed dwellings. The longitudinal recordings defined an accurate knowledge of the occupant's energy profile; initially by taking the mean demand over the four years of energy readings. Although this mean value was important, further analysis concludes that the third or fourth year demand is a more representative figure to use to describe the dwellings, hence the values used as a baseline to calibrate the dynamic building simulations (Bros-Williamson et al., 2017).

This section seeks to define and analyse the dilapidation obtained through the measurements of air permeability and wall U-value. These values are then included into a re-calculation of the dwelling performance factor (DPF) using compliance modelling tools (SAP2009) with recorded and steady state values to obtain a heat loss coefficient and dilapidation factor, later used in further longitudinal evaluation of the dwellings. Two intervals between recorded data will be considered; interval 1 from 2012 to 2014 and interval 2 from 2014 to 2016. The information analyses all thirteen dwellings that underwent envelope measurements over the evaluation period however, further analysis of the longitudinal environmental impact will focus on the three dwellings used in the dynamic simulation exercise in Chapter 4. Alongside the fabric dilapidation the relevant space heating demand will be quoted; a correlation which has been confirmed already in Chapter 4 and by Bros-Williamson et al. (2016).

5.2.1. Dilapidation by thermal transmission

Chapter 4 shows disparities in the results between the as-designed and the as-built measured U-values from; 2012 just after handover, 2014 after two years of occupation and 2016 after four years of occupation. This data shows the performance gap between the design predictions. However, for the purpose of change between measurements the ratio as a fraction between intervals is calculated, as well as the difference (**Δ**) of thermal transmission (W/m^{2}K). Figure 5-1 and Table 5-1 show the U-value differences and ratio of between intervals.

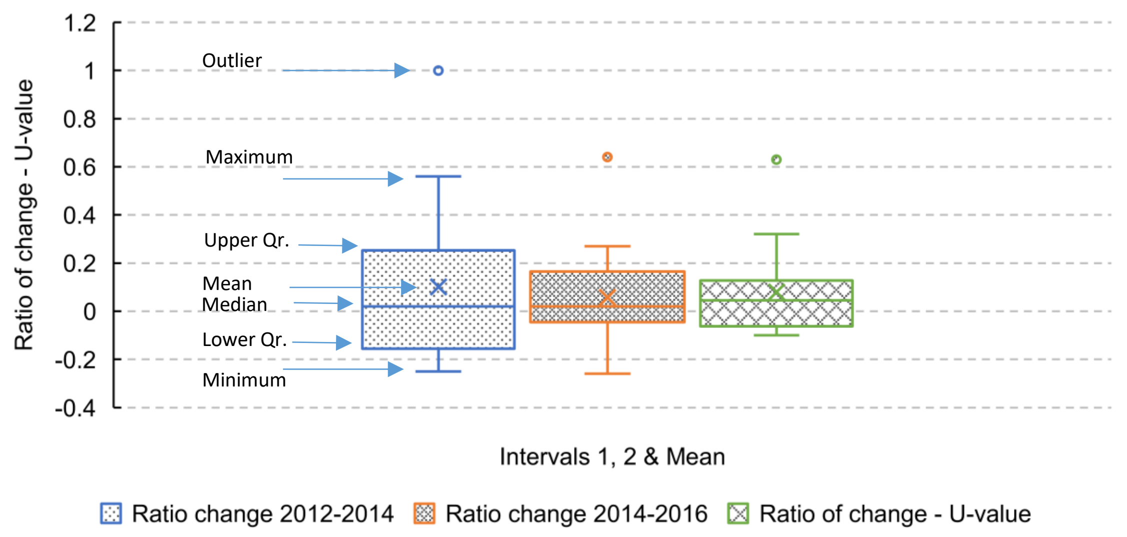


Figure 5-1: Ratio of change between interval measurements – In-situ U-value of walls

Although the mean of each dwelling could be used as the preferred rate of change, it is the median that is best suited between all the dwelling results as it disregards the outliers to produce a reliable ratio and difference between intervals. During the first and second intervals a 0.02 (2%) rate of change is obtained. Considering the mean of the median interval ratio values a value of 0.045 (4.5%) is derived. The outliers taken by the median values quoted above, all come from the measurements in dwelling SD.8.23 with an unprecedented wall type. Figure 5-1 further explains the results of rate of change between intervals.

The box plot in Figure 5-1 shows a larger sparsity in the upper and lower quartiles measurements in the first interval compared with the second interval where readings are much more clustered together. The median, however, remains the same (0.02), despite the mean ratio change being higher (0.045). The maximum values also reduce between the first and second values, however the minimum values are similar as each other.

Despite there being a small thermal transmission value difference between the dwellings and the two intervals, its repeatability on the heat loss around the dwellings walls over subsequent years will impact the most on energy demand.

Table 5-1: Difference between U-value measurements and interval ratio

	Interval 1 (2012 – 14)		Interval 2 (2014 – 16)		Mean between intervals	
Dwelling code	**Ratio**	**U-value Δ (W/m²K)**	**Ratio**	**U-value Δ (W/m2K)**	**Ratio**	**U-value Δ (W/m2K)**
F.1.4	0.05	0.01	-0.23	-0.05	-0.09	-0.02
F.2.5	0.17	0.05	0	0	0.08	0.03
F.3.12	0.35	0.07	-0.26	-0.07	0.05	0
B.4.14	-0.11	-0.05	-0.03	-0.01	-0.07	-0.03
B.5.16	-0.17	-0.04	0.05	0.01	-0.06	-0.02
SD.6.17	**0.56**	**0.14**	**-0.03**	**-0.01**	**0.27**	**0.07**
SD.6.18	**-0.15**	**-0.02**	**0.27**	**0.03**	**0.06**	**0.01**
T.7.19	**-0.13**	**-0.02**	**0**	**0**	**-0.06**	**-0.01**
T.7.20	0.22	0.04	-0.09	-0.02	0.07	0.01
T.7.21	-0.17	-0.03	0.13	0.02	-0.02	0
SD.8.23 - BW	1	0.13	0.27	0.07	0.63	0.1
SD.8.23	0	0	0.64	0.09	0.32	0.05
SD.9.24	0.04	0.01	0.04	0.01	0.04	0.01
SD.10.33	-0.25	-0.07	0.05	0.01	-0.1	-0.03
Mean	0.1	0.02	0.06	0.01	0.08	0.01
Median	0.02	0.005	0.02	0.005	0.045	0.005
Min	-0.25		-0.26		-0.1	
Max	0.56		0.27		0.32	
Upper Qr	0.207		0.165		0.127	
Lower Qr	-0.145		-0.045		0.0625	
Outlier	1		0.64		0.63	
SD	0.33	0.06	0.22	0.04	0.19	0.04

5.2.2. Dilapidation by air permeability

The airtightness tests (ATT) expressed as air permeability (q50) results, were undertaken during three periods; after construction for building control requirements (2012), after two years of occupation (2014) and then after four years of occupation (2016). The highest ratio in Interval 1 came from dwelling SD.6.18 at 2.81 (280%) or nearly three times more than the first test with a difference in q50 of 1.55 $m^3/h.m^2$@50Pa. However, this was not the highest difference in results. Dwelling SD.10.33 and F.2.5 had differences as high as 2.29 and 1.99 $m^3/h.m^2$@50Pa respectively. The median air permeability differences came as 1.44 $m^3/h.m^2$@50Pa. Table 5-2 and Figure 5-2 show that interval 1 has a large sparsity of values compared with the second interval with a more compressed set of values resulting in a smaller median value. Interval 2 shows a much lower median ratio of 0.07 (7%) with a median difference in results of 0.24 $m^3/h.m^2$@50Pa. The mean of results between the two intervals reveal a high ratio of decline in air permeability. The median between intervals of all dwellings came at 0.24 or 24% with a difference of 0.90 $m^3/h.m^2$@50Pa.

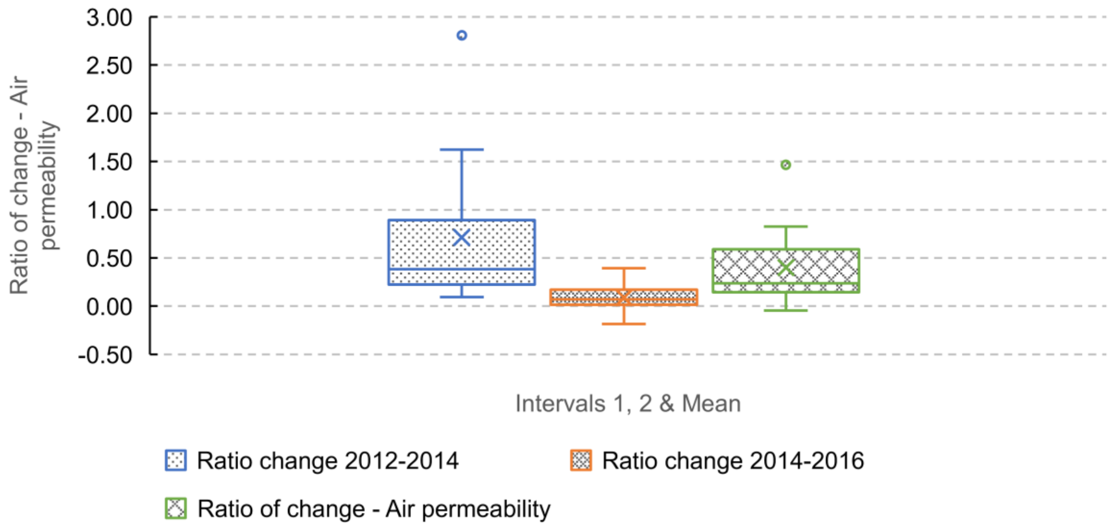


Figure 5-2: Ratio of change between interval measurements – dwelling air permeability

Analysing the results from 2012, only depressurisation tests were undertaken, compared with tests in 2014 and 2016 that included the mean between pressurisation and depressurisation. Such methodology was more representative of the dwellings true air permeability, testing the dwellings envelope in both directions of flow. Another observation is that Interval 1 was a period of adjustment for the occupiers in which “building snagging” took place requiring certain adjustments and improvements, also the dwelling structures settled during this first year impacting on the air tightness. Additionally, there is evidence that during the first years of occupation a lot of do-it-yourself (DIY) by the occupiers occurred; this was evident in dwelling SD.10.33 where the resident changed the interiors, such as bathroom linings, new appliances penetration (clothes dryer, etc). During Interval 2 a significant improvement was noted in dwelling SD.6.17, due to a living room window replacement and external wall interventions.

Table 5-2: Difference between air tightness tests (ATT) results and interval ratio

	Interval 1 (2012 – 14)		Interval 2 (2014 – 16)		Mean between intervals	
Dwelling code	**Ratio**	**ATT Δ ($m^3(h.m^2)$@50Pa)**	**Ratio**	**ATT Δ ($m^3(h.m^2)$@50Pa)**	**Ratio**	**ATT Δ ($m^3(h.m^2)$@50Pa)**
F.1.4	0.22	0.69	0.06	0.22	0.14	0.46
F.2.5	0.83	1.99	0.39	1.72	0.61	1.86
F.3.12	0.29	0.63	0.002	0.005	0.15	0.32
B.4.14	1.63	3.25	0.03	0.15	0.83	1.70
B.5.16	0.89	2.12	0.22	1.00	0.56	1.56
SD.6.17	**0.09**	**0.34**	**-0.19**	**-0.75**	**-0.05**	**-0.20**
SD.6.18	**2.81**	**1.55**	**0.12**	**0.26**	**1.47**	**0.90**
T.7.19	**0.45**	**1.73**	**0.03**	**0.18**	**0.24**	**0.95**
T.7.20	0.16	0.75	0.22	1.22	0.19	0.98
T.7.21	0.31	1.44	0.00	-0.02	0.15	0.71
SD.8.23	0.17	0.50	0.07	0.24	0.12	0.37
SD.9.24	0.38	1.19	0.09	0.40	0.24	0.80
SD.10.33	1.05	2.29	0.09	0.38	0.57	1.34
Mean	0.71	1.42	0.09	0.38	0.40	0.90
Median	0.38	1.44	0.07	0.24	0.24	0.90
Min	0.09		-0.19		-0.05	
Max	1.63		0.39		0.83	
Upper Qr	0.89		0.17		0.59	
Lower Qr	0.22		0.01		0.14	
Outlier	2.8		-		1.47	
SD	0.74	0.82	0.13	0.59	0.39	0.57

It is fair to conclude that further tests are required between intervals to show whether there is an alignment to the first or second Intervals of this research. Despite this, there is a continued decline in air permeability which provides enough evidence of a continued reduction in air tightness (less air-tight).

5.2.3. Dilapidation of dwellings – stating a factor of dilapidation

In line with intervals of wall U-value and air permeability measurements and the attributed heat loss, an as-built defined dwelling performance factor (DPF) could be calculated. In this context the re-calculation of the dwelling's DPF produced a "quasi-steady state" heat loss coefficient. This calculation was important because it defined a heat loss value using the measured envelope performance results. Just as the measured values in the above sections, a dilapidation ratio emerges as a DPF, shown in Figure 5-3.

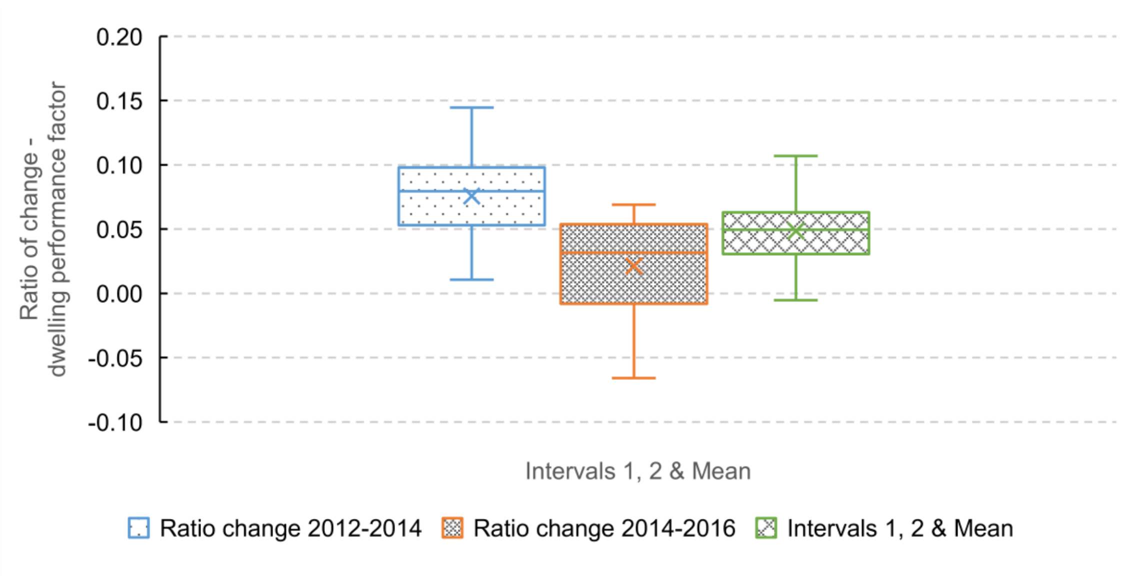


Figure 5-3: Ratio of change between interval measurements – dwelling performance factor

Figure 5-3 shows Interval 1 and 2 ratio results with mean ratio results between the two Intervals. Also shown in Table 5-3, the mean and median result for Interval 1 of 0.08 (8%) ratio between results are the same, which signifies none or little impact from outliers. However, the median difference in DPF is 4.99 W/K. The spread of results in Interval 1 is small which shows consistency between the dwellings performance changes.

Interval 2 presents a consistent but lower set of ratio between results. There are three dwellings that show a negative (improvement) in their DPF, such as dwelling F.1.4, F.3.12 and SD.6.17; -0.02(-2%), -0.07 (-7%) and -0.02 (-2%) respectively. This is also reflected in the actual DPF difference in readings with F.1.4 reducing by 1.55 W/K, SD.6.17 by 1.94 W/K and the largest in dwelling F.3.12 by -3.90 W/K. However, the overall median ratio of Interval 2 is smaller than Interval 1 at 0.03 (3%). Also relevant are the maximum and minimum values calculated; Interval 1 has ratios of 0.14 (14%) and 0.01 (1%) respectively different to Interval 2, 0.07 (7%) and -0.07 (-7%). Mean values of all dwellings show that the median ratio is 0.05 (5%) between calculations and a median difference of 3.76 W/K.

Table 5-3: Difference between DPF calculations, results and interval ratio

	Interval 1 (2012 – 14)		Interval 2 (2014 – 16)		Mean between intervals	
Dwelling code	Ratio	diff (W/K)	Ratio	diff (W/K)	Ratio	diff (W/K)
F.1.4	0.01	0.78	-0.02	-1.55	-0.01	-0.39
F.2.5	0.14	8.60	0.07	4.69	0.11	6.64
F.3.12	0.12	6.23	-0.07	-3.90	0.03	1.17
B.4.14	0.08	7.88	0.00	0.00	0.04	3.94
B.5.16	0.07	4.72	0.04	3.15	0.05	3.93
SD.6.17	**0.12**	**12.60**	**-0.02**	**-1.94**	**0.05**	**5.33**
SD.6.18	**0.08**	**4.70**	**0.04**	**2.82**	**0.06**	**3.76**
T.7.19	**0.08**	**4.99**	**0.01**	**0.83**	**0.05**	**2.91**
T.7.20	0.06	3.33	0.07	4.16	0.06	3.74
T.7.21	0.05	3.33	0.01	0.83	0.03	2.08
SD.8.23	0.08	7.66	0.06	6.70	0.07	7.18
SD.9.24	0.08	6.71	0.03	2.87	0.06	4.79
SD.10.33	0.03	1.67	0.04	2.50	0.03	2.09
Mean	0.08	5.63	0.02	1.63	0.05	3.63
Median	0.08	4.99	0.03	2.50	0.05	3.76
Min	0.01		-0.07		-0.01	
Max	0.14		0.07		0.11	
Upper Qr	0.08		0.05		0.06	
Lower Qr	0.06		-0.01		0.03	
Outlier	0.14		-		-	
SD	0.04	0.06	0.04	0.03	0.03	0.03

5.2.4. Concluding remarks

The recorded in-situ U-value of the walls and other components U-value such as windows, floors and roof are a determining factor in the dwelling's envelope performance and thermal efficiency. Equally the dwellings air permeability and the ability to retain heat in the building to avoid infiltration ventilation heat loss. Evaluating the median values of the mean between Intervals, the dilapidation ratio of change from the air permeability is higher than the wall U-value, 0.07 (7%) and 0.045 (4.5%) respectively, indicating that air infiltration plays a larger role in the dwelling's thermal performance. The results tell us that the wall thermal transmission dilapidation is slower (smaller ratio of change) at this two-year interval testing than the air permeability which has shown that it dilapidates quicker, more so in Interval 1 which appears to be affected by early occupation structure settling and dwelling re-adjustment period. It indicated that the thermal qualities of the envelop materials, primarily the insulation used, have a slower dilapidation than those of the air infiltrating out of the envelope, thus a predominant decline in air permeability. With Interval 1 suffering from this settling and re-adjustment period, it questions whether it should be used as the natural dilapidation ratio of change and whether Interval 2 is a better ratio to take. More test of using these intervals and conditions should clarify this.

The calculation of the dwellings performance factor (DPF) directly provides a measure of heat loss therefore it is a good indicator of dilapidation as it combines many envelope and efficiency figures. The first Interval of the DPF ratio has clearly changed in-line with the large ratio obtained in Interval 1 of the air permeability measurements. However, as shown in Table 5-4, the values shown represent a 2-year period between intervals, therefore a DPF of 0.05 (5%) would halve to represent a single year result, thus a DPF of 0.025 (2.5%).

The application of a dilapidation factor therefore must have a combined heat loss coefficient, such as the DPF applicable into a whole dwelling energy demand calculation. Applying the yearly ratio of change to a calculation of energy demand would impact directly on its longitudinal energy demand considering an estimated dilapidation of the dwelling's envelope. Table 5-4 shows a summary of the results obtained to implement in subsequent section of this analysis.

Table 5-4: Summary of median ratios of change between intervals

	Interval 1	Interval 2	Mean of intervals
Wall U-value	0.08	0.03	0.05
Air permeability	0.38	0.07	0.24
DPF	0.08	0.03	0.05

5.3. Longitudinal prediction of energy demand

In this section calibrated simulations and degree day's methods are used to obtain space heating and cooling energy demand under the conditions proposed by the climate change weather files. The two techniques are then compared to provide evidence of the best method of applying coefficients of dilapidation from the ratios derived in previous sections.

5.3.1. Estimating heating demand

One technique adopted in this research to estimate heating demand has been the use of calibrated dynamic building energy simulations (DBES). This type of simulation technique allowed the use of future probabilistic climate change weather files over time and record the resultant space heating energy demand. A second technique calculated heating energy demand using heating degree day (HDD) methods. It achieved this by proposing suitable baselines and then using the probabilistic future weather files, particularly external mean dry-bulb temperatures to obtain daily and yearly energy demands. Both techniques are tested and then compared in order to understand two different levels of estimation of energy and how suitable they are to future weather patterns and the application of dilapidation figures over time.

5.3.2. Simulated heating energy demand

Having analysed and modelled in detail the three dwellings along with the selection of the most appropriate probabilistic climate change weather files, it was then suitable to merge them to identify the impact of climate change over the three overlapped time periods. The Edinburgh UKCP09 probabilistic climate files were added to the calibrated models and simulations re-run to obtain monthly space heating energy demand considering the medium and high CO_2 scenarios at the 10th, 50th and 90th probabilistic percentiles. The probabilistic space heating energy demand is obtained firstly using the CIBSE Edinburgh test reference year (TRY) baseline file, from which the original probabilistic files are created (CIBSE, 2015; Eames et al., 2010). From these results, a percentage difference between the time frames and the probabilistic percentiles is calculated which is applied directly onto the Dunfermline space heating demand baseline. This has been done to understand the difference between probabilistic weather file and measured weather data. The Edinburgh TRY future weather files are composed of twelve months of meteorological data representing the most average month from a 22 year period, typically 1983–2004 (Eames et al., 2010). The Dunfermline baseline originates from the weather station data during 2016 and aligned to the calibrated model and actual space heating demand of dwellings analysed. A method of comparing these sources of weather files is to observe the external dry-bulb temperature over a twelve-month period. Figure 5-4 shows the recorded Dunfermline temperature with a mild January, February and March compared with Edinburgh TRY weather, which is colder. However, autumn period in Dunfermline during 2016 (September and November) is colder than Edinburgh TRY weather. Dunfermline weather recorded a twelve month mean temperature of 9.8 ˚C whilst Edinburgh TRY of 8.3 ˚C; a 1.4˚C difference.

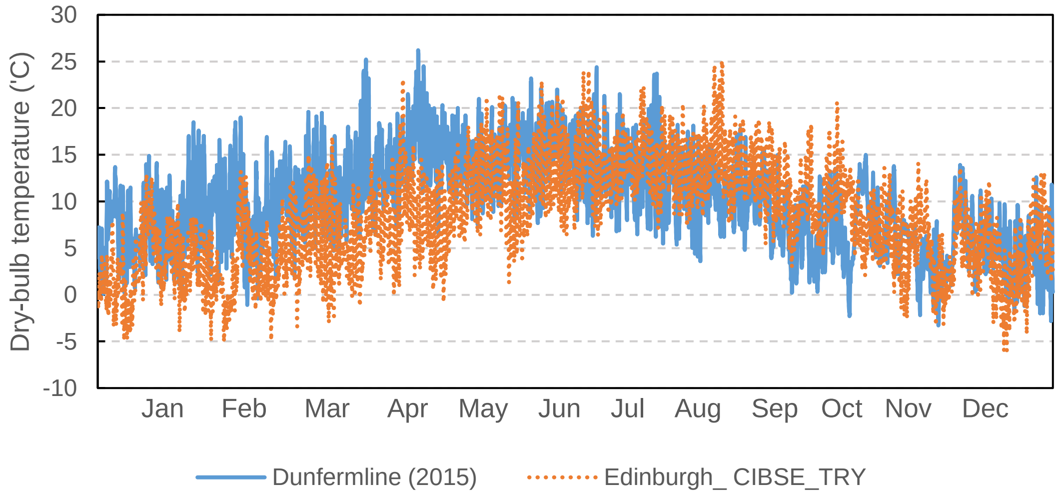


Figure 5-4: Difference in dry-bulb external temperatures - Dunfermline and Edinburgh TRY

The impact of such displacement on baseline space heating energy demand is shown in Figures 5-5 and 5-6 below. Figure 5-5 shows space heating energy demand for dwelling SD.6.17 using two probabilistic space heating demand baselines. Although there is a wide separation between them, a trend of decline in energy demand is analysed. During the 2030's considering the three probabilistic scenarios; 10, 50 and 90th, a decline of 12%, 30% and 45% respectively has been modelled. The 2050's shows a larger decline; 17%, 39% and 57% respectively, whilst during the 2080's; 25%, 45% and 68% respectively. The lowest demand is at a 90th percentile declining to 703 kWh/yr compared with the calibrated model of 2,180 kWh/yr.

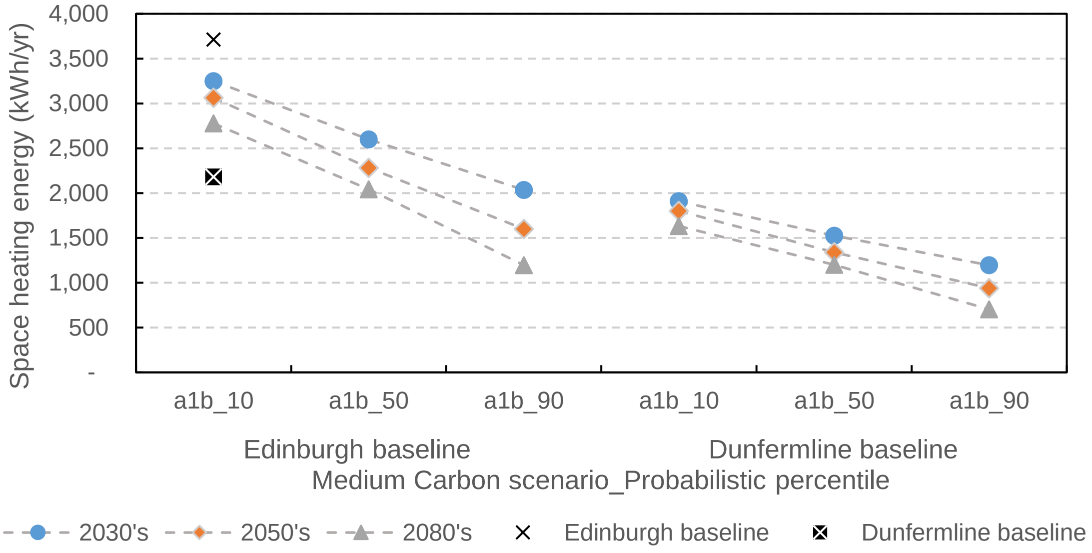


Figure 5-5: Medium CO_2 scenario impacting on space heating - Dwelling SD.6.17

A high CO_2 emission scenario was modelled showing that little was done to mitigate climate change. Figure 5-6 and Table 5-5 show a faster rate of decline in space heating demand. The 2030's present a decline of 10%, 20% and 49% respectively considering the three probabilistic percentiles. During the 2050's further decline is shown; 18%, 40% and 62% respectively. The 2080's shows; 28%, 55% and 81% respectively. The 90th percentile probabilistic heating demand reaches as low as 425 kWh/yr compared with the Dunfermline baseline.

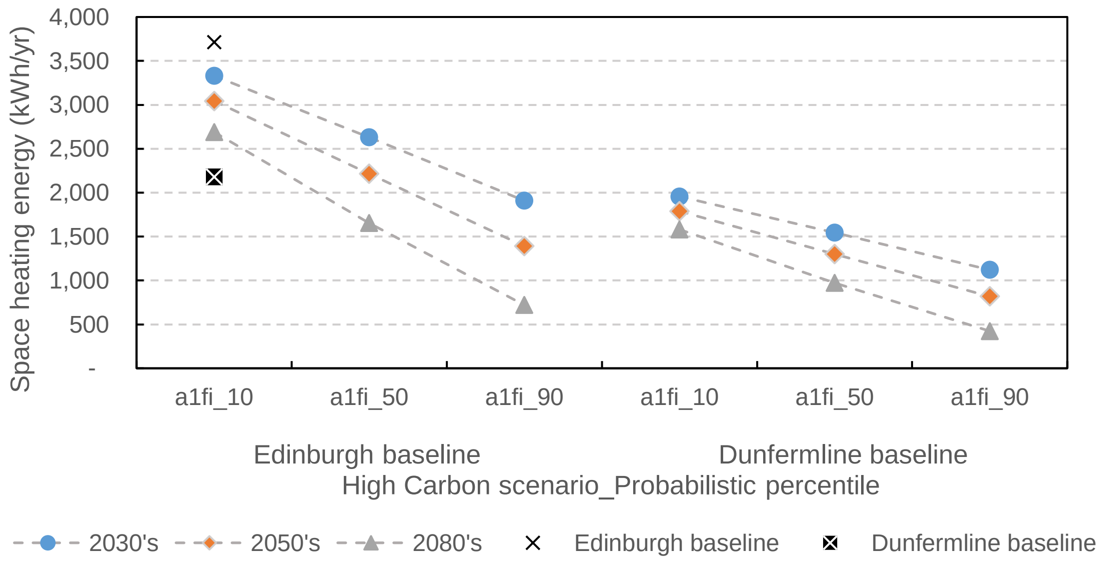


Figure 5-6: High CO_2 scenario impacting on space heating - Dwelling SD.6.17

Table 5-5: Percentage decline in space heating energy as modelled for Dwelling SD.6.17

	Medium CO_2 scenario (a1b)			**High CO_2 scenario (a1fi)**		
	Probabilistic percentile					
Time frame	10th	50th	90th	10th	50th	90th
2030's	-12%	-30%	-45%	-10%	-29%	-49%
2050's	-17%	-39%	-57%	-18%	-40%	-62%
2080's	-25%	-45%	-68%	-28%	-55%	-81%

Dwellings SD.6.18 and T.7.19 also underwent the same analysis as above, charting the two baselines under the different timelines and probabilistic percentiles. Tables 5-6 and 5-7 show the percentage decline between the CO_2 scenarios and probabilistic percentiles as a summary of dwellings SD.6.18 and T.7.19 simulated models.

Table 5-6: Percentage decline in space heating energy as modelled for Dwelling SD.6.18

	Medium CO_2 scenario (a1b)			**High CO_2 scenario (a1fi)**		
	Probabilistic percentile					
Time frame	10th	50th	90th	10th	50th	90th
2030's	-19%	-28%	-47%	-10%	-27%	-48%
2050's	-19%	-34%	-54%	-21%	-39%	-60%
2080's	-27%	-44%	-61%	-28%	-51%	-76%

Table 5-6 shows the percentage decline modelled for dwelling SD.6.18, although the declines are not equal to dwelling SD.6.17, they do present similarities in the trend of decline. This difference may be due to factors in the model such as occupancy or indoor temperatures impacting set point temperatures and heating demand.

Table 5-7: Percentage decline in space heating energy as modelled for Dwelling T.7.19

	Medium CO_2 scenario (a1b)			**High CO_2 scenario (a1fi)**		
	Probabilistic percentile					
Time frame	10th	50th	90th	10th	50th	90th
2030's	-7%	-19%	-30%	-7%	-19%	-32%
2050's	-12%	-25%	-39%	-12%	-27%	-44%
2080's	-17%	-31%	-50%	-20%	-39%	-61%

Although the impact is lower for dwelling T.7.19, just as it's shown in Table 5-7, the buildings conditions and occupancy patterns may have an influence on this. Other considerations may be the fuel type used for space heating; dwelling T.7.19 is electrically heated whereas SD.6.17 and SD.6.18 are gas heated.

5.3.2.1. Impact of increased indoor temperatures

A reference to indoor temperatures and risk of discomfort and overheating is made through the modelled ambient conditions and the applied UKCP09 future weather files. A similar analysis with the Edinburgh test reference year (TRY) baseline file was made of the three dwellings.

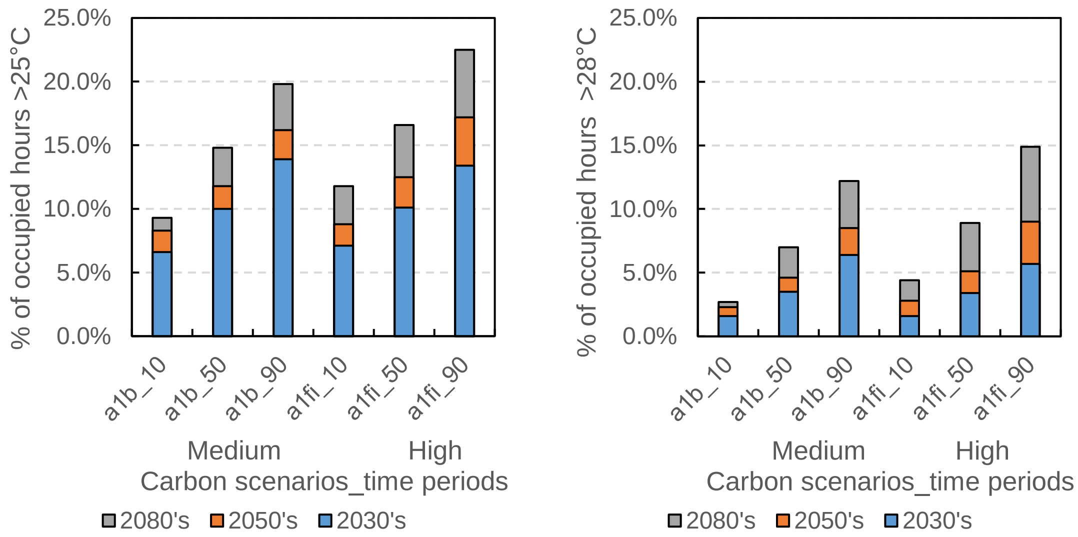
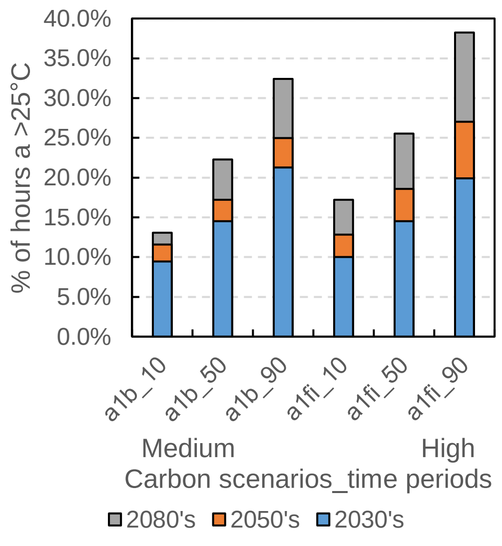


Figure 5-7 (left): % of occupied hrs >25°C, SD.6.17

Figure 5-8 (right): % of occupied hrs >28°C, SD.6.17

Figures 5-7 and 5-8 above show the modelled indoor ambient temperature for dwelling SD.6.17 using future weather files at different CO_2 scenarios, probabilistic percentiles and periods. The results are analysed as percentage of occupied hours reaching the threshold of feeling warm (>25°C) and dwelling overheating (>28°C). Describing the 50th probabilistic percentile, at a medium CO_2 scenario, the percentage of hours reaching 25°C increases from 10% in the 2030's to 12% in the 2050's and finally up to 15% in the 2080's. Included in this analysis is overheating under the same considerations; 3.5% in the 2030's, 4.6% in the 2050's and 7% in the 2080's. In a high CO_2 scenario during the 2080's at a 50th probabilistic percentile reaches 16.6% of occupied hours >25˚C with 9% of the occupied time being attributed to % of hours >28˚C.

Dwelling SD.6.18 is analysed in Figures 5-9 and 5-10 below. A similar trend is observed in the % increase during occupied hours. However, a decisive way of understanding the risk of increasing indoor temperatures is to observe the share of the % of hours >28˚C within the % occupied hours >25˚C. Simulations where the larger share of the total is by the % of hours above 28˚C will be more of an impact to occupant discomfort as more overheating is experienced. In dwelling SD.6.18 the largest share of >28˚C % hours are observed in the 50th and 90th probabilistic percentile. During the 2080's at a medium CO_2 scenario and 50th percentile, 10% of hours >28˚C form part of the total hours >25˚C of 22%, close to half. Equally at a 90th percentile and medium CO_2 scenario during the 2080's, 18% corresponds to hours >28˚C out of the total observed >25˚C of 32%, close to half of the hours. This share is different in the 90th percentile in the 2080's, 22% >28˚C and 38% >25˚C corresponding to a 60% share of this total.



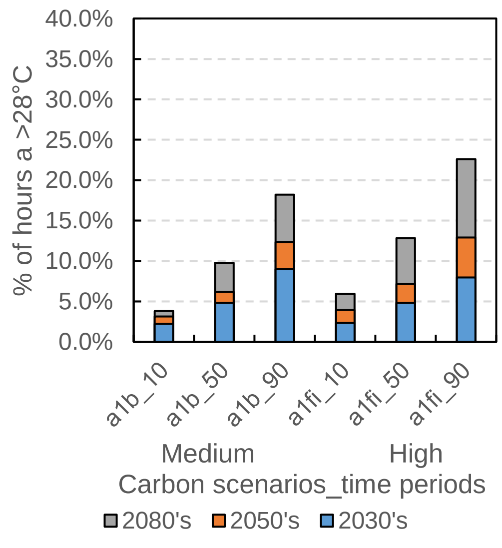
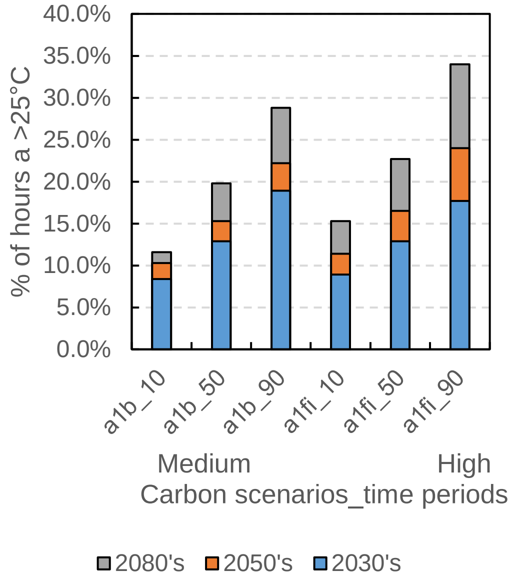


Figure 5-9 (left): % of occupied hrs >25°C, SD.6.18

Figure 5-10 (right): % of occupied hrs >28°C, SD.6.18

A similar analysis can be made in dwelling T.7.19 where this share increases between the CO_2 scenarios and the probabilistic percentiles. A trend in which overheating is the more predominant risk, bringing discomfort among occupants leading to less energy for space heating and more for cooling. This can be seen in Figures 5-11 and 5-12 below.



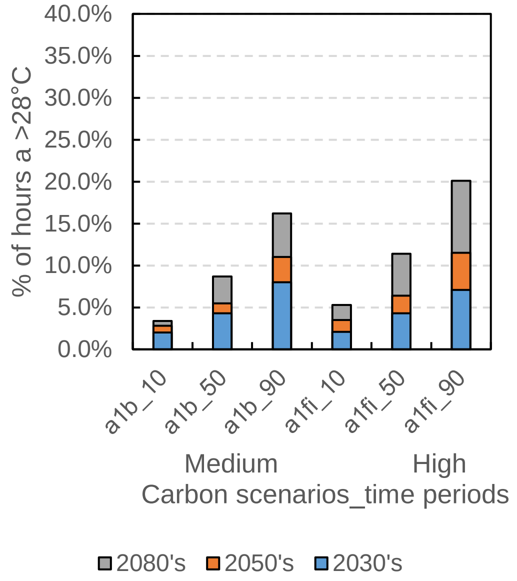


Figure 5-11 (left): % of occupied hours >25°C, T.7.19

Figure 5-12 (right): % of occupied hours >28°C, T.7.19

5.3.3. Heating demand using degree days

The second technique adopted is the use of heating degree day calculations to estimate heating energy demand for the three dwellings. To account for a longitudinal analysis and the impacts of climate change, a Edinburgh TRY mean weather file is used with UKCP09 probabilistic scenarios.

A first approach is to extract the UKCP09 dry-bulb temperature data for the three times lines, CO_2 scenarios and three probabilistic percentiles. This allowed for a similar analysis as presented in previous sections. In order to do this, similar internal temperature baselines were used as presented in Chapter 4. This allowed a first glimpse of the heating energy demand calculated by degree day data and dwelling performance factors accounting for the dwellings heat loss (W/K). This process concluded in very poor correlations between the simulated and degree day energy demand results. As a result, the baselines were modified considering increased indoor temperatures, expected rise in solar gains and internal gains from plugged appliances. Occupancy patterns and heating technology also impacted on the different baselines. For example, dwellings SD.6.17 and SD.6.18 with 10.8˚C and 12.5˚C baselines respectively had high internal gains through plugged appliances and higher number of occupants. The opposite was observed in dwelling T.7.19 with a higher baseline of 18.4˚C occupied by two energy frugal retired residents with less of a reliance on high powered plugged appliances.

Figure 5-13 displays dwelling SD.6.17 space heating declining according to the stipulated time frames and CO_2 scenarios, showing a similar trend as that observed in simulated models.

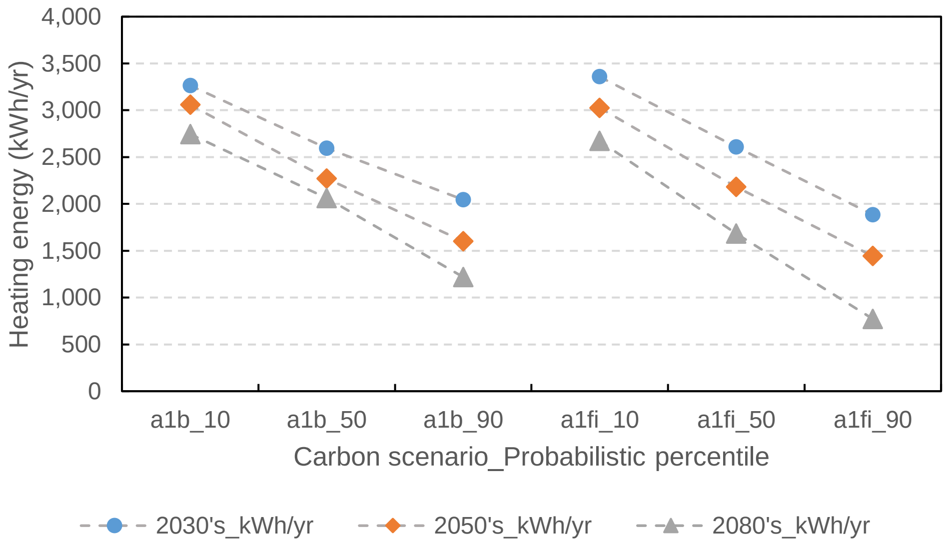


Figure 5-13: Probabilistic estimated energy for space heating – dwelling SD.6.17

Similarly, Figure 5-14 for dwelling SD.6.18 estimations of energy show declines in heat energy with distinct similarities between the 2030's and 2050's medium and high CO_2 scenarios, however in the 2080's the two scenarios are different, particularly the high scenario where energy for space heating reaches 700 kWh/yr at a 90th percentile, whilst the medium scenario 1000 kWh/yr.

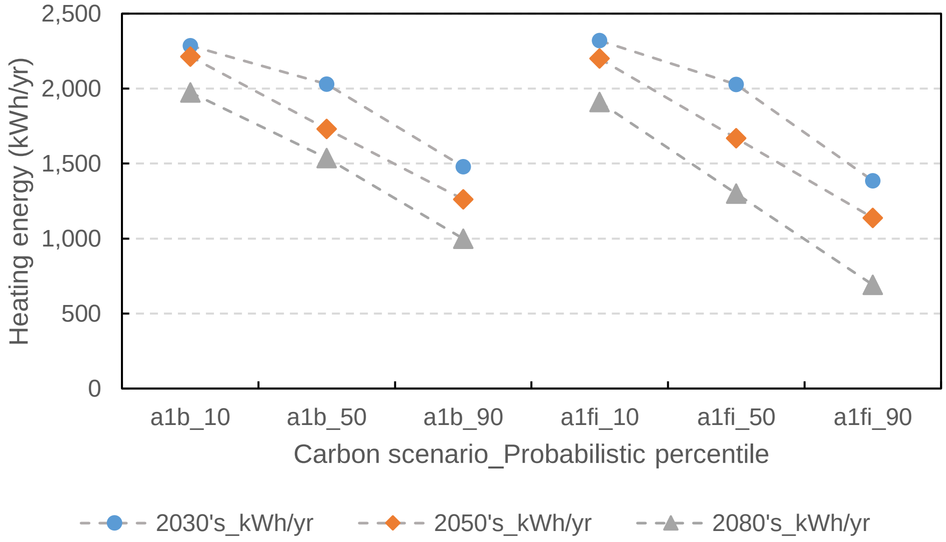


Figure 5-14: Probabilistic estimated energy for space heating – dwelling SD.6.18

Dwelling T.7.19 shows higher energy demand, also shown in the recorded energy and simulate energy using probabilistic weather data. Figure 5-15 shows this in detail by using the degree day data. Although 2030's and 2050's results decline similarly, it's the 2080's data that exposes the biggest decline where the impact of rising temperatures influences space heating energy demand.

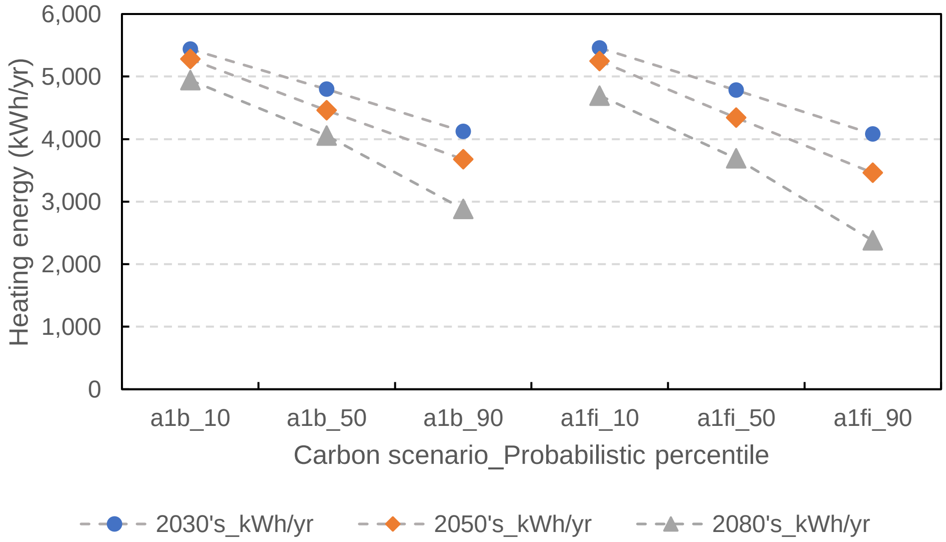


Figure 5-15: Probabilistic estimated energy for space heating – dwelling T.7.19

5.3.4. Estimating cooling energy demand

The simulations produced in this research were not fit for optimising cooling technology therefore two methods were tested; the use of cooling degree days and the calculation of energy from a cooling device installed in rooms based on the number of occupied hours above the 25˚C threshold simulated in Section 5.3.2. With increased periods of discomfort due to the rising temperatures, occupants tend to use cooling alternatives more often, particularly during summer periods, displacing energy for heating to energy for cooling.

5.3.5. Cooling demand using simulated internal conditions

The indoor temperature analysis shown above in Figures 5-7 to 5-12 predict a risk of occupants feeling warm and experiencing overheating in an upwards trend between the time periods. The results show that increased external temperatures have affected internal temperatures by having more hours above recommended conditions, thus reducing the need for energy for space heating. In this study, such weather patterns and files were helpful to predict not only the internal temperature conditions, but also the requirements of energy demand for space cooling. The cooling energy demand follows the methodology outlined in Chapter 3 of this thesis where the percentage of hours above the thresholds are used as the upper limit of comfort, anything above would indicate the need for cooling to bring down temperatures. Energy demand considers these hours of cooling demand, the cooling power capacity of the chiller and the device efficiency.

The demand of cooling energy in dwelling SD.6.17 is summarised in Figure 5-16. In the two CO_2 scenarios it is evident that the cooling energy demand increases according to the probabilistic percentiles, timelines and increased external dry-bulb temperatures. At the 10^{th} percentile, demand reaches between 225 kWh/yr and 320 kWh/yr at the medium CO_2 scenario. The 90^{th} percentiles shows it rises between 450 kWh/yr and 675 kWh/yr.

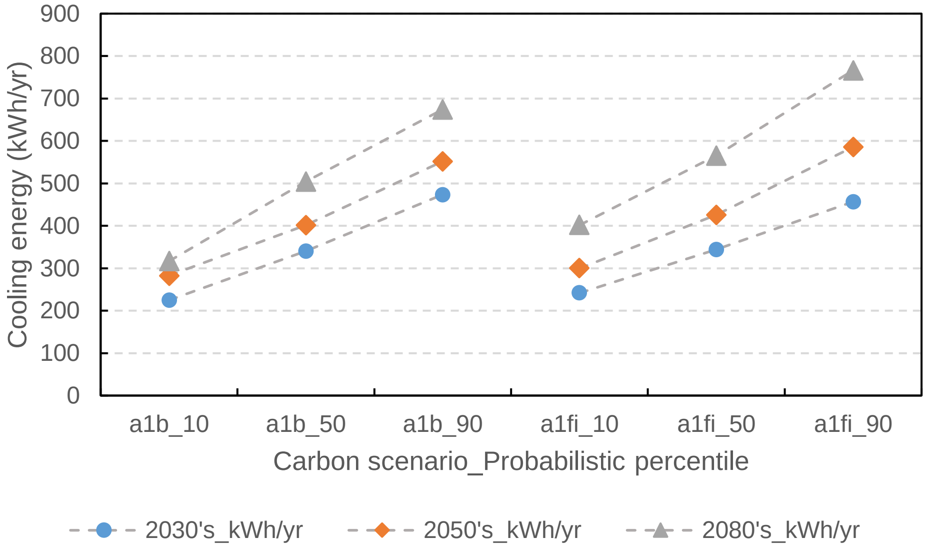


Figure 5-16: Estimated cooling energy demand of hours above thresholds, dwelling SD.6.17

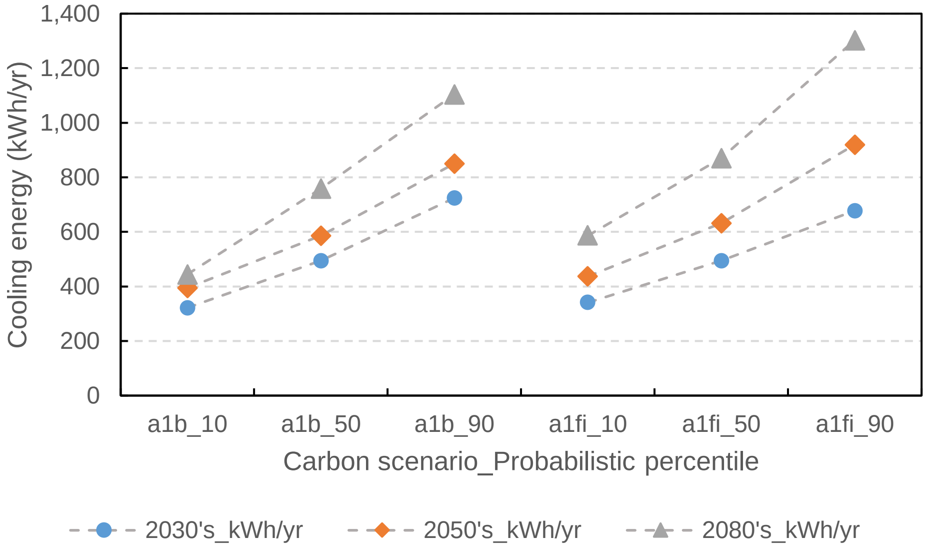


Figure 5-17: Estimated cooling energy demand of hours above thresholds, dwelling SD.6.18

Dwelling SD.6.18 presents a much higher demand of cooling energy, as seen in Figure 5-17. The lower 10th percentile shows timelines in a medium CO_2 scenario clustered between 300 and 450 kWh/yr. In the high CO_2 scenario that cluster range is increased to approximately 590 kWh/yr. High probabilistic percentiles (90th) in both CO_2 scenarios show a widening between timelines; medium CO_2 scenario between 750 and 1,100 kWh/yr whilst the high CO_2 scenario between 700 and nearly 1,300 kWh/yr.

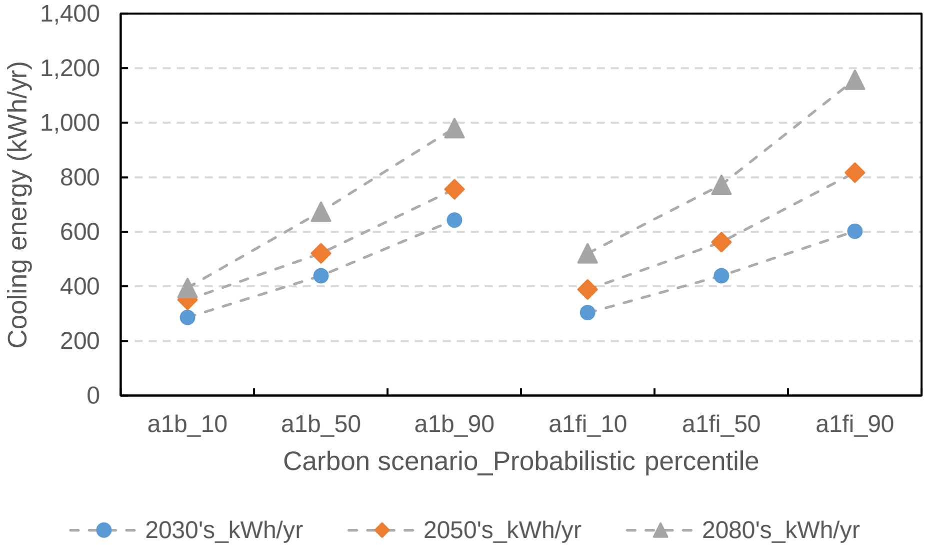


Figure 5-18: Estimated cooling energy demand of hours above thresholds, dwelling T.7.19

The cooling energy demand for dwelling T.7.19 show a similar trend as that from dwelling SD.6.18, however the figures are lower. For example, in the 90th percentile figures in the medium CO_2 scenario; the demand ranges from 650 to 950 kWh/yr. In the high CO_2 scenario, the 2030's timeline follows a similar trajectory as the medium scenario but during 2080's it peaks at 1,150 kWh/yr.

5.3.6. Cooling demand using degree days

A similar exercise was done with degree day data for obtaining cooling energy demand as stated by CIBSE, (2006). To calculate the heating degree day baseline, an indoor air set point temperature is subtracted from sensible gains in the building (solar, people, lights and machines), daytime fabric gains (thermal mass), and latent gains. However, CDD baseline requires some considerations on cooling system components such as; fan temperature rise, fan efficiency and a temperature reduction due to night-time cooling. Taking the above components and using an indoor set point of 25˚C, the baseline temperature for dwelling SD.6.17 resulted in 14.4˚C, considering that the dwelling was not fitted with an MVHR system. As shown in the HDD calculation, the values used in the calculation of the temperature baselines produced variants for the three dwellings to achieve degree day and energy demand data. Table 5-8 summarises annual totals of CDD and energy demand for cooling (kWh/yr).

Table 5-8: Annual cooling degree days and the cooling energy demand – Dwelling SD.6.17

Time frames		Medium CO_2 (a1b) 10th	50th	90th	High CO_2 (a1fi) 10th	50th	90th
		Probabilistic percentile					
2030's	CDD	95	174	339	87	186	297
	kWh/ yr	189	348	679	175	372	595
2050's	CDD	122	234	451	146	278	492
	kWh/ yr	244	467	902	293	556	984
2080's	CDD	150	373	685	218	476	860
	kWh/ yr	307	762	1,397	445	971	1,754

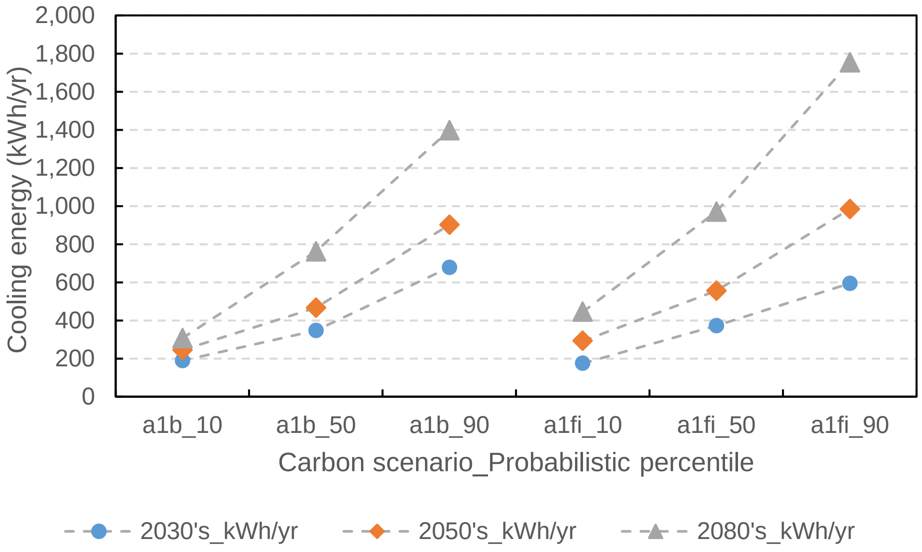


Figure 5-19: Cooling energy demand using CDD data, dwelling SD.6.17

The energy for cooling calculation in dwelling SD.6.17 shows how in the medium CO_2 scenario the demand starts clustered between 200 and 250 kWh/ yr. As the probabilistic percentiles increase and the timelines differ, the demand increases and differences between the timelines appear until reaching the 90th percentile where in the 2030's there is an expected demand of 700 kWh/yr, 900 for the 2050's and 1,400 kWh/yr for the 2080's. A similar trend is experienced in the high CO_2 scenario, with an apparent increase in demand values.

For dwellings SD.6.18 and T.7.19, the use of MVHR considers a recirculation system and therefore some changes in its calculation of cooling baseline temperature. With the different envelope performance considerations, dwelling SD.6.18 has used a baseline of 12.7˚C and Table 5-9 and Figure 5-20 show the CDD and the cooling energy demand of the timelines.

Table 5-9: Annual cooling degree days and the cooling energy demand, dwelling SD.6.18

		Medium CO_2 (a1b)			High CO_2 (a1fi)		
		Probabilistic percentile					
Time frames		10th	50th	90th	10th	50th	90th
2030's	CDD	218	351	570	228	366	529
	kWh/ yr	326	524	850	340	547	788
2050's	CDD	276	441	702	299	489	764
	kWh/ yr	411	658	1,046	446	730	1,140
2080's	CDD	319	607	981	434	731	1,199
	kWh/ yr	466	887	1,435	635	1,069	1,753

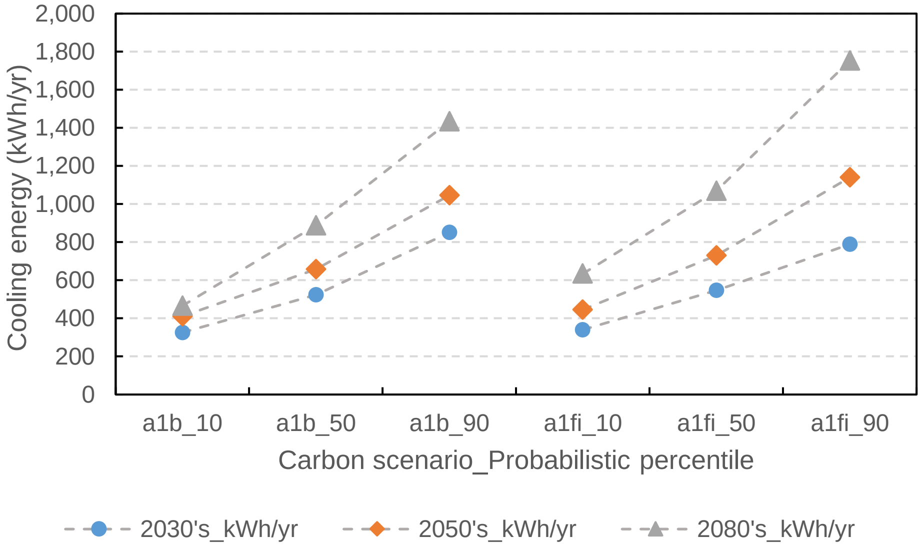


Figure 5-20: Cooling energy demand using CDD data, dwelling SD.6.18

Dwelling SD.6.18, shows similar trends between the timelines to dwelling SD.6.17, albeit with a higher energy demand. This may be due to the higher gains and thermal capacity of the envelope used in the compliance calculations.

Retrofitting a mini split system into dwellings SD.6.18 and T.7.19 could become a cheaper and less onerous task as it already uses a heat pump condenser unit for heating purposes. The baseline used was 13.2˚C resulting in CDD and energy demand as shown in Table 5-10 and Figure 5-21.

Table 5-10: Annual cooling degree days and the cooling energy demand, dwelling T.7.19

Time frames		Medium CO_2 (a1b)			High CO_2 (a1fi)		
		Probabilistic percentile					
		10th	50th	90th	10th	50th	90th
2030's	CDD	175	291	497	177	305	451
	kWh/ yr	267	446	760	271	466	690
2050's	CDD	221	373	621	245	421	676
	kWh/ yr	339	570	950	375	644	1,034
2080's	CDD	259	532	888	363	649	1,090
	kWh/ yr	397	814	1,358	556	993	1,668

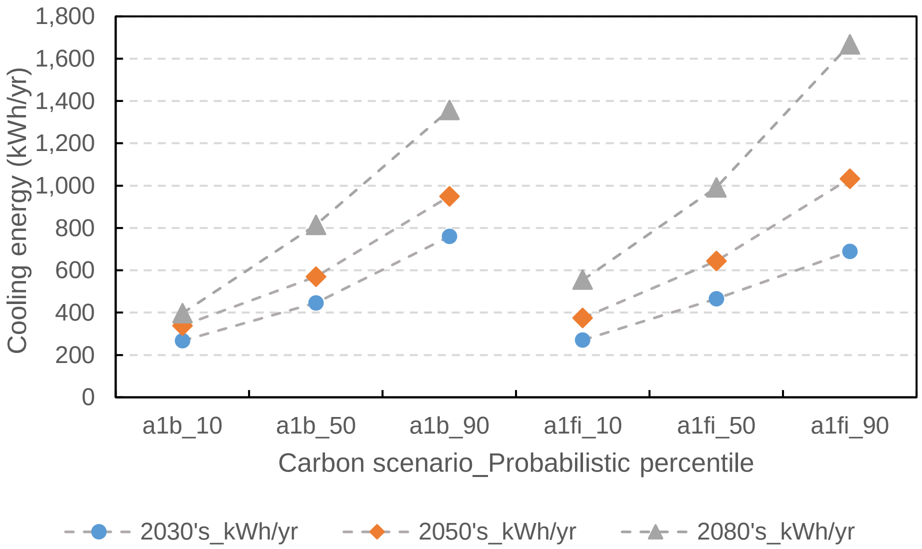


Figure 5-21: Cooling energy demand using CDD data, dwelling T.7.19

5.3.7. Total energy demand – simulated and degree day.

The two techniques adopted in this research for obtaining heating and cooling demand considered shifts in future weather. These did so by either applying future weather files into calibrated simulations or by using external dry bulb temperature shifts in the calculations of heating and cooling degree days, subsequently resulting in energy demand. Table 5-11, Table 5-12 and Table 5-13 below describe the normalised energy demand differences between the three dwellings and the three timelines in the central estimate (medium CO_2 scenario – a1b) using a 50% probabilistic percentile. Such estimates are acceptable as they lay between the least likely and more likely statistical probability based on the future weather projections produced by the UKCP09 future weather programme (Eames et al., 2010; Gething, 2010).

Table 5-11: 2030's energy demand

	Heating ($kWh/m^2/yr$)		Cooling ($kWh/m^2/yr$)	
Dwelling	Simulated	HDD	Simulated	CDD
SD.6.17	26.81	26.78	3.51	3.59
SD.6.18	21.13	21.61	5.26	5.57
T.7.19	57.54	57.66	5.28	5.36

Estimated heating demand in the 2030's timeline obtained by the two prediction techniques show little difference between each other, as seen in Table 5-11. This is partly due to the use of identical weather data but also in the baseline temperature used in the degree day data, both for heating and cooling. The heating degree day data underwent a sensitivity analysis to obtain similar readings as those obtained in the simulated energy demand. This bottom-up method reduced the baseline temperature due to increased indoor temperatures, solar gains and indoor sensible gains. Cooling energy for the simulated demands in the three dwellings followed the results of percentage of hours above 25˚C, a threshold that indicates that occupants are feeling warm and suffering overheating. The demands for cooling between the two techniques are also similar, due to the baseline bottom-up sensitivity analysis to match simulated values. Dwelling SD.6.17 shows a lower mean normalised demand of energy for cooling at 3.55 $kWh/m^2/yr$ compared to dwellings SD.6.18 and T.7.19 with a demand of 5.4 $kWh/m^2/yr$. This difference is due to the higher percentage of hours above the 25˚C threshold, however the two dwellings are occupied more hours than dwelling SD.6.17, with at least one adult in the dwellings at all time.

Table 5-12: 2050's energy demand

	Heating ($kWh/m^2/yr$)		Cooling ($kWh/m^2/yr$)	
Dwelling	Simulated	HDD	Simulated	CDD
SD.6.17	31.59	23.43	4.15	4.82
SD.6.18	19.32	18.42	6.24	7.00
T.7.19	53.17	53.62	6.26	6.85

During the 2050's, as shown in Table 5-12, the two techniques have distinct differences between each simulation and calculation. There are some larger differences shown in dwelling SD.6.17 demand for heating where the simulated is higher than the degree day data by 8.2 kWh/m^2/yr. Larger differences are seen in the cooling energy, where simulated demand is higher than the degree day data by a mean difference of >0.65 kWh/m^2/yr. The degree day data, particularly the cooling demand results show larger differences due to the overestimation of the cooling system and its performance in the 2050's. Assumptions were used in the calculations that remained similar to the 2030's figures that are expected to change over time, such as fan efficiency, and also the possibility of more than one mini split system installed in the dwelling, such a bedroom or kitchen, thus hypothetically causing disparity in results.

Table 5-13: 2080's energy demand

	Heating (kWh/m^2/yr)		Cooling (kWh/m^2/yr)	
Dwelling	Simulated	HDD	Simulated	CDD
SD.6.17	21.06	21.28	5.20	7.86
SD.6.18	16.27	16.37	8.08	9.44
T.7.19	48.85	48.71	8.11	9.79

Table 5-13 shows the analysis of the energy demand for the three dwellings during the 2080's timeline. Heating demand shows small differences between the simulated and degree day data. However, the cooling demand shows larger disparity between both techniques, where degree day data overestimated demand compared with simulated predictions.

5.3.7.1. Total environmental impact

In order to predict the impact to the environment from the energy demand over time, the three dwellings fuel consumption was converted into the equivalent CO_2 emissions emitted. A reasonable assumption is to use the initial CO_2 fuel factors per kWh consumed at the compliance calculations in 2012. However, for an adequate longitudinal study to the 2080's estimated factors produced by the UK Government (BEIS, 2017 & BEIS, 2018) show declining factors for electrical CO_2 emissions reaching the 2100's, useful to calculate environmental impact over time. The factors are dependent on the fuel used for heating and cooling during the same timelines set by the UKPC09 future weather probabilistic predictions. The Department of BEIS, (2017) as seen in Figure 5-22, optimistically aim for a CO_2 impact factor for electricity to decline to 0.028 kgCO$_2$e/kWh from 2050 onwards, aiming towards a decarbonised electrical grid system powered by renewable sources and storage technology such as hydrogen fuel cells.

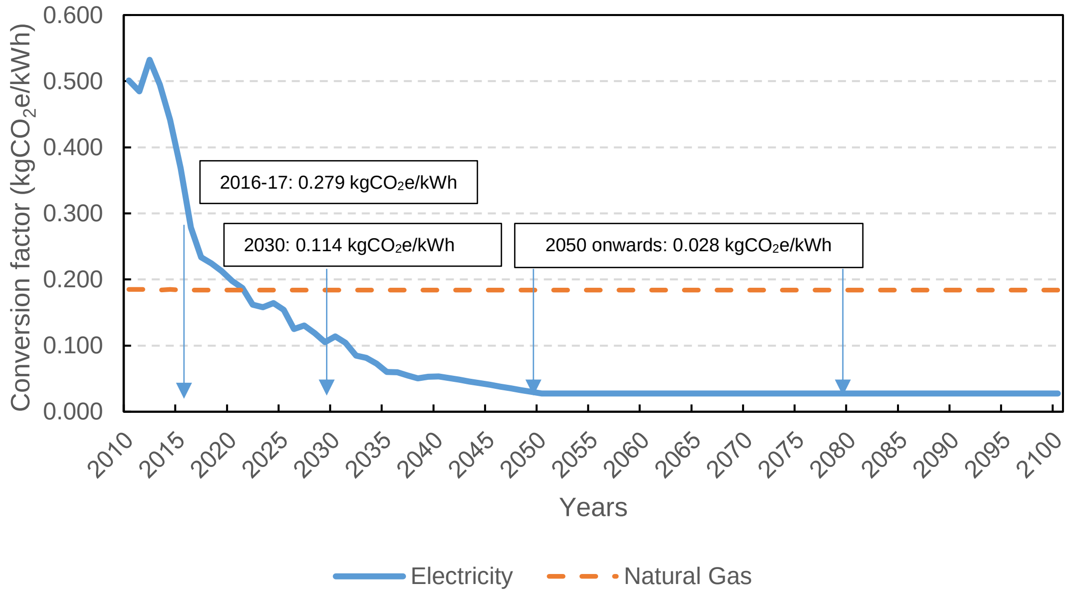


Figure 5-22: Electricity emissions factors to 2100, kgCO$_2$e/kWh.

This reduction not only benefits buildings but also other industries, particularly transport as cities move towards electric powered vehicles. Low CO_2 grids for other fuels used for heating such as natural gas, also seen in Figure 5-22, have kept an unchanged CO_2 factor below the 0.20 kgCO$_2$e/kWh, also predicted not to differ for the rest of the century. Such factors will be harder to achieve CO_2 reductions and neutrality in the grid system due to imports and possible new sources such as shale gas reserves (Scanlan, 2018).

Another determining factor is the cost of fuel over time as shown in Figure 5-23 (BEIS, 2017). It is predicted that to achieve decarbonisation of the electrical grid, prices of the unit of electrical energy (£p/kWh) will marginally increase in the mid 2020’s to 20.0 £p/kWh but lowering marginally and stabilising at 19.11 £p/kWh at the start of the 2030’s. Natural Gas peaks at 5.22 £p/kWh in 2014 and decreases to 4.00 £p/kWh in 2018. The cost then increases slightly until stabilising in 2030 at 5.00 £p/kWh throughout de century to 2100's.

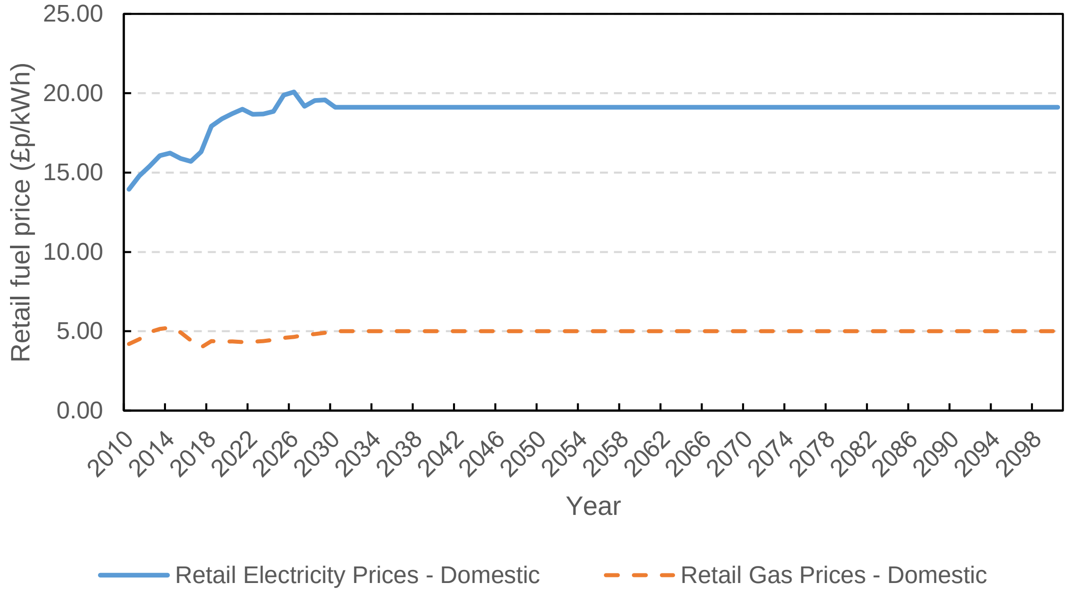


Figure 5-23: Retail Electricity and Natural Gas Prices at a central estimate.

Using the central estimate of 50% probabilistic percentile for the energy demand results obtained with the calibrated simulations of the three dwellings, the following normalised CO_2 emissions throughout the three times lines are analysed for heating and cooling. Annual normalised energy demand for heating, shown in Figure 5-24 against the normalised CO_2 emissions ($kgCO_2/m^2/yr$) demonstrate how the CO_2 intensity impacts on the longitudinal environmental impact. Dwelling SD.6.17 and 18, both heated using natural gas, show a steady reduction in heating energy and normalised CO_2 emissions. Emissions range between 5 and 7 $kgCO_2/m^2/yr$ in 2016 reducing below 5 $kgCO_2/m^2/yr$ in the 2080's. Dwelling T.7.19, an electrically heated property, begins with a high CO_2 emission of 20 $kgCO_2/m^2/yr$ and drastically falls below the emissions of SD.6.17 and SD.6.18 due to the CO_2 factors reducing near to zero. Despite the high energy demand, the CO_2 impact of the electrical grid is less of an environmental impact once the electrical grid is decarbonised after the 2050's.

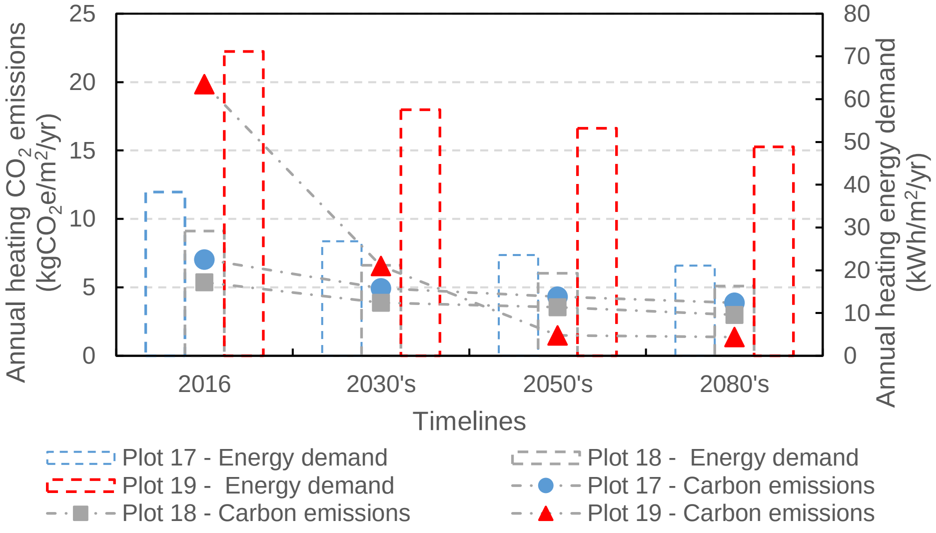


Figure 5-24: Normalised heat energy demand & CO_2 emissions

The environmental impact of the consumed energy for cooling taking the central estimate of a medium CO_2 scenario and at a 50th probabilistic percentile is shown in Figure 5-25 below. The graph shows that in 2016 it is assumed that none or very little cooling is required. However, further analysis for the cooling demand responding to the indoor temperature rises shows a gradual increase in demand, between 3.5 to 5.5 kWh/m^2/yr in the 2030's to near 8 kWh/m2/yr in the 2080's. The demand for Dwelling SD.6.17 is low and rises little through the timelines, however dwellings SD.6.18 and T.7.19 follow a larger incremental demand through the timelines. The environment impact follows a similar path to heating, where a high impact is shown in the 2030's with Dwelling SD.6.17 emitting 0.4 kgCO_2/m^2/yr and both Dwelling SD.6.18 and 19 emitting 0.6 kgCO_2/m^2/yr, showing a 50% differential between the dwellings. During the 2050's and 2080's a decrease in CO_2 emissions is modelled, this shows how the CO_2 emissions from all three dwellings, despite the higher demand of energy for dwellings SD.6.18 and T.7.19, is brought down to results between 0.10 and 0.15 kgCO_2/m^2/yr. Apart from showing a smaller differential between the dwellings, it also shows that the CO_2 factor decrease for energy demand impacts a great deal on the dwellings overall environmental impact.

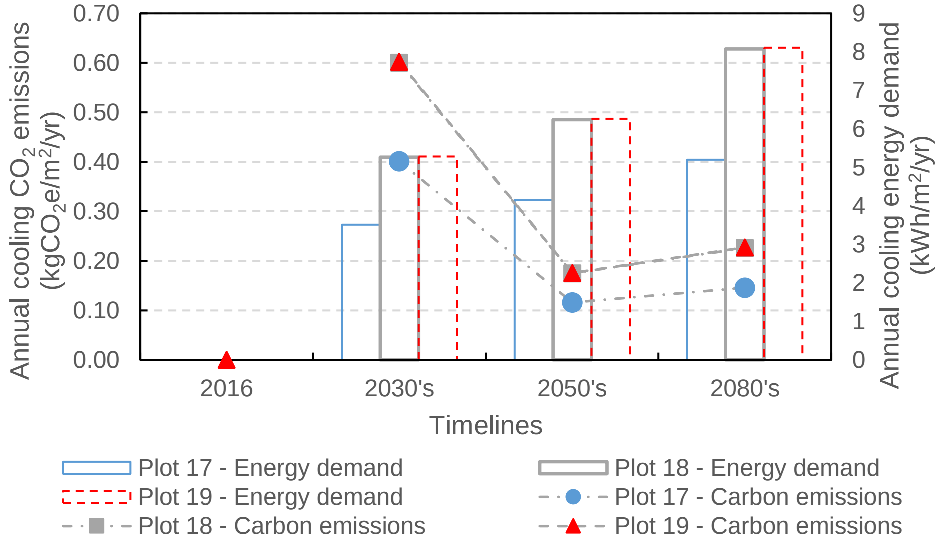


Figure 5-25: Normalised cooling energy demand & CO_2 emissions

5.3.8. Concluding remarks

The comparison of the two techniques shows that degree day data is only a reliable method against the calibrated models using simulated results if doing short term predictions. For results to be directly comparable, the calculations need to apply declines in technology efficiency and dilapidation of envelope performance. In all three timelines and dwellings, the simulated values are lower than the degree day data. This concludes simply that degree day data overestimates demand and that it is not suitable for such long-term studies as the estimation of baseline temperatures is dependent on many factors that it wrongly predicts, impacting on energy demand. The simulated data and estimations are based on models that are calibrated with actual monitored data and a full probabilistic weather file (temperature, humidity, rainfall, etc), not just external dry-bulb temperature. Consequently, longitudinal results are a more reliable.

The environmental impact of the changes over the timelines due to climate change probabilistic estimates have been summarised as impact for heating and cooling demand. Such data has been presented using a central estimate of a medium CO_2 scenario at a 50th probabilistic percentile. The analysis shows that the impact depends on the CO_2 factors applied and the fuel used for the demand of energy. Current demand using electricity can negatively disadvantage the evaluation of dwellings because of its high CO_2 factor compared to natural gas.

There is evidence to believe that the UK and Scottish governments are driving for the decarbonisation of the electrical grid from the 2030's onwards. This may lower the CO_2 factors of electricity for every kWh consumed, however cost attributed to this may increase as shown in Figure 5-23. Despite the stable CO_2 factor of natural gas up to the 2100's, the cost of the fuel will remain substantially lower than electricity. This shows that electricity may be the future in heating and cooling and that many buildings are being designed to be serviced by cheap electrical technology that will cost the consumer/ property user more during its operational lifetime.

The following section will explore the consolidation of the different dilapidation factors analysed in Sections 5.2 and 5.3 to show its impact on energy demand over time. The analysis will show the impacts individually and collectively to then understand the longitudinal environmental impact of the dwellings.

5.4. Inclusive environmental impact of dwellings

This research has produced results for the demand of energy at different periods and timelines of the three selected dwellings. The first method used monitored four years of as the as-built and occupied periods of energy demand later compared with the as-designed energy demand and environmental impacts. This gave a new baseline to conduct further studies evidencing a gap in performance against predicted energy demand. The second method used baselines to calibrate simulations using the probabilistic UKCP2009 future weather files providing a future longitudinal energy demand and environmental trajectory. A third method applies a dilapidation factor from results obtained in Section 5.2, which is seldom integrated into longitudinal studies.

This section of the chapter will seek to chart the environmental impact trajectory of the three dwellings considering the three different impacts and methods shown throughout the research so far. Such display of the environmental impact will help to compare against initial predictions of performance and targets of reduction of CO_2 emissions.

5.4.1. Sample gap in performance – Space heating

From the retrieved energy demand data, it was possible to separate energy for space heating and energy for water heating, as explained in Chapter 4, Section 4.3.3 and 4.3.4. Using the space heating only and comparing it against the predicted values calculated through the compliance thermal model SAP2009, a discrepancy between as-designed and as-built was revealed which stated a gap in performance. However, a true representation of performance did not come from the first year of occupation and after analysing the data carefully, it was concluded that the mean between year 3 and 4 best represented the occupants energy demand (Bros-Williamson et al., 2017).

Re-stating the performance gap between the design and the third and fourth year of occupation gives an indication of the dwelling's displacement of performance, evidencing how new house building disguises any achievable environmental targets created by false energy consumption predictions. Such gap in performance puts the dwellings in a different baseline to which longitudinal environmental impacts can begin from. As stated with the energy demand analysis, the dwellings were calibrated with this final mean value of energy use for space heating which acts as a baseline for the three dwellings located in Dunfermline. However, the dwellings were then simulated using the Edinburgh weather file for the subsequent climate change impact analysis, which created a new the baseline. Nevertheless, the performance gap is evident in the actual energy demand retrieved over the occupied years as observed in Table 5-14.

Table 5-14: Dwelling performance gap in normalised energy for space heating

		Space heating (kWh/m^2/yr)					
Dwelling Code	TFA (m^2)	Design	Year 1 (2012-13)	Year 2 (2013-14)	Year 3 (2014 -15)	Year 4 (2015 - 16)	Mean (Year 3 & 4)
SD.6.17	96.92	39.45	43.91	18.56	21.63	24.16	22.89
SD.6.18	93.96	21.59	19.86	30.24	24.08	25.75	24.91
T.7.19	83.20	4.31	57.86	52.44	54.11	59.86	56.99

Table 5-14 shows the dwellings actual normalised space heating energy demand and the aspired design value. It also shows the considered new baseline of energy for space heating as a mean between the third and fourth year of occupation. Dwelling SD.6.17 shows a drop in energy consumption with a difference between designed and built (DBDA) of 16.56 kWh/m^2/yr. The DBDA of dwelling SD.6.18 shows an increase of 3.32 kWh/m^2/yr. Dwelling T.7.19 shows a large DBDA of 52.67 kWh/m^2/yr due to many factors such as long occupied hours, the age of the occupants and the final efficiency of the air source heat pump (ASHP) used for heating. The three scenarios provide show that the performance gap can be related to the building fabric performance, but also represented in many facets of the buildings use. The above performance gap is also shown as an environmental impact in Table 5-15.

Table 5-15: Dwelling performance gap in normalised CO_2 emissions for space heating

		Space heating (kgCO_2e/m^2/yr)					
Dwelling Code	TFA (m^2)	Design	Year 1 (2012-13)	Year 2 (2013-14)	Year 3 (2014 -15)	Year 4 (2015 - 16)	Mean Year 3 & 4
SD.6.17	96.92	7.26	8.08	3.41	3.98	4.44	4.21
SD.6.18	93.96	3.97	3.65	5.56	4.43	4.74	4.58
T.7.19	83.20	1.20	16.14	14.63	15.10	16.70	15.90

Fuel use and its associated CO_2 factor of energy demand plays a big part in the environmental impact of the dwellings. Both SD.6.18 and SD.6.17 have a similar mean CO_2 emissions factor hence a similar normalised yearly CO_2 emission given that natural gas is the primary fuel type for space heating. In contrast, dwelling T.7.19 uses electricity with a higher CO_2 factor for every unit of energy consumed therefore a much higher CO_2 emission result. The above summary is important as it states the baseline for the monitored dwelling during subsequent longitudinal projections and environmental impact over time.

5.4.2. Dilapidation over time

Section 5.2 explores the changes observed after repeated monitoring to evidence the heat loss coefficient and dwelling performance factor (DPF) used as a dilapidation factor of the dwellings. This calculation combines ventilation technology efficiencies with envelope performance, U-value and air infiltration.

The stated bi-yearly interval factor of dilapidation, as shown in Table 5-3, is halved and applied as a yearly cumulative percentage ratio of each dwelling's design baseline DPF value. This forms a longitudinal dilapidation from the 2016 baseline up to 2080, matching the climate change projections. The applied % factor is shown in Figure 5-26 showing an increase as applied yearly.

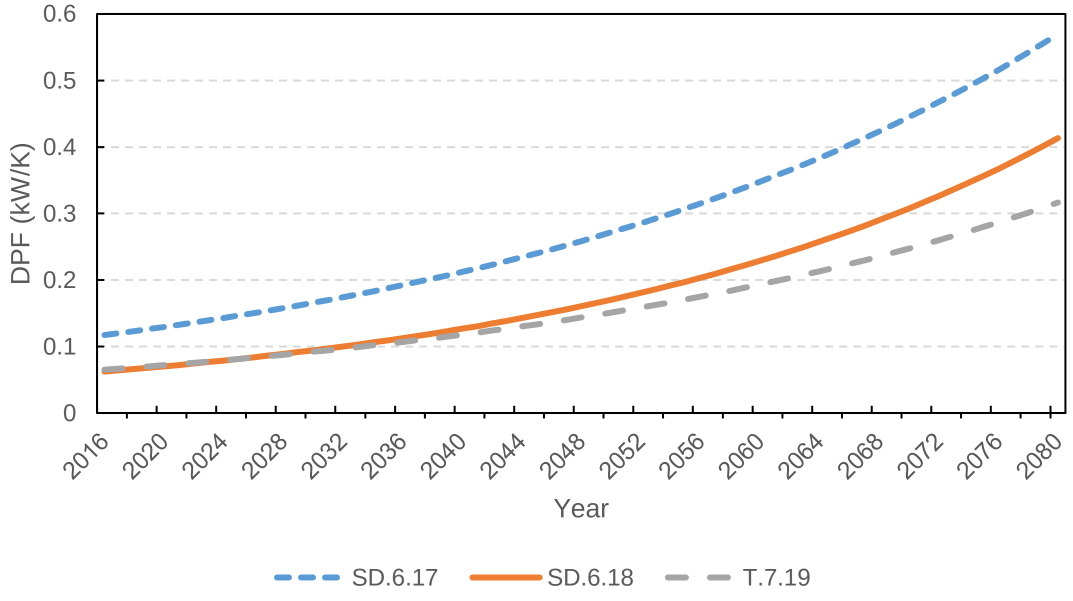
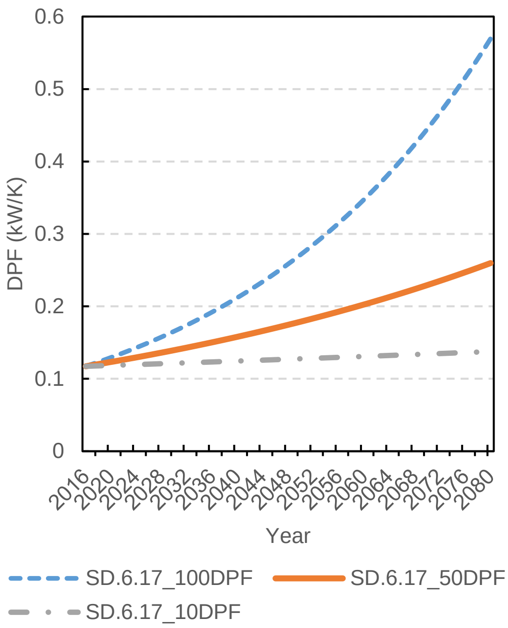


Figure 5-26: Cumulative increase of DPF using a yearly dilapidation ratio of change

Dwelling SD.6.17 shows a baseline DPF of 0.117 kW/K at the 2016 starting point compared with dwellings SD.6.18 and T.7.19, 0.062 and 0.065 respectively. Subsequently the three dwellings increase their yearly factor as it approaches 2080; SD.6.17 rises to 0.57 kW/K at a rate of 2.5% per year, dwelling SD.6.18 rises to 0.41 kW/K at a rate of 3.0% and T.7.19 rises to 0.32 kW/K at a rate of 2.5%.

The DPF applied as a yearly ratio of envelope efficiency, as shown in Figure 5-26 is a direct response to the two intervals analysed through envelope field testing and measurements over a four-year period. This yearly rate of dilapidation at 2.5% in dwellings SD.6.17 and T.7.19 and 3.0% in SD.6.18 is a large increment and rate of envelope dilapidation. If applied longitudinally through to 2080 the DPF increases six-fold above the baseline in 2016. This shifting DPF combines steady state and field test results during a period still considered as early occupation where most changes and settlement occurs. For this reason, it is adequate to consider distinctive scenarios of DPF as a rate of impact. Thus, three scenarios are proposed; DPF at 100%, considered as a worst-case-scenario applying the full impact of the calculated DPF, a medium impact of a DPF at 50% of dwelling dilapidation using half the assumed DP and a lower rate of dilapidation using a DPF at 10% which considers a 90% decline of the early occupation calculation assuming a slow rate of envelope performance decline, perhaps a more realistic dilapidation rate.



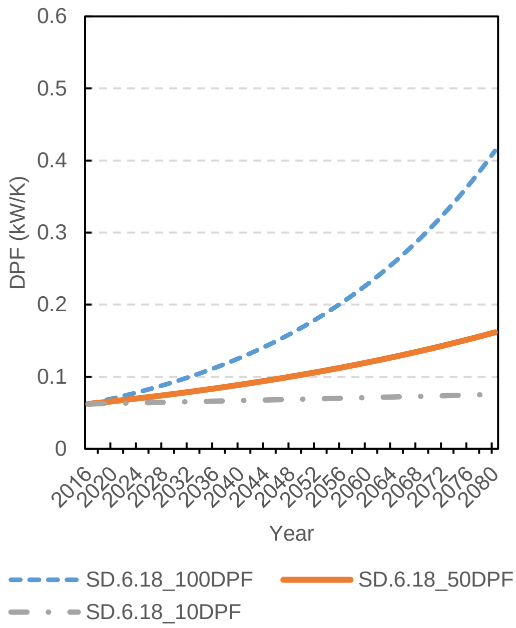


Figure 5-27 (left): DPF applied to dwelling SD.6.17

Figure 5-28 (right): DPF applied to dwelling SD.6.18

Figures 5-27, 5-28 and 5-29 below show the proposed scenarios of DPF for each of the analysed dwellings. Figure 5-27 shows the DPF of SD.6.17, beginning at the baseline in 2016 and rising with the applied 100% DPF. As it approaches 2080, a figure of 0.6 kW/K is obtained; at a 50% DPF it reaches 0.26 kW/K and at a 10% DPF it reaches 0.14 kW/h. These scenarios, associated with the envelope performance and ventilation heat losses, can calculate energy demand, which can result in a longitudinal dwelling performance trajectory.

A similar trajectory of the DPF impact can be observed in Figure 5-28 for dwelling SD.6.18 which starts with a lower DPF of 0.0623 kW/K. It reaches 0.41

kW/K in 2080 after applying a 100% DPF, whilst 0.16 kW/K with a 50% DPF and a dwelling envelope performance of 0.075 kW/K using a 10% DPF.

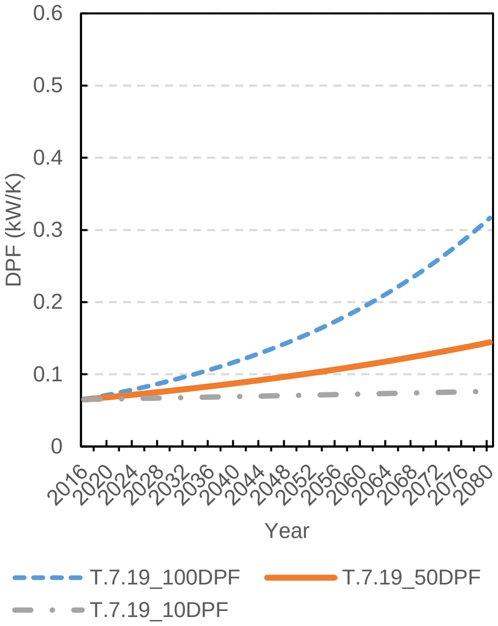


Figure 5-29: DPF applied to dwelling T.7.19

For dwelling T.7.19 shown in Figure 5-29, with a baseline in 2016 of 0.065 kW/K, the yearly obtained DPF of 3.0% per year applied fully as a 100% probability reaches 0.315 kW/K in 2080. A 50%DPF reaches 0.14 kW/K as a medium impact of dilapidation and a 10%DPF low impact reaches 0.076 kW/K.

The different DPF's and probability scenarios subsequently follow a quasi-steady state heat loss evaluation over the already devised timelines in the climate change analysis; 2030's, 2050's and 2080's using the future weather external temperature values and the adjusted internal ambient temperatures. Such relationship between the DPF and internal and external mean daily temperature differences are used in a dwelling heat loss calculation by obtaining the hourly proportion of demand (multiplying it by 24 hours) which results in total daily energy demand (kWh). Subsequently to quantify the environmental impact ($kgCO_2e/m^2/yr$) with the effects of a dilapidation factor and climate change, a factor of CO_2 emission per kWh calculated is applied.

5.4.3. Longitudinal trajectory considering all impacts

It is considered that after the above analysis, the three previous instigated aspects; 1) gap in performance, 2) climate change scenarios and 3) DPF, have a direct influence on the longitudinal environmental performance of dwellings and should be applied conjunctively. To display this, the three aspects have been applied over the climate change timelines by; a) applying the gap in performance to the initial baseline, thus not using compliance baselines and b) applying impacts from climate change at a medium (a1b) CO_2 scenario at a 50% probabilistic percentile and the corresponding DPF to calculate longitudinal dwelling heat loss. These are applied considering that there is a distinction between the design aspirations of energy demand and the actual as-built demand and that as the dwellings mature over time their envelope will also decline and deteriorate, hence changes in DPF with dilapidation of the building envelope.

A fuel price for the associated units of energy consumed is also shown, defining the affordability of such dwelling over time. To produce such longitudinal approach, CO_2 factor changes and cost of the unit of energy into the future as shown in Figures 5-22 and 5-23 are considered which are linked to policy and expected changes in the UK's energy mix.

5.4.3.1. Longitudinal energy and CO_2 emissions projections

As a first longitudinal projection, the total normalised energy heating and cooling demand is shown. All three dwellings have been analysed separately to understand their different changes over time.

Dwelling SD.6.17 shown in Figure 5-30 and 5-31, indicates the baselines figures taken as the 2016 starting point of the expected trajectory of energy demand and associated CO_2 emissions. Two figures are shown, one as the calibrated model using the weather station file for Dunfermline and the other is the baseline for Edinburgh used for the climate change projections and subsequent analysis. A small distinction is observed which shows the first indication of climate change effects. The Edinburgh weather file is based on historical mean values whilst the Dunfermline file is from 2016. The simulated demand using a constant design DPF shows a downward trajectory as climate change considers warmer temperatures hence less energy for space heating; despite adding energy for cooling. The normalised energy demand, as seen in Figure 5-30 is expected to reach 27 kWh/m^2 by the 2080's despite its baseline of 40 kWh/m^2. Subsequently, projections using the yearly cumulative DPF and changing climate are applied as a worst-case scenario 100% DPF from the 2016 baseline increasing steadily to 110 kWh/m^2 in the 2080's. Less of a dilapidation appears in the 50% DPF that reaches 53 kWh/m^2 in the 2080's. A minimal impact applied with a 10% DPF compared with the simulated demand at design stage.

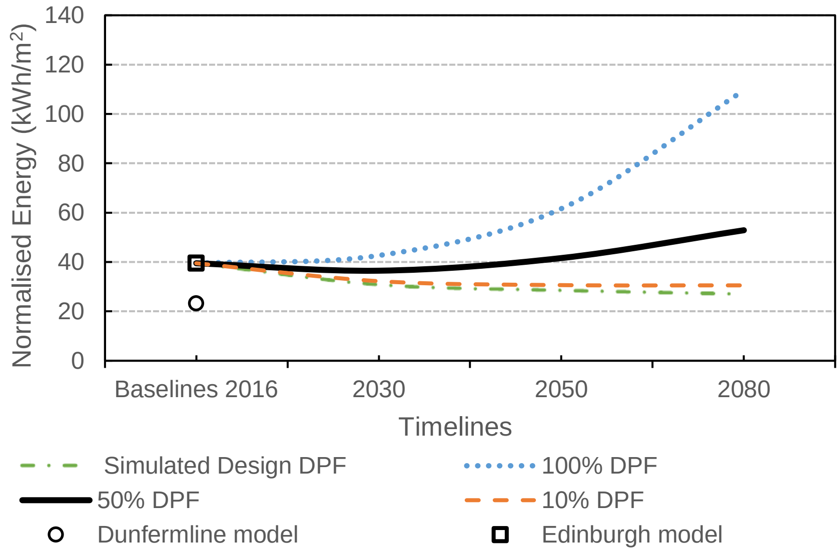


Figure 5-30: Longitudinal projection of normalised energy demand – dwelling SD.6.17

The environmental impact shown in Figure 5-31 has a similar trajectory to energy demand. The results show that by the 2080's a worst-case scenario of 100% DPF increases to 20 $kgCO_2/m^2/yr$, whilst the 50% DPF reaches 9 $kgCO_2/m^2/yr$ and the 10% DPF reduces to 5 $kgCO_2/m^2/yr$, similar to the simulated design trajectory using a constant DPF.

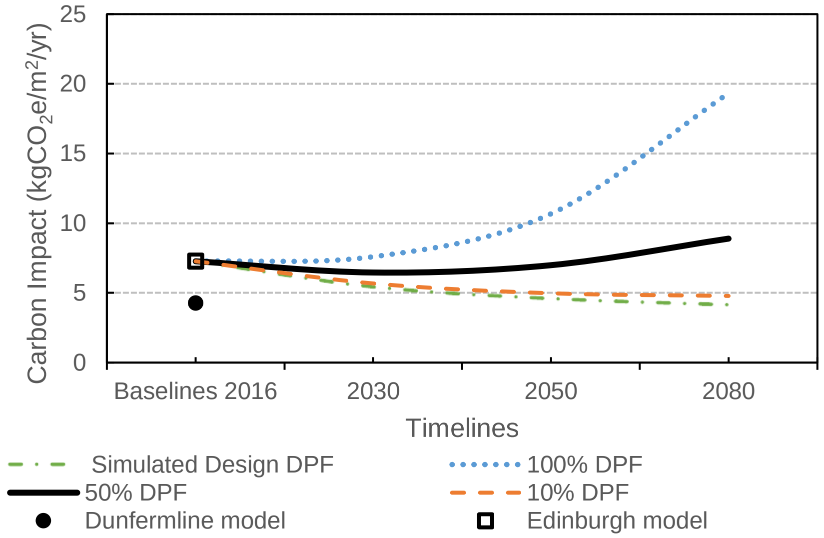


Figure 5-31: Longitudinal projection of normalised CO_2 emissions – dwelling SD.6.17

An analysis of dwelling SD.6.18 as shown in Figure 5-32 shows that after parting from a 33 kWh/m^2 baseline the simulated dwelling using just the future weather predictions and the design DPF, the energy demand trajectory is in a steady downwards direction reaching 27 kWh/m^2 by the 2080's. Applying a 100% DPF increases energy demand threefold to 130 kWh/m^2 by the 2080's which intensifies the impact of a high dilapidation of the building fabric.

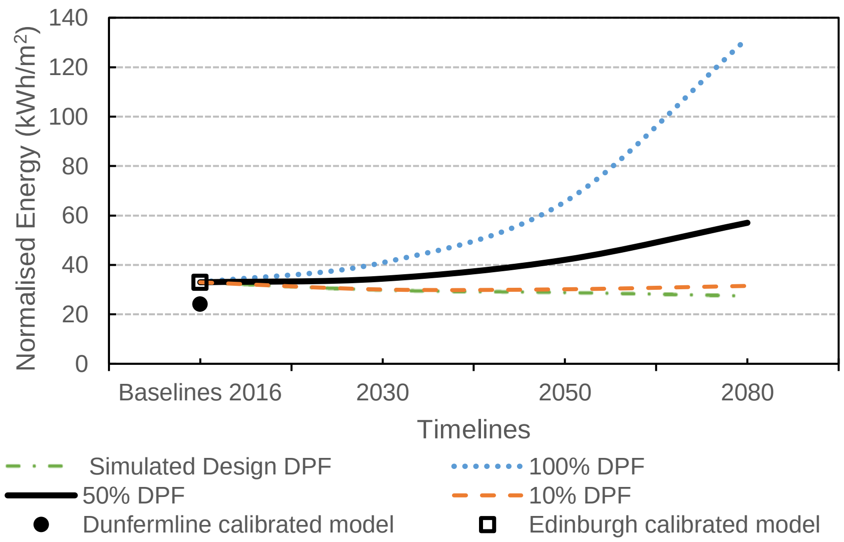


Figure 5-32: Longitudinal projection of normalised energy demand – dwelling SD.6.18

A 50% DPF, considered as less of a rate of dilapidation has less of an upward effect on the dwellings energy demand by reaching 60 kWh/m^2 by the

2080's. With the introduction of a 10% DPF, the building fabric has not dilapidated as fast and by the 2080's consumes 31 kWh/m^2, however in this scenario, climate change has more of an impact than dilapidation.

The environmental impact of dwelling SD.6.18 applying factors for fuel consumed in space heating (natural gas) and cooling (electricity) are shown in Figure 5-33. The dilapidation as a 100% DPF potentially reaches 23 kgCO_2/m^2/yr, an increase of 4 kgCO_2/m^2/yr compared to dwelling SD.6.17. However, the smaller dilapidation impacts of 50% DPF show a steady increase of CO_2 emissions reaching 9 kgCO_2/m^2/yr by the 2080's, whilst the 10% DPF decreases with climate change impacts to just under 5 kgCO_2/m^2/yr by the same period.

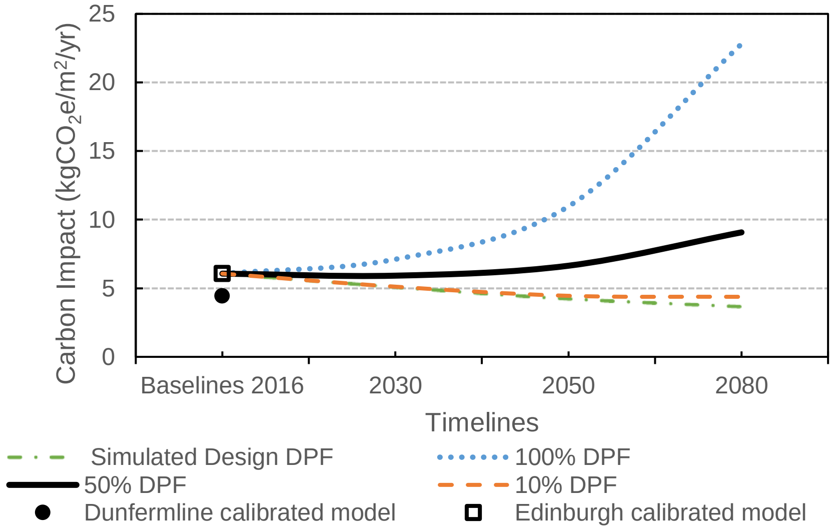


Figure 5-33: Longitudinal projection of normalised CO_2 emissions – dwelling SD.6.18

Figure 5-34 shows the longitudinal trajectory of energy demand considering scenarios of dilapidation in dwelling T.7.19. Despite staring at a higher baseline of 70 kWh/m^2 due to the large electrical energy consumption from the air source heat pump, there are similarities in the trends of energy demand. Applying the 100% DPF increases the normalised energy demand to 225 kWh/m^2 by the 2080's; a difference of 110 kWh/m^2 and 95 kWh/m^2 between dwellings SD.6.17 and SD.6.18 respectively. Applying a 50% DPF, the 2080's demand increases to 110 kWh/m^2, whilst applying a 10%DPF the demand remains constant with little change approximately at 60 kWh/m^2.

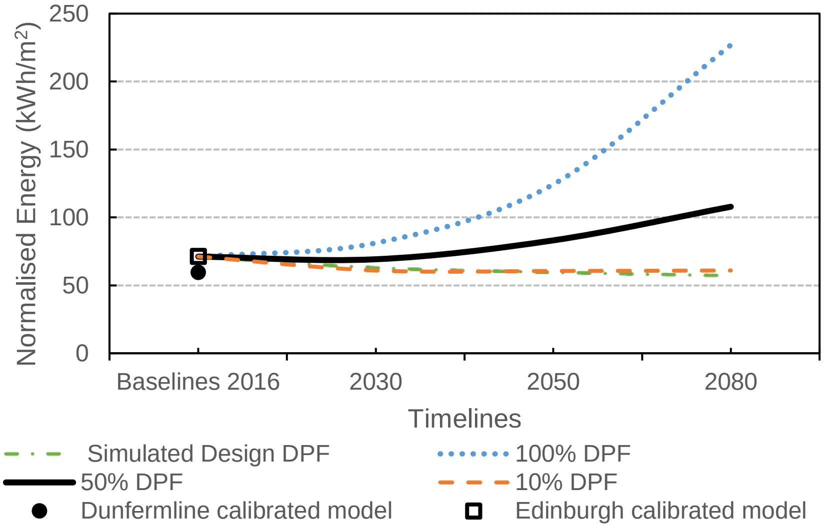


Figure 5-34: Longitudinal projection of normalised energy demand – dwelling T.7.19

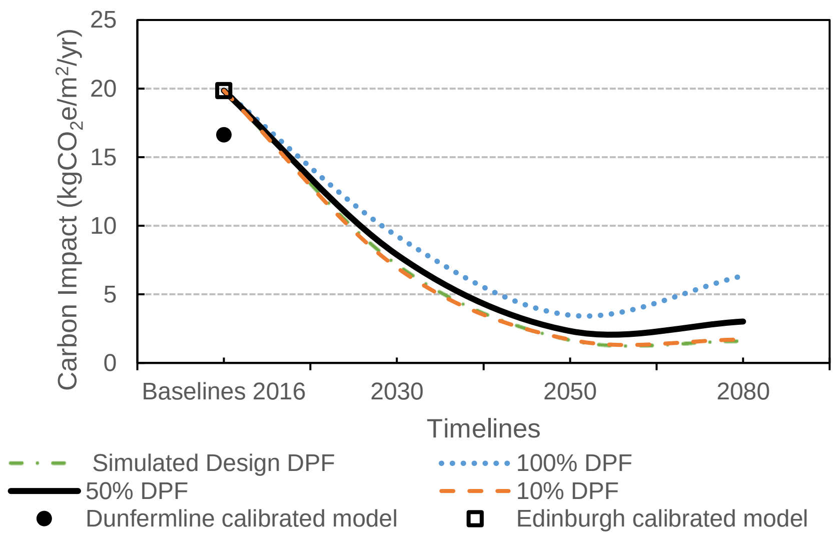


Figure 5-35: Longitudinal projection of normalised CO_2 emissions – dwelling T.7.19

A different longitudinal trajectory is shown in Figure 5-35 of the environmental impact analysis of CO_2 emissions emitted. The baseline begins much higher than the other two dwellings at 20 $kgCO_2/m^2$/yr. However, the emissions diminish substantially despite the higher energy demand over time. Such change in trajectory is due to the buildings dependence on electricity which after the 2030's its factor for every kWh consumed is expected to lower considerably, hence the downwards trend in CO_2 emissions. By the 2080's, when applying a 100% DPF, its CO_2 emissions lowers to 6.5 $kgCO_2/m^2$/yr. Similarly, scenarios of 50% DPF reaching 3 $kgCO_2/m^2$/yr and at 10% DPF emitting below 2

$kgCO_2/m^2/yr$. This trajectory shows the importance of the expected decrease in factors of CO_2 emissions for natural gas and electricity that show a large disparity in future decades.

5.4.3.2. Impact of dilapidation to the affordability of the dwellings

It is worth considering the impact of a dilapidated envelope in the context of how affordable the cost of energy is to the occupiers. The analysed dwellings are marketed as affordable social rented accommodation, owned and managed by a Registered Social Landlord (RSL). The payment of energy is the responsibility of the occupiers who from the onset in the development were promised an energy efficient dwelling, particularly in energy for space and water heating.

Section 5.4.1 defined the gap in performance and the difference between design and actual energy (DBDA). The early occupation of the dwellings showed that the occupants were in an adjustment period, whilst years three and four showed that the occupant's energy demand stabilised and became more representative of the occupants and dwellings demand of energy for space and water heating. As shown in Table 5-16, despite this transition period from the early occupation and the stabilisation of energy demand, dwelling SD.7.17 reduced its demand and hence its total yearly payments for space heating energy from a design prediction of £183/yr to £112/yr. The DBDA in dwelling SD.6.18 was small, yet £50/yr more was spent compared with the design predictions. Dwelling T.7.19 shows a large DBDA where the design expectation was £710/yr; compared with the actual spend of £766/yr in year four of the measurements.

Table 5-16: Cost of energy for space heating during the field tests and measurements

		Space heating cost of energy (£/kWh/yr)					
Dwelling Code	TFA (m^2)	Design	Year 1 (2012-13)	Year 2 (2013-14)	Year 3 (2014 -15)	Year 4 (2015 - 16)	Mean Year 3 & 4
SD.6.17	93.96	183.11	203.81	86.14	100.39	112.13	106.26
SD.6.18	83.2	330.53	304.07	463.00	368.58	394.19	381.39
T.7.19	83.2	55.25	740.88	671.41	692.91	766.44	729.68

Also relevant is the longitudinal cost of energy considering climate change predictions and the dilapidation of the envelope applying the three DPF probability scenarios. As reported by the Scottish Government (2017), in 2016 26.5% of Scottish households were fuel poor and although this research did not account for the employment and socioeconomic levels of occupants, the relationships between cost of energy and building envelope energy efficiency were of relevance. This study contributes to the longitudinal analysis of new dwellings in the social rent sector, relevant to the energy demand changes which impact the long-term affordability of the dwellings and consequently its ability to perform without being a large burden to owners and occupiers.

Applying a similar methodology as that of total energy demand and related CO_2 emissions; retail price of fuel consumption over time has followed the predictions by BEIS (2017) and analysed in Section 5.3.7.1 and Figure 5.23. Considering this trajectory of the retail price and the energy demand applying the three levels of DPF scenarios, the following Figures are described.

Figure 5-36 presents the analysis of how dwelling SD.6.17 reacts to dilapidation and the associated annual cost throughout the 2030's, 2050's and 2080's. The simulated baseline of Edinburgh placed at £163.70/yr increases to just below £500/yr in the 2080's when applying the 100% DPF. If a 50% DPF is applied, the cost increases steadily over time reaching £225/ yr. A 10% DPF shows a similar trajectory than the simulated climate change predictions following a steady DPF used at the design stage, reaching costs of £120/yr and £109/yr.

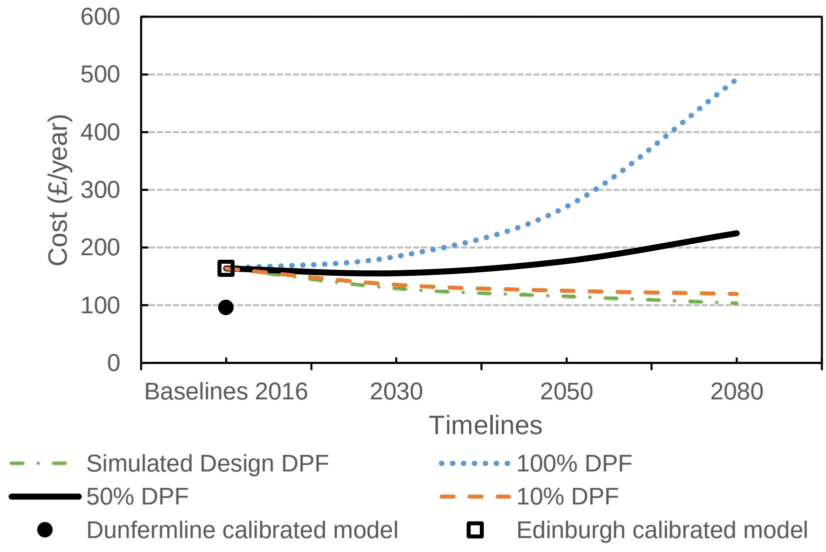


Figure 5-36: Annual cost of energy applying the dilapidation scenarios – dwelling SD.6.17

The analysis of dwelling SD.6.18 shown in Figure 5-37 is similar to SD.6.17, however they differ in the starting 2016 baseline where SD.6.18 is lower at £120/yr . Despite this, when applying the 100% DPF the annual expenditure in the 2080's reaches the same figure, around £500/yr. This happens as a result of the faster rate of dilapidation calculated using a higher annual cumulative factor. Applying a 50% DPF has a cost of £200/yr during the 2080's, whilst a 10% DPF has a small effect by decreasing the cost to £100/yr, similarly to the constant DPF reacting to future weather patterns where heating demand is decreasing and cooling demand is not large enough to make a difference.

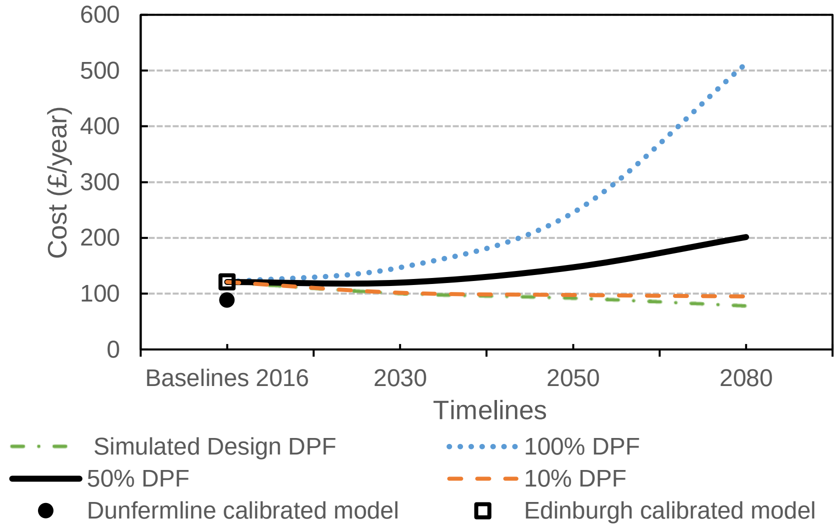


Figure 5-37: Annual cost of energy applying the dilapidation scenarios – dwelling SD.6.18

The yearly cost of energy of T.7.19, shown in Figure 5-38. It differs because of both its fuel type (electricity) and heating technology impacting on the dwelling's affordability. Baseline annual cost in 2016 is just below the £1,000/yr and if a 100%DPF is applied it reaches a staggering £3,500/yr by the 2080's. Applying a 50%DPF, the figure rises steadily to £600/yr more than the 2016 baseline (£1,550/yr). A 10% DPF is slightly higher decreasing to £900/year. However, the dominant factor in this dwelling is the fuel type which its retail price per kWh consumed is in an upwards trajectory until it peaks in the 2030's at just under £20/kWh three times more than the cost per kWh of natural gas.

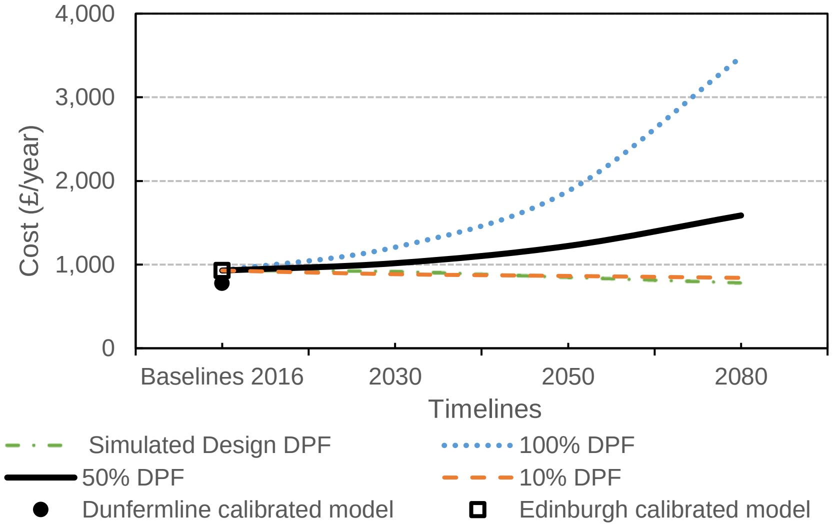


Figure 5-38: Annual cost of energy applying the dilapidation scenarios – dwelling T.7.19

5.4.4. Comparative analysis of relative impacts

In order to understand the different energy and CO_2 emission impacts on the three analysed dwellings, a staged approach was modelled. This approach included separating three important aspects that longitudinally would impact the performance of the dwellings. The first relates to the longitudinal impact of only the dilapidation of the building fabric considering the three dwelling performance factors (DPF's); 100%, 50% and 10%. It follows the DPF's with the impact of climate change but without the consideration of cooling to alleviate overheating. The last impact considers the additional CO_2 emissions of cooling with the added impact of climate change and the DPF levels.

Figure 5-39 shows the separation of impacts for dwelling SD.6.17, with the three DPF's and the application of the different aspects considered. By 2080 the 100% DPF shows an increase of CO_2 emissions to nearly 35 $kgCO_2/m^2/yr$ and down by 14 $kgCO_2/m^2/yr$ once the climate change impact has been applied. Cooling doesn't represent a large environmental impact, however there is a need for it as expressed in section 5.3.6. In 2050 the impact of 100% DPF is 16 $kgCO_2/m^2/yr$ whilst climate change lowers by 6 $kgCO_2/m^2/yr$ to 10 $kgCO_2/m^2/yr$. In 2030 the change between 100% DPF and the addition of climate change is 3 $kgCO_2/m^2/yr$. The 50% DPF during the 2080's has a lower impact due to its decreased dilapidation factor. Considering DPF only, its impact is 15 $kgCO_2/m^2/yr$

whilst with climate change it lowers by 6.5 $kgCO_2/m^2/yr$ to 8.5 $kgCO_2/m^2/yr$, with cooling similarly placed. A 10% DPF keeps CO_2 emissions below 10 $kgCO_2/m^2/yr$ and a change between DPF only and the climate change is not as large an impact as the other DPF levels.

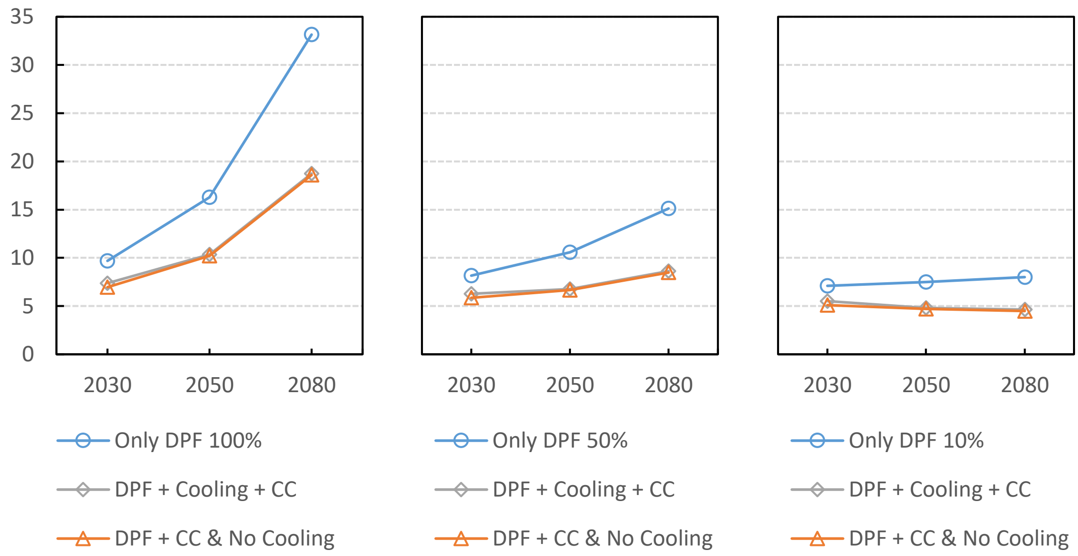


Figure 5-39: Comparative analysis of the impacts for dwelling SD.6.17

A similar trajectory and impact are observed in Figure 5-40 for dwelling SD.6.18 where the environmental impact of the DPF's is higher than the considerations of climate change and cooling. However, it is important to point out that climate change impacts are considerable once applied.

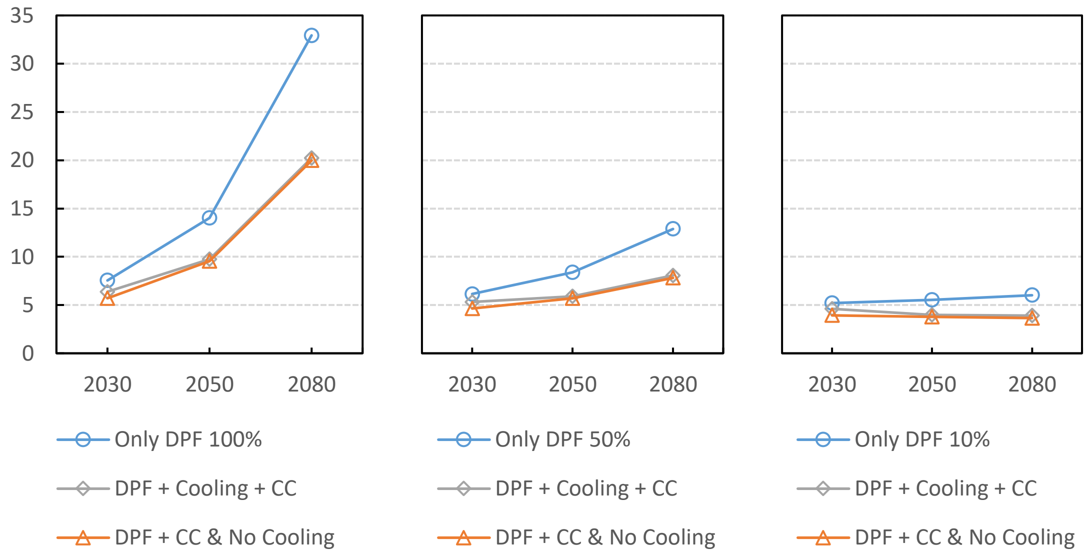


Figure 5-40: Comparative analysis of the impacts for dwelling SD.6.18

Dwelling T.7.19 shows a distinct trajectory over the analysed timelines and impact scenarios. This dwelling considers the low CO_2 emission factors of electricity proposed by the 2050's. Figure 5-41 shows the application DPFs, with and without climate change. During the 2030's with a high CO_2 factor the difference between the dilapidation 100% DPF only and the application of climate change is approximately 2 $kgCO_2/m^2/yr$. With a lower CO_2 emission factor in 2050's the 100% DPF decreases to 4.3 $kgCO_2/m^2/yr$ to later increase again in the 2080's. Even with the introduction of climate change, the impact lowers by the same 2 $kgCO_2/m^2/yr$ to 6.3 $kgCO_2/m^2/yr$. This DPF level has a large impact on the performance compared with the 50% and 10% DPF levels which show that they are susceptible to lower impacts according to the decrease of CO_2 factors in the 2050's.

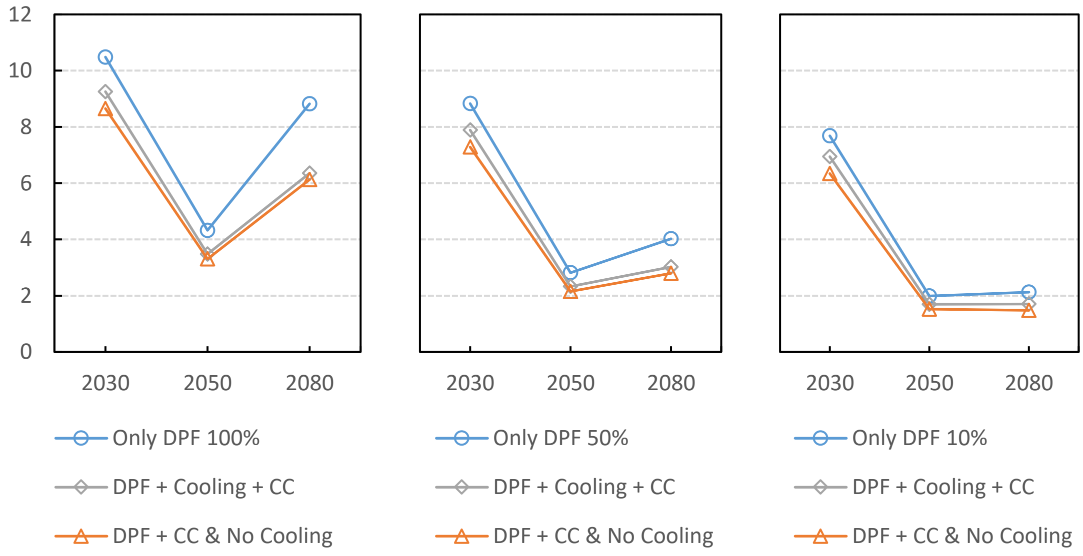


Figure 5-41: Comparative analysis of the impacts for dwelling T.7.19

Although CO_2 emissions for cooling do not represent a large impact in Figures 5-39, 5-40 and 5-41, when analysed as annual energy demand and cost, there can be a significant impact to the household. Not considered here is the cost of the warranty installed cooling system (capital and labour) on top of its annual running cost. Tables 5a, 5b and 5b in Appendix 5a shows the energy and CO_2 emissions for the comparative analysis between the staged approach between DPF's dilapidation, climate change and cooling. Cooling for dwelling SD.6.17 in the 2030's and 2050's considering a 50% DPF both account for approximately 4.0 kWh/m^2/yr, whilst in the 2080's this increases to 5 kWh/m^2/yr. For dwelling SD.6.18 considering a 50% DPF the energy demand is 6, 7 and 9 kWh/m^2/yr for set periods between 2030's, 2050's and 2080's respectively. Equally for T.7.19 the demand of energy for cooling between the same set periods is 6, 7 and 10 kWh/m^2/yr. This at a glance does not seem a large demand however, considering the dwellings are located in central Scotland where temperatures will increase slowly, there are other more southernly placed locations where cooling will be needed due to longer periods of overheating and occupant discomfort.

This comparative analysis of the impacts provides an important split between the dilapidation stages, climate change and cooling where energy demand and CO_2 emissions are accounted for. Although this information is useful to distinguish these impacts separately, given the current scenario the built environment is exposed to all three impacts therefore should be considered conjunctively.

5.4.5. Concluding remarks

This section has presented three determining envelope changes which consequentially have an impact on the dwellings heat loss performance and its longitudinal performance over time. Within the sample of three dwellings analysed in detail, the gap in performance over the four years during in-situ testing and monitoring were described in detail to show the impact the difference between as-designed and as-built has on the baseline used in a longitudinal analysis. This analysis showed that the first two years of the dwelling's occupancy was more of an adjustment period of the occupants and a period in which the dwelling settled structurally. The subsequent two years after this early occupation settled into a more representative energy demand of the occupiers and overall energy demand. Baselines and model calibration used year four energy demand, which is quoted in model calibrations and in the results and analysis Chapters.

As a continuation of Section 5.2.3 and following the demand analysis of the three dwellings, it was important to state the impact of the envelope performance changes. Recorded through bi-yearly in-situ tests such as air permeability and thermal transmission and merged into the steady state energy compliance model (SAP), a set of new heat loss coefficients as dwelling performance factors (DPF) were proposed. These changing DPF results during bi-yearly intervals produced a mean ratio (percentage increase) of change which in turn provided a deterioration or as it has been referred to in this research, the dilapidation of the building envelope. It was found that this percentage increase was high and could be referred to as the worst-case-scenario applying a very fast deterioration and impact on the heat loss of the building. This resulted in the introduction of two additional deterioration scenarios; 50% DPF and a 10% DPF matching other probabilities of impact on the analysed dwellings. These additional probabilities of dilapidation provided a more accurate and realistic interpretation of the levels of dilapidation.

This section finalises with longitudinal trajectories of energy demand, its CO_2 emission impact and the cost implications over the three timelines considering the gap in performance, the dilapidation of the building fabric and the impact of Climate change. Important to realise in this analysis of impact of dilapidation is that it shows changes in envelope performance and rates of impact which are relevant to the trajectory of dwellings environmental performance. Such analysis is an inclusive approach to understand the behaviour of these dwellings over time, critical to understand their impact against environmental targets.

The following sections lead on to explaining how these projections of dwelling performance and impact on the environment match against the policy driven targets. Equally, set design aspired targets are included using both compliance assumptions and Building Regulations and energy driven design standards such as Section 7 of the Scottish Building Regulations and *Passivhaus*. Required questions arise over the way the dwellings align to current targets, but also the tipping point at which dilapidation plays a big part in the heat loss of the dwellings. It also raises questions around the best remediations to retrofit the dwellings and increase performance to assure dwelling longevity.

5.5. Environmental tipping point and scenarios of retrofit

Forecasting energy demand and CO_2 emissions over long periods of time has its implications given the diversity and complexity of each building and in the case of dwellings, the changes in occupancy patterns, let alone the performance of the envelope and the technology used. The methods applied in this research, have adopted the use of calibrated dynamic models and quasi-steady state estimation of energy demand, supported by the longitudinal measurements of actual energy demand, envelope performance and occupancy patterns. However, as a trajectory and long-term pattern is predicted with many significant impacts on the environment, these can be irrelevant unless targets and aspired performance levels are introduced in the analysis.

This section seeks to explore the addition of targets and measures to obtain tipping points to identify if dwellings meet the aspired levels of performance at design and in the future to comply with targets. Also important are the actions taken to correct such disparity, considering improvements and interventions, particularly to the building envelope.

5.5.1. Defining the best baselines and CO_2 emission targets

Stating targets against energy demand often consider many factors, most of which relate to the reduction of CO_2 emissions from different sectors. This makes it difficult to relate to smaller developments and individual dwellings. However, the Scottish Government have set ambitious plans for all sectors to collectively reduce CO_2 emissions by set time periods. This section revisits these Climate Change Bill to find a relevant target to use in a longitudinal analysis of the three dwellings in this research. There are different methods adopted to compare against, providing a good indication of a tipping point in which the dwellings are no longer environmentally viable.

A method of benchmarking to the measured and proposed energy and CO_2 emissions obtained in the sections in this chapter is to revisit the criteria proposed by the Design Standards. Two methodologies are adopted; 1) use expected compliance space heating normalised energy figures and their equivalent environmental impact results, and 2) use data from the CO_2 emission target baselines, typically a 1990 baseline, by acquiring results of similar dwelling types designed in the 1990's with the Building Regulations of that time. This second method uses compliance calculated (BREDEM) space heating normalised values to which CO_2 emission targets at different timelines can be applied, as set in the 2009 and 2018 Climate Change Acts.

The three dwellings analysed in detail were designed to comply with two different standards; the Scottish Building Regulations, Section 6, Energy and 7, Sustainability of the Technical Handbooks, (SBS, 2011). Dwelling T.7.19 achieved Gold level and dwelling SD.6.17 passed Section 6 only. Dwelling SD.6.18 used the *Passivhaus* criteria and space heating demand in Table 5-17.

Table 5-17: Summary of targets and Standards used at the design stage

Dwelling	Standard	Space heating criteria ($kWh/m^2/yr$)	Equivalent CO_2 impact ($kgCO_2e/m^2/yr$)*1
SD.6.17	SBS 2010	>40	7.8*2
SD.6.18	SBS 2010, *Passivhaus*	15	2.97
T.7.19	SBS 2010, Section 7 Gold	30	15.51

*1 Calculation using 2011/12 CO_2 factors for kWh of fuel for space heating

*2 Design Compliance DER space heating equivalent is used

Additionally, the CO_2 values calculated from the SAP2009 compliance tools are used as targets, given that this is the expected environmental impact from such a building at the design stage, as shown in Table 5-18.

Table 5-18: Compliance results obtained at the design stage

Dwelling	Main fuel type for space heating	Space heating result ($kWh/m^2/yr$)	Equivalent CO_2 impact ($kgCO_2e/m^2/yr$)*1
SD.6.17	Natural Gas	39.5	7.8
SD.6.18	Natural Gas	21.6	4.27
T.7.19	Electricity	3.85	2.0

*1 Calculation using 2011/12 CO_2 factors for kWh of fuel for space heating

The results for the three dwellings analysed show that not all results comply with their respective standards. SD.6.18, despite being designed to the Passive House standard, when calculated using SAP2009, it doesn't comply with its criteria. However, when using the appropriate *Passivhaus* Planning Package (PHPP) calculations it passes and fulfils all the requirements. This dwelling considering space heating only, confidently complies with the Gold level for space heating requirement by achieving <30 kWh/m^2/yr. SD.6.17 passes Section 6 (Energy) and complies with the Bronze level criteria, however it also reaches the Silver level criteria which states that dwellings should achieve ≤40 kWh/m^2/yr. Dwelling T.7.19 complies with Gold level criteria at the design stage.

The second method applied to obtaining targets of environmental impact considering space heating demand data from typical similar buildings built in the 1990's under BREDEM models, first developed in the early 1980s (Anderson et al., 1985; Dickson et al., 1996; Henderson and Shorrock, 1986). A lot of experimentation of early domestic building energy demand was also developed which helped to predict the delivered energy of typical dwellings at the time. Work by Dunster et al. (1994); Shorrock and Henderson, (1990) & Allen and Pinney, 1990) helped to define some of the early assumptions of energy demand. The use of space heating demand in this research was able to define a baseline easily applied as climate change targets up to the 2050's and from there obtain an indication of how the dwellings would be performing longitudinally.

Table 5-19: Estimated demand of energy for the 1990's as a baseline for targets

Publication author (date)	Space heating (kWh/yr)	Normalised space heating (kWh/m^2/yr)	Equivalent CO_2 (natural gas) (kgCO_2e/m^2/yr)*4	Equivalent CO_2 (electricity) (kgCO_2e/m^2/yr)*5
(Dunster et al., 1994)	12,500	129*1 133*2 150*3	23.37 24.10	115.68
(Allen and Pinney, 1990)	14,200	146*1 151*2 170*3	26.45 27.36	131.4

*1: Normalisation using SD.6.17 treated floor area (96.92 m^2)

*2: Normalisation using SD.6.18 treated floor area (93.96 m^2)

*3: Normalisation using T.7.19 treated floor area (83.20 m^2)

*4: Only applied to dwellings using natural gas as main fuel type (SD.6.17 & SD.6.18)

*5: Only applied to dwelling using electricity as main fuel type (T.7.19)

Work by Dunster et al. (1994) and Allen and Pinney, (1990) defined mean values for space heating in local authority dwellings of different construction types and fuel type. This creates a good approximation to the dwellings in this study and helps to define a more accurate representation of energy demand in the 1990's. Table 5-19 shows the assumptions of space heating for similar dwellings using emission factors per fuel type from 1990 where natural gas had a factor of 0.1812 $kgCO_2/kWh$ (Baggott et al., 2004) and electricity a factor of 0.770 $kgCO_2/kWh$ (DEFRA, 2010; Zheng and Li, 2011).

The equivalent CO_2 emissions for estimated 1990 levels of space heating demand are shown in Table 5-19 considering the normalisation factors equivalent to the dwellings in this research. To simplify the figures, the two sources of demand data for space heating in 1990 have been normalised using equivalent treated floor area of the dwellings in this research. Dwelling SD.6.17 using natural gas as the heating fuel has a 1990 CO_2 emission of 24.91 $kgCO_2e/m^2/yr$. The CO_2 emissions for SD.6.18 are equivalent to 25.73 $kgCO_2e/m^2/yr$. Equivalent values for a dwelling like T.7.19 in 1990 using electricity as its main space heating fuel were 123.5 $kgCO_2e/m^2/yr$.

Table 5-20: Estimated environmental impact using CO_2 emission targets up to 2050

Targets	Target reduction ($kgCO_2e/m^2/yr$) 1 (natural gas)	2 (natural gas)	3 (electricity)
1990 baseline	24.91	25.73	123.5
2020 target (56%)	10.96	11.32	54.34
2030 target (66%)	8.46	8.74	41.99
2040 target (78%)	5.48	5.66	27.17
2050 target (90%)	2.49	2.57	12.35

The 1990 baselines defined by Table 5-19 is used to apply the Climate Change Act of 2018 targets, considering both interim and final 2050 percentage drops

(The Scottish Government, 2018; The Scottish Parliament, 2018). Table 5-20 states the expected percentage reduction later used in subsequent sections.

5.5.2. Environmental impact against targets - An anticipated case for retrofit

Considering the medium CO_2 scenario at a 50th probabilistic percentile for the three-timelines and the applied DPF factors and scenarios, the 2018 Climate Change Act of CO_2 emission targets are placed longitudinally. An analysis of the dwellings environmental impact is used to predict a tipping point in which it is estimated that the dwellings no longer perform against its design (compliance and standards), aspired performance and the Scottish Government set targets (The Scottish Parliament, 2018).

Figure 5-42 below shows the longitudinal analysis of dwelling SD.6.17 considering the 1990 baseline and the time-line reductions according with CO_2 emission targets. The consideration of zero CO_2 emissions is anticipated to be after 2050, however a commitment on this date has yet to be given by Scottish Government, and for this study it is achievable by the 2080's. The longitudinal trajectory of dwelling SD.6.17 shows CO_2 emission targets and design compliance results (shown equal in this dwelling). Time stamping overlaps between targets, climate change predictions and DPF scenarios are shown in the red circles with dates of an estimated CO_2 figure. These are regarded as tipping points (TP) at which a target is met requiring a change of direction; often an increase or decrease in CO_2 emissions predicated by energy demand. TP1 below shows the 1990 target declines and the design compliance and standards crossing over between the 100%DPF predicted performance line. This TP shows that the 100%DPF reaches targets as soon as 2032 and increasing steadily beyond that. TP2 reaches the targets but is below the compliance/ standards when its crosses the 50%DPF predictions approximately in 2035. This shows a close approximation to TP1 considering the rate of dilapidation is 50% apart. However, it is clear differences in DPF aren't apparent until after the 2040's. TP3 appears in 2042 for the 10%DPF prediction line. The three TP's described appear between approximately 2030 and 2040 showing that this decade is crucial to the dilapidation of the dwelling. A final TP is TP4 appearing later in 2070 when compliance calculations and design standards cross with 50%DPF as it increases to the 2080 predictions.

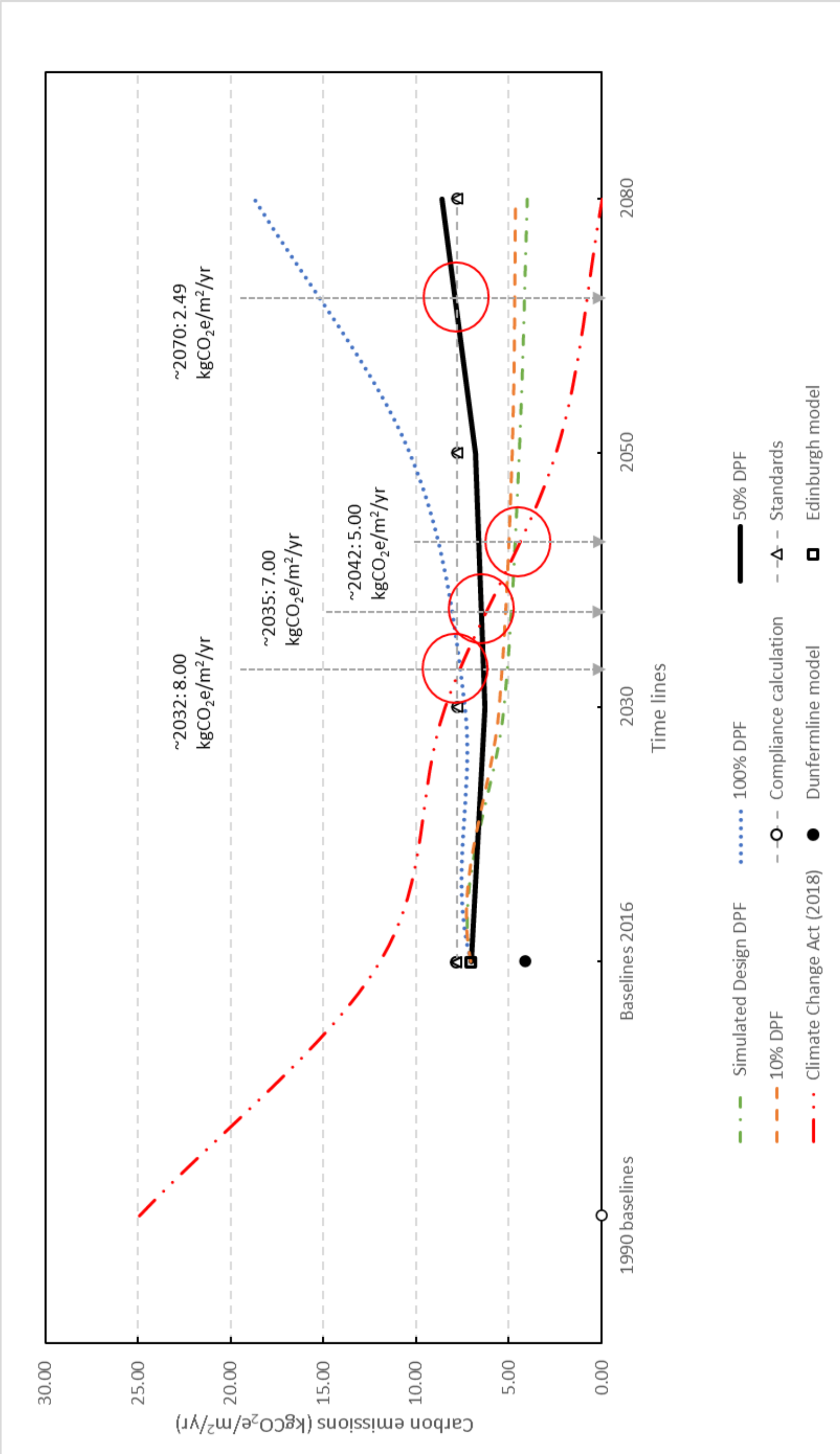


Figure 5-42: Longitudinal analysis of CO_2 for space heating – dwelling SD.6.17

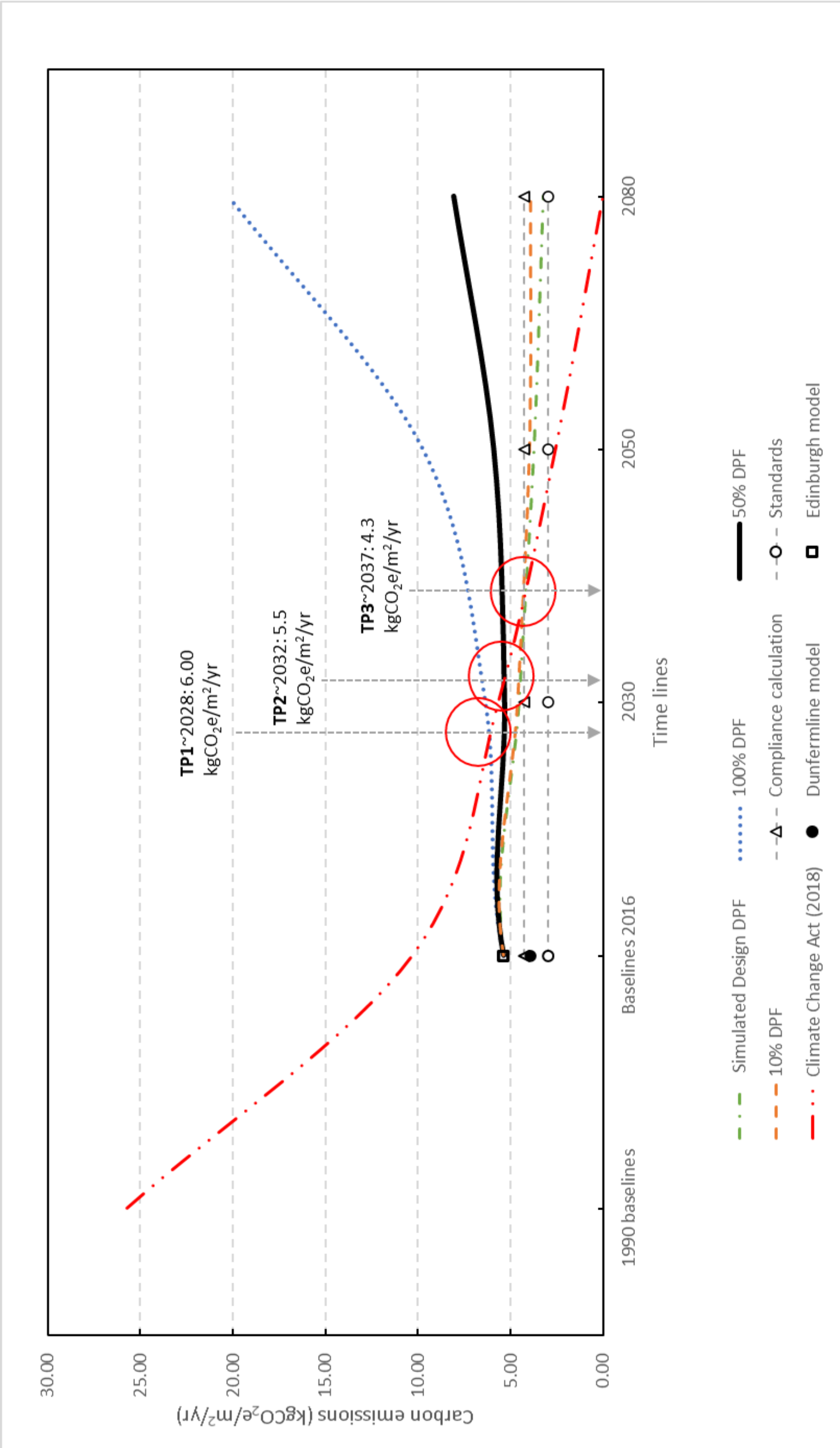


Figure 5-43: Longitudinal analysis of CO_2 for space heating – dwelling SD.6.18

A similar analysis is made of the longitudinal trajectory of dwelling SD.6.18. Climate Act 2018 targets and the standards and compliance calculations and targets were displayed in Figure 5-43. Significant differences appear in the timelines when TP's occur in comparison with SD.6.17. This is evident in TP1 occurring approximately in 2028 when the 100%DPF crosses the Climate change 2018 target line at 6.5 kgCO_2e/m^2/yr. Following that point is TP2 which occurs in 2031 when the target crosses the 50%DPF at 5.5 kgCO_2e/m^2/yr. By 2037 a third tipping point occurs (TP3) at 4.3 kgCO_2e/m^2/yr when the targets cross conjunctively between the 10%DPF and the compliance calculations. The three TP's show a period in which, regardless of the dilapidation intensity, the dwellings performance is no longer in line with the targets between 2028 and 2037. Interestingly, 10%DPF and the Simulated design DPF beyond TP3 are placed between the compliance calculations and design targets used at the design stage. This shows that for this dwelling, if dilapidation occurs at a slower rate, it is likely that the design predictions are an accurate account of its performance.

The analysis of dwelling T.7.19 follows the previous description of the DPF and dilapidation of the building envelope impacting on the environment. This dwelling uses electricity for all energy demand. This dwelling responds longitudinally with predictions of CO_2 emission factors (BEIS, 2017). Electricity CO_2 emission factors decrease substantially after the 2030's making the use of this fuel less of an environmental impact than natural gas which predicts little change in emission factors. Figure 5-44 below shows four TP's which impact the performance of the dwelling. The past CO_2 emission factors are so high in the 1990's that the baseline and typical environmental impact from dwellings heated and cooled with electricity is high and therefore much more than the actual and simulated scenarios in the longitudinal trajectory of the dwelling. The first TP (TP1) appears in 2025 early in the trajectory where the DPF predictions of dilapidation decrease to reach 15.5 kgCO_2e/m^2/yr, which is similar to the design standards of SBS (2011) Section 7 Sustainability Gold level. This first TP is not of real concern, as a downwards trajectory of CO_2 emissions follows this date. Other dwellings show increase of emissions after most TP's. TP2 appears in 2050 at an impact of 2.0 kgCO_2e/m^2/yr where all predicted emissions meet the design compliance calculation. Beyond this point, CO_2 emissions follow a similar trajectory except for 100%DPF in 2065 with a small increase meeting the Climate Act 2018 target at 3 kgCO_2e/m^2/yr, shown as TP3. The other DPF scenario predictions meet the Climate Act 2018 target in 2075, as it dips down to reach net zero CO_2 emissions (≤0 kgCO_2e/m^2/yr) in 2080, shown as TP4. At this point, the dwelling now emits less energy than the compliance calculations at the design stage.

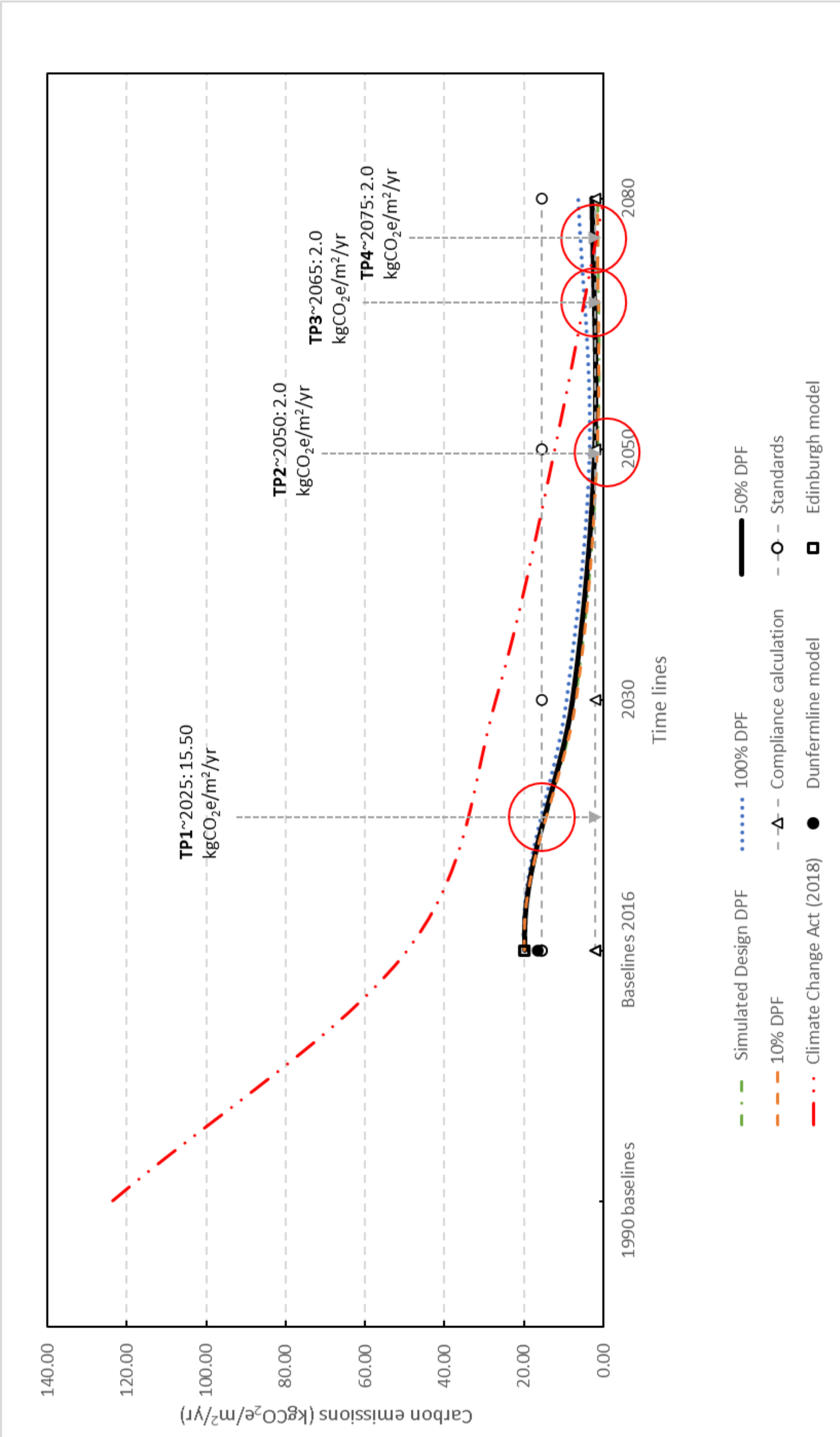


Figure 5-44: Longitudinal analysis of CO_2 for space heating – dwelling T.7.19

5.5.3. Linkages to retrofit of new dwellings

The identification of the estimated time in which tipping points occur and the linkages with the dilapidation factors or dwelling performance factors (DPF’s) provide a time line in, which depending on the intensity of dilapidation, the dwelling no longer achieves CO_2 emission targets and no longer aligns itself to the aspired building standards and compliance calculations.

Figure 5-39 shows that dwelling SD.6.17, presents a timeline between 2030 and 2040 when the TP’s occur at both the 100%DPF and 50%DPF dilapidation scenarios. These TP’s indicate that an intervention is required to avoid further environmental impact eventually being costly to residents and equally lowering thermal discomfort. Intervention will be required during the 2030’s to avoid this, lower dilapidation intensity can possibly lead to a similar trajectory as 10%DPF. This will require a retrofit of the building fabric in the form of reducing heat loss by infiltration and thermal transmission (U-value), components which are essential in the reduction of a DPF.

The analysis presented for dwelling SD.6.18 in Figure 5-40 presents a different timeline when intervention is required, at the first TP. TP1 appears before 2030 and continues with TP2 and TP3 occurring in the late 2030’s. Although intervention in this dwelling may be required before, it may be related to the fact that this dwelling was improved and corrected in various areas of the building fabric during 2015-16 interval. This contributed to its decrease in air leakage thus improving the DPF. Additionally, the observed rate of dilapidation during the two intervals was lower than SD.6.18; thus, explaining why TP1 appears approximately 5 years sooner.

The analysis shown in Figure 5-41 shows a different perspective to the trajectory and TP’s of an electrical space heated dwelling. Although the dwelling consumes more than the compliance calculations and the building standard it was designed against, its environmental impact reduces over time as a result of the expected reduction in CO_2 emission factors after 2030’s. Although the TP’s appear at a later stage in this dwelling’s trajectory, this does not take into effect the high amounts of energy consumed which affects the occupant’s expenditure on energy. Improvements are required to lower emissions below the current 2016 figures to match the compliance calculations, regardless of lowering of CO_2 emissions after the 2030's. Interventions, aligned to the TP's that reach the Climate Change Act of 2018 for this dwelling could be more significant if done later after 2050.

The use of DPF in this chapter was to achieve a measure of dilapidation, first showing that the 100%DPF scenario was a reaction of early occupancy where most changes and adjustments took place and where the rate of dilapidation is the greatest. Examples of this can come in the form of timber structure settling, building services badly covered and sealed through the building fabric or poorly adjusted windows and doors that don't seal properly accelerating uncontrolled ventilation heat loss. As observed in the early sections of this chapter, the largest ratio of change between intervals came in the air leakage of the dwellings; thermal transmission had a smaller ratio of change. Work by NHBC Foundation (2011) supports this as testing concluded that shrinkage and settlement provides additional adventitious ventilation. The introduction of DPF's can serve for two purposes; 1) to propose different intensity levels of building dilapidation and, 2) it can highlight interventions to improve the envelope by reducing air leakage or thermal transmission, and other factors.

5.5.3.1. Evaluation of scenario-specific retrofit of dwellings

Testing conducted during the first four years of occupation provided vital performance data of the dwelling's envelope, which was used to re-calculate DPF, which combined with the simulated climate change energy demand produced a longitudinal account of the dwelling's performance. The longitudinal approach overlaid onto CO_2 emission targets estimated tipping points of underperformance that could be remediated by an envelope retrofit measure. However, applying measures will not provide a seamless solution as buildings are dynamic in nature, responding to unaccounted climatic fluctuations, occupancy changes and maintenance programmes that have endless scenarios and interchangeable possibilities. The use of the DPF scenario levels to show dilapidation can be applied in reverse, as a measure to indicate the level of intervention and retrofit to maintain performance that is aligned to targets.

Referring to Section 5.2, the largest change observed in the in-situ testing between intervals came from the decrease in air tightness as a result of higher air permeability results. Differences between measurements and the intervals revealed large discrepancies between pre-occupancy and first interval results and shrinking and structure settling period in the next set of measurements during interval 2. Such discrepancies are difficult to control; however, they do have an impact on the dwelling's performance over time. Alternative changes to the dwellings plumbing and electrical services can also influence the infiltration of the dwelling and its efficiency by creating new penetrations through the fabric and uncovering old ones that usually remain open causing a rise in infiltration levels.

The dwellings in this development have shown that the decline in U-values, particularly in walls have been slow, as seen in Figure 5-1 and Table 5-1, therefore it may be difficult to address weak points where performance levels will decline in the future. A characteristic that influences performance and thermal efficiency of components is the accumulation of humidity between materials (layers) also known as interstitial condensation. Particular attention is due to humidity stains of proprietary render boards of external walls, see Figure 5-45 and water penetration on rendered board joints, see Figure 5-46, a) and b).

Figure 5-45: Humid render boards at vertical and horizontal framework

Figure 5-46: Gaps between render boards (a) close to down pipe. (b) above window.

The reason behind such stains is not clear yet, however the accumulation of humid surfaces and possibly internal elements of the component, may decrease the thermal resistance of such materials affecting the overall thermal transmission values over time. Apertures between render boards can, with time, expose the structure causing increased air leakage.

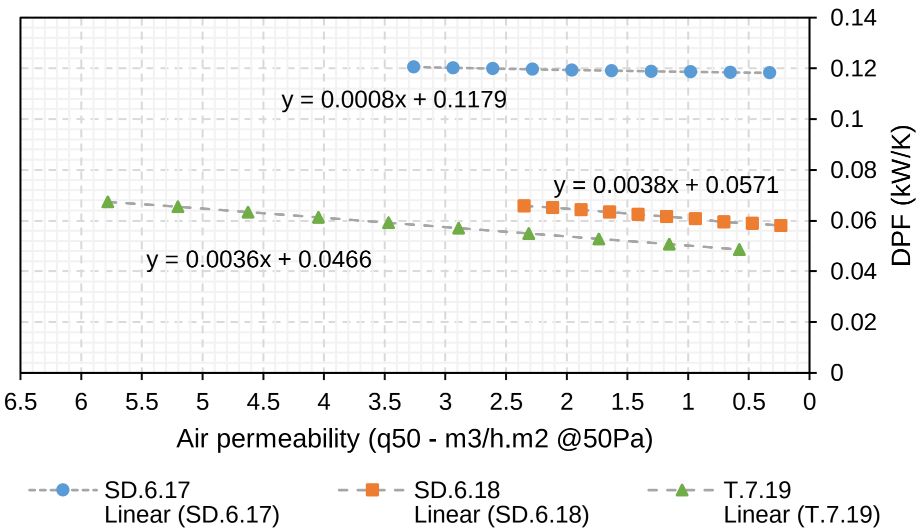


Figure 5-47: Linear relationship between air permeability reduction and DPF for all dwellings

In order to achieve lower DPF’s, a reduction of air permeability, particularly in the rate of decline is required. However, it is difficult to estimate how much would be needed to lower values that would impact energy demand and be within the targets. Such relationship can be explained by Figure 5-47, by using the quasi-steady state compliance modelling. A 10% reduction is made on the air permeability of the last measurement recorded in 2016 and keeping U-values as constant (2016).

The baseline air permeability values, obtained from the last measurements, were decreased by 10% and inserted back into the compliance model (SAP2009) to produce a new DPF value. The linear relationship and correlation between a decreasing air permeability and its DPF is shown in Figure 5-47 for all dwellings. SD.6.17 presents a slow rate of decline, equally, the decline in air permeability for dwelling SD.6.18 shows a medium rate of decline. For dwelling T.7.19, the rate of decline in DPF and air permeability is more prevalent and significant. Figure 5-47 shows how some dwellings are more susceptible to change in heat loss from air permeability than others; this is the case between SD.6.17 and T.7.19. Air permeability for SD.6.17 is not as significant, meaning that changes in air leakage will not impact greatly the energy performance. Dwelling T.7.19 is the opposite, a change in air permeability, even at a 10% decline, can be significant. This relationship shows the importance of air tightness, it has the potential to improve heat loss and energy efficiency.

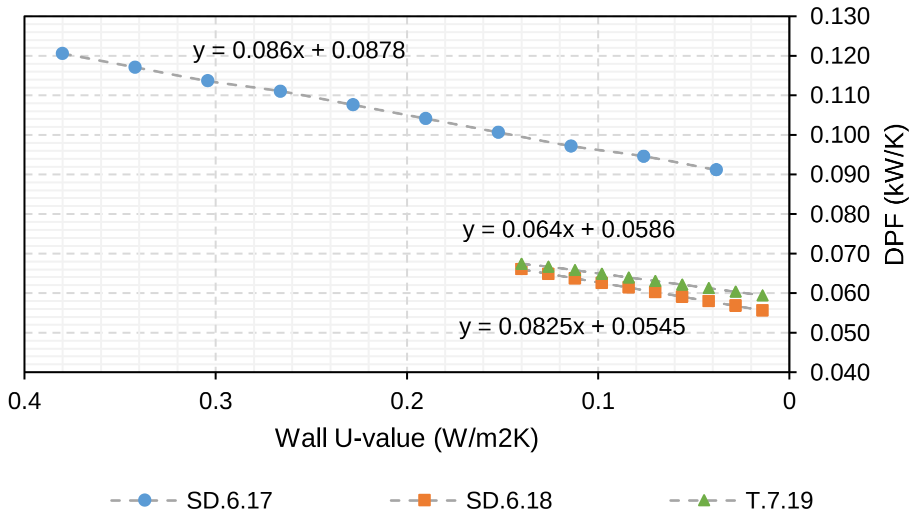


Figure 5-48: Linear relationship between U-value (wall) reduction and DPF for all dwellings

Figure 5-48 shows a similar relationship between the wall U-value and the resulting DPF. As the U-value is decreased from the starting baseline, or last measured wall U-value, a changing DPF is obtained when added into the compliance model. This time, U-value plays an important factor in dwelling SD.6.17 as the linear relationship is shown as a steeper decreasing line that extends down to low U-values. This relationship is different for dwellings SD.6.18 and T.7.19 where the DPF decreases and is clustered together. However, the baseline values are already low, and to decrease it further would result in unprecedented values, i.e. below the 0.10 W/m^{2}K. This analysis shows that the U-value in walls has a greater impact in dwelling SD.6.17 than the others.

Both graphs in Figures 5-47 and 5-48 have produced linear regression formulas that can be used to estimate DPF's with changing U-value and air permeability values. Instead of estimating DPF's with lower values of envelope performance, an estimate of values at the point of retrofit or tipping point would indicate a value relevant to that timeline. Obtaining this value at this point would show how much of an improvement is required to reach compliance or sustainability and energy standards, i.e. applying a retrofit to achieve an improved envelope with less heat loss. This is applied in conjunction with the dwelling tipping point years. This relationship considers the estimated year with the DPF scenarios at 100%, 50% and 10% and estimated air leakage and U-value.

Tipping points for dwelling SD.6.17 are as follows; TP1 2032, TP2 2035 and TP3 2042 with the DPF's; 100% DPF at 0.174 kW/K, 50% DPF at 0.1480 kW/K and 10% DPF at 0.1250 kW/K respectively. By applying the correlation formula, inserting an incremental air permeability value and U-value of the wall, a match with the TP DPF's were identified. As observed for this dwelling, the change in air permeability has little effect on the changing DPF. Matching the TP years to the DPF's gave very high values, unprecedented for such dwellings. On this basis, the wall U-value analysis in Table 5-21 shows TP1 as approximately 1.0 W/m^{2}K, which is a high value, but this result considers a 100% DPF dilapidation scenario. For TP2 at a 50% DPF scenario, a U-value of 0.7 W/m^{2}K and for TP3 0.45 W/m^{2}K, close to the measured in 2016.

Table 5-21: Increased U-value matching the DPF and TP year – dwelling SD.6.17

DPF	U-value (W/m^2K)	TP & DPF scenario
0.1205	0.38	Baseline
0.1222	0.4	
0.1265	0.45	10%DPF – TP1
0.1308	0.5	
0.1351	0.55	
0.1394	0.6	
0.1437	0.65	
0.1480	0.7	50%DPF – TP2
0.1523	0.75	
0.1566	0.8	
0.1609	0.85	
0.1652	0.9	
0.1695	0.95	
0.1738	1	100%DPF – TP1
0.1781	1.05	
0.1824	1.1	
0.1867	1.15	
0.1910	1.2	

A similar approach is taken for dwelling SD.6.18, shown in Table 5-22 and 5-23. It applies the air tightness and U-value approximate values in line with the TP year and its estimated DPF.

The TP's for SD.6.18 are as follows; TP1 2028, TP2 2031 and TP3 2037 with the DPF's; 100% DPF at 0.089 kW/K, 50% DPF at 0.0779 kW/K and 10% DPF at 0.0664 kW/K respectively. Tables 5-22 and 5-23 provide the air permeability (q50) and wall U-value matching the DPF and the TP's shown in other graphs for longitudinal analysis. At a 100%DPF where a TP1 occurs the equivalent estimated DPF and air infiltration are 0.0894 kW/K and 8.5 $m^3/h.m^2$@ 50Pa. TP2 approximately reaches 5.5 $m^3/h.m^2$@ 50Pa with a 50%DPF of 0.078 kW/K and for a 10%DPF reaching 2.5 $m^3/h.m^2$@ 50Pa a DPF of 0.0667 kW/K is achieved. The wall U-Value analysis shown in Table 5-23, presents a wider spread of values in order to reach the TP's at the DPF scenarios. A 100%DPF at the TP1 provides a U-vale of 0.42 W/m^2K which is a substantial increase to the last value recorded of 0.14 W/m^2K. The TP2 at a 50% DPF shows a U-value of 0.28 W/m^2K and for the TP3 a similar value as the recorded of 0.14 W/m^2K.

Table 5-22 (left): Estimated air permeability values at the TP's year – dwelling SD.6.18

Table 5-23 (right): Estimated wall U-value at the TP's year – dwelling SD.6.18

DPF	q50 ($m^3/h.m^2$ @50Pa)	TP & DPF scenario
0.0628	1.5	
0.0647	2	
0.0666	2.5	10%DPF - TP3
0.0685	3	
0.0704	3.5	
0.0723	4	
0.0742	4.5	
0.0761	5	
0.078	5.5	50%DPF - TP2
0.0799	6	
0.0818	6.5	
0.0837	7	
0.0856	7.5	
0.0875	8	
0.0894	8.5	100%DPF - TP1
0.0913	9	
0.0932	9.5	

DPF	U-value (W/m^2K)	TP & DPF scenario
0.0644	0.12	
0.0652	0.13	
0.0661	0.14	10%DPF - TP3
0.0669	0.15	
0.0677	0.16	
0.0685	0.17	
0.0694	0.18	
0.0702	0.19	
0.0710	0.2	
0.0718	0.21	
0.0727	0.22	
0.0735	0.23	
0.0743	0.24	
0.0751	0.25	
0.0760	0.26	
0.0768	0.27	
0.0776	0.28	50%DPF - TP2
0.0784	0.29	
0.0793	0.3	
0.0801	0.31	
0.0809	0.32	
0.0817	0.33	
0.0826	0.34	
0.0834	0.35	
0.0842	0.36	
0.0850	0.37	
0.0859	0.38	
0.0867	0.39	
0.0875	0.4	
0.0883	0.41	
0.0892	0.42	100%DPF - TP1
0.0900	0.43	
0.0908	0.44	

Dwelling T.7.19 presents a different set of results. All three DPF scenarios appear below the CO_2 emission targets but above the compliance calculations. In environmental impact terms, rather than tipping points, this dwelling has less of an impact as the CO_2 factors for electricity are predicted to decrease, being less of an environmental concern. If lower the TP approach is performed on the energy demand, this presents a different picture. Energy demand reached targets above the initial compliance calculations as soon as 2025 at 100%DPF with an actual DPF of 0.081 kW/K, 2035 at 50%DPF with a DPF of 0.0775 kW/K and 2065 at 10%DPF with a DPF of 0.0692 kW/K.

Table 5-24 (below left): Approximate air leakage values at the TP's year – dwelling T.7.19

Table 5-25 (below right): Approximate wall U-value at the TP's year – dwelling T.7.19

DPF	q50 ($m^3/h.m^2$ @50Pa)	TP & DPF scenario
0.06676	5.6	
0.06748	5.8	
0.0682	6	
0.06892	6.2	
0.06964	6.4	10%DPF - TP3
0.07036	6.6	
0.07108	6.8	
0.0718	7	
0.07252	7.2	
0.07324	7.4	
0.07396	7.6	
0.07468	7.8	
0.0754	8	
0.07612	8.2	
0.07684	8.4	
0.07756	8.6	50%DPF - TP2
0.07828	8.8	
0.079	9	
0.07972	9.2	
0.08044	9.4	
0.08116	9.6	100%DPF - TP1
0.08188	9.8	
0.0826	10	

DPF	U-value (W/m^2K)	TP & DPF scenario
0.06884	0.16	
0.06948	0.17	10%DPF - TP3
0.07012	0.18	
0.07076	0.19	
0.0714	0.2	
0.07204	0.21	
0.07268	0.22	
0.07332	0.23	
0.07396	0.24	
0.0746	0.25	
0.07524	0.26	
0.07588	0.27	
0.07652	0.28	
0.07716	0.29	
0.0778	0.3	50%DPF - TP2
0.07844	0.31	
0.07908	0.32	
0.07972	0.33	
0.08036	0.34	
0.081	0.35	100%DPF - TP1
0.08164	0.36	

The linear correlation for both air permeability and U-value present a uniform distribution which makes prediction of values under the TP's and the DPF scenarios easier. Table 5-24 presents estimated air permeability at the TP years at the applied DPF scenarios. At the 100% DPF in 2025 the value has increased to 9.6 $m^3/h.m^2$@ 50Pa. Applying the 50%DPF and at the TP 2 in 2030, the value is estimated to be 8.6 $m^3/h.m^2$@ 50Pa and at TP1 in 2040 approximately 6.4 $m^3/h.m^2$@ 50Pa. Equally, Table 5-25 presents the values for the wall U-value linked to the corresponding TP's and the DPF scenarios. At TP1 applying a 100% DPF the wall U-value increases to 0.35 W/m^2K, whilst TP2 applying a 50%DPF with a 0.30 W/m^2K U-value. For the 10%DPF in TP3 the U-value increases slightly from the last value recorded, from 0.14 W/m^2K to 0.17 W/m^2K.

5.5.3.2. Interpretation of the values to apply retrofit interventions

The analysis performed in Section 5.5.3.1 estimated the building envelope performance at the years in which environmental targets were surpassed, i.e. when the tipping points occur. With these performance values estimated and aligned to equivalent DPF's of each dwelling, improvements can be proposed that can lower the heat loss, thus the environmental impact. This approach can maintain the dwellings performance and reduce the rate of dilapidation, particularly in the 100% and 50% DPF which have larger effect on the dwellings environmental impacts.

For dwelling SD.6.17 air permeability does not have a large impact on heat loss. This is shown as having a small rate of change in the DPF and the value for air permeability in Figure 5-41. This may be partly due to the reduction of air leakage from the first to the second intervention where an improvement is recorded. U-value has a larger effect on the heat loss although harder to propose interventions in new buildings unless insulation has been damaged (humidity or taken out). In order to reach lower DPF's from the three TP's; 1.0, 0.7 and 0.45 W/m^2K respectively, down to the proposed at design stage, additional internal or external wall insulation may be required, part of a retrofit scheme by the RSL.

The analysis made for dwelling SD.6.18 considers interventions concerning air permeability and the wall U-value to lower DPF down to compliance and design levels. Air tightness at 8.5 and 5.5 $m^3/h.m^2$@ 50Pa can be reduced to lower values to keep the compliance estimates and Passive House criteria by lowering air infiltration, good maintenance and building envelope improvements. At the estimated TP's, the risk of failure around seals and gaskets in openings is greater, therefore considering replacement can help to reduce infiltration. As the occupancy years continue, service penetration can have an impact on uncontrolled ventilation, especially as repairs and replacement of services occur. Sealing gaps and holes at these stages should be common practices among the RSL service and maintenance teams to reduce such leakage. A combination of thermal transmission interventions should contribute to the lowering of the dwelling DPF. This comes with the introduction of interventions that address any water ingress into the walls and other components in order to lower U-values affected through the years where material dilapidation can reduce thermal efficiency. Reducing U-values from 0.42 W/m^2K and 0.28 W/m^2K to near compliance estimated values, or in this dwelling, the last measured in 2016, can be achieved by reducing thermal bridging at weak points (connections and joints) or by adding additional layers of insulation and repairing insulation due to water ingress and humid surfaces.

A similar analysis is made for dwelling T.7.19 where estimated performance values can be reduced after an intervention programme considering solutions such as increasing air tightness and lowering wall U-Value. Air permeability during the last round of measurements resulted in high readings, above 5.5 $m^3/h.m^2$@ 50Pa. Estimations for air leakage at the tipping points show that a considerable effort is required to lower the values to compliance level estimates from 9.6 in 100%DPF to 8.6 and 6.4 $m^3/h.m^2$@ 50Pa in subsequent DPF scenarios. In combination many interventions can contribute to the reduction of wall U-value, these will be like those mentioned before.

This analysis has set precedents and estimated values for the identified tipping points and DPF scenarios. Although heat loss and its resultant increased energy demand cannot be accountable to only the building envelope dilapidation, much of the performance values linked to retention of heat in buildings are predicated on how efficient and therefore how low uncontrolled infiltration and thermal transmission values are throughout the lifetime of the dwelling. There are other important factors to consider but were not part of this research.

5.5.4. Brief outline of other important factors

The longitudinal performance of the dwellings will be affected by many factors established by not only the quality of the building envelope but by other physical change processes instigated by occupancy, deteriorated efficiency of building services, climatic conditions, and building maintenance strategies. Below are some factors, which although not analysed in this research, contribute to poor dwelling performance, operability and adding to higher energy demand.

- **Reduced efficiency of building services**

Although not analysed in detail, the drop of efficiency in HVAC systems influences the amount of fuel used. Installed HVAC systems contribute to the gap in performance which greatly increases with the lack of baseline performance data given by system manufacturers on the systems themselves. The as-built and commissioned systems often misquote the actual operational efficiency, and although seasonal coefficient of performance is now used to gauge efficiency, there are still differences in what has been installed and the quoted technical guidance in marketing information (de Wilde et al., 2011). As part of the dwelling performance factor (DPF), ventilation and heat efficiencies are considered; for this research compliance factors and estimations were used.

- **Increase precipitation levels with climate change**

In this research the impact of climate change on future weather has increased the risk of overheating by contributing to the rise in indoor temperatures, affecting the dwellings thermal comfort. This has also contributed to the decrease in space heating and an increase in space cooling. Worth considering, is the annual increase in precipitation due to climate change, contributing to rising water levels, flooding and above all dilapidation of the building envelope. Increased exposure to precipitation adds to the vulnerability of building materials and the risk of water penetration which creates cracks in external renders, moist building materials and structural damage (Cavalagli et al., 2019). These have a direct influence on building performance by the dilapidation of the envelope creating air leakage pathways through gaps and cracks, adding to the risk of increased infiltration heat loss and degraded thermal envelope by increased thermal conductance on account of humid materials.

- **Maintenance**

A reactive maintenance approach that applies a radical intervention and retrofit programme can be at first a cost-effective means of addressing problems however, not considered are inactive periods creating occupant disruption and, in some cases, partial or in the social rent sector total decant of dwellings. Such practices can in the long run be more costly. Preventative maintenance can be introduced through a schedule-proposed set of interventions of replacement of materials, technology and components. However, these are more common in HVAC systems that have determinate service and efficiency life span that is easily identified and replaced. After conducting yearly surveys of the properties in this research over a four-year period, a reactive maintenance response to occupant complaints and emergency calls has been the common approach in this development.

- **Occupant misguidance**

Increased energy demand should no longer be solely attributed to occupants, but also accountable are dwelling designers, RSL housing team members and handover teams who are not properly informing occupants on how best to operate dwellings, particularly those with added technology, smart controls and renewable systems. Although first time occupants in the analysed dwellings were part of a controlled post occupancy study that documented the handover and occupant dwelling briefing programmes, this knowledge of the inadequate operation of dwellings diminished and fragmented in the years after early occupation. The RSL provided induction sessions and monitored handover procedures with added dwelling guidance, technology demonstrations and best operation manuals. However, during the study, and after talking to residents, the gap in knowledge between what was said in these early years widened, adding to occupant misinterpretation of technology, adequate operation of controls and configuration of efficient ways of managing energy use and decline in indoor thermal conditions. The result of this widening gap in knowledge is exacerbated during occupant turnover where new residents are allocated the available property. This happened to two of the analysed dwellings, where the occupants had secondary information on the dwelling operation and at handover RSL housing officers were not capable or knowledgeable to explain the atypical sustainable features, technology and conditions.

- **Thermal mass – Low vs high envelope thermal capacitance**

The housing industry in Scotland has approached housing shortages and the need to deliver efficient and long-lasting properties by adopting rapid and light weight buildings (Hacker et al., 2008). This has led to advantages in the selection of materials that are easily erected, locally sourced and easily assembled, with most designs adopting timber or light steel off-site methods of construction. This tendency to use lightweight materials in housing has detached the benefits of thermal inertia in the building envelope. Such properties contribute to the displacement of external temperatures or can act as a thermal capacitor contributing to a rise in mean radiant surface temperatures that contribute to thermal comfort. Except for massive timber structures such as dowel laminated timber or cross laminated timber structures; beam and post insulated envelopes or cassette wall, roof and floor closed insulated panels have a reduced thermal capacitance in comparison to brick, block, stone or clay masonry construction. The ability to store energy from solar radiation or indoor space heating benefits the indoor conditions and can reduce energy requirements (heating and cooling).

5.5.5. Concluding remarks

This section of the chapter has taken a large body of data and results of the three dwellings in a longitudinal manner by projecting the analysis performed in section 5.4 and matching it against design criteria, compliance calculations and Scottish Government environmental targets. To show this, a series of tipping point time stamps have been defined against the different dwelling performance factor scenarios. Also analysed has been the way in which the tipping points can act as a trigger for interventions and improvements. To define these, compliance models were used to obtain new DPF's with a defined reduction of air permeability and wall U-value. This created a linear regression correlation to forecast changing DPF's resulting in estimated thermal envelope performance values (air permeability and U-value) aligned to the tipping points for each dwelling.

Once tipping point thermal values were estimated, a clear definition of retrofit was proposed in order to achieve better DPF's leading to decreasing heat loss and reduced environmental emissions. Hence, such improvements at set points defined by the tipping points gave a time stamp of when retrofit is needed and to what capacity the retrofit could be made, or what type of intervention to apply. Focusing on building envelope performance, retrofit scenarios would seek to reduce air leakage by uncontrolled infiltration through sealing gaps, cracks and holes as well as badly fitted services or resident DIY work. Improving U-values is more of a challenge, unless areas within the building envelope have a defined problem and clear deficiency in performance, such as humid wet insulation or clear thermal bridging. It is therefore difficult to propose a total insulation re-fit involving internal or external wall insulation.

A clear outcome from this research is that at some point, regardless of the rate of dilapidation, dwellings require an improvement and retrofit intervention. This section has also showed that climate change on its own even with the reduction of space heating and increased cooling demand still manages to impact environmentally if CO_2 factors for consumed natural gas remain high. Electrically heated and cooled dwellings have the advantage that their environmental impact (low CO_2 factors) decrease post 2050's, however cost to the occupier will be high due to sustained high fuel price. High demand of natural gas, although detrimental to the environment, remains the cheaper alternative, an option which most RSL's and homeowners prefer.

5.6. Chapter conclusions

This analysis chapter has been able to redefine the importance of longitudinal measurements of dwelling performance. Throughout this study, the repeated testing of the selected dwellings; first the thirteen different construction type dwellings in the development and then three significant dwellings that encompassed a mixture of dwelling type, different design aspirations, heating technology and occupancy.

This chapter began by stating three determining factors that shape the performance of the dwellings analysed. The results chapter helped to show the actual data retrieved after in-situ tests and the longitudinal monitoring programme. Many correlations were found between occupants, dwellings type, use of services and energy demand. However, the aspects that were of importance in this research and that influenced energy demand, were envelope performance from tests conducted bi-yearly of air permeability and thermal transmission. The repeated tests alongside the design predicted values provided a launch pad to estimate the changes over the years or the intervals between tests. This evidence of changes between tests provided causes for the displacement in energy demand between the aspired design calculations. The first section of this chapter defines this as a recorded dilapidation of the building envelope by stating the ratio of change between intervals and the difference in values over the four years of occupation. The revealing outcomes from this analysis are that dilapidation through air permeability in dwellings such as SD.6.18 and T.7.19 and that SD.6.17 due to its intervention work to correct badly sealed windows in the living room and improvements in its gable wall, actually improved after the first interval of tests.

Relevant to this research was how the envelope tests contributed to the changes in heat loss coefficient composed of ventilation, infiltration and envelope heat loss. The definition and calculation of dilapidation of the DPF provided a dilapidation factor that could be used in combination with climate change simulation modelling, and future weather files (external temperature shifts) to predict energy demand for space heating and cooling. To measure the different rates of DPF affecting building envelope performance, alternative DPF's were proposed that would show probable scenarios of dilapidation. These were proposed as a 50% and 10% considering the 100% DPF regarded as worse-case-scenario calculation. These additional dilapidation scenarios were added to the dwelling longitudinal analysis against calibrated simulations.

Having stated a DPF and its impacts on energy demand, the environmental impact due to CO_2 emissions and cost of energy, a longitudinal picture provided an understanding of how these dwelling could behave over time. Although these projections are important, they are meaningless until they are aligned to quantifiable targets, design aspirations and compliance calculations. To define this, the longitudinal environmental impact projections were analysed further by overlaying recent Scottish Government Climate Act CO_2 emission targets on typical baselines, often referred to 1990 CO_2 emissions. Baselines are predicated on the availability of historical data, in this case dwelling space heating energy demand. Although the dwellings in this development go back to 2012, it is not a viable time period to apply targets. For that reason, approximate emission values for typical housing in 1990 were obtained providing a starting point to apply the CO_2 reductions set out by Scottish Government targets.

The longitudinal projections conclude with a series of tipping points (TP) that show where performance falls below targets and compliance values. Such tipping points are defined as periods in which an intervention is required and action is needed to remediate this increased environmental impact. Such interventions are predicated on the calculation of air permeability and U-values after a DPF linear regression analysis to act as the basis to which intervention to apply and to what capacity. Many intervention methods for the reduction of air leakage and thermal transmission are proposed, both to avoid further tipping points and to decrease the environmental impact over time.

Important to this chapter is to state when interventions are required and also what level of action is required in the shape of retrofit actions and interventions. This chapter has stated not only a dilapidation factor to apply over time to estimate performance, but it has defined which intervention makes sense according to the dwelling type and any problems identified in surveys and inspections.

The next Chapter in this research seeks to revisit the aims and objectives of this thesis and show whether the methods and analysis set out and its interpretation have reached the originally set hypothesis. It also states where further research is required utilising the datasets presented in this analysis or with a larger sample size for more confidence in the assumptions and predictions. Studies of this nature, that present an estimated account of future scenarios, are dependent on many factors that influence the direction of performance and energy demand, this is typical of dynamically operated building.

Chapter 6

Conclusions and future research

6.1. Introduction

This chapter seeks to conclude on the results and analysis in alignment with the aim and research questions and to revisit the proposed hypothesis. The chapter first discusses the important achievements and outlines the contribution to knowledge from the research. Finally, the chapter refers to limitations of the present study and future opportunities to expand the research.

6.2. Key outcomes of the research

It was found that a fundamental contributor to higher than expected operational energy demand in new-build dwellings can be predicated by the quality of design and construction phases. Yet the construction industry fails to understand the dynamism and inconsistent nature of buildings over their whole-life occupation. Studies based on discrepancies between the as-designed and as-built focus primarily on how buildings fail to perform as they were first intended, hence emphasising a performance gap. Although it is important to identify this gap and ways to reduce it, building diagnostics through post occupancy and building performance evaluations rarely expand beyond the early stages of occupation, failing to understand the longitudinal performance of buildings. The aim of this thesis was to understand the relationship between building envelope performance and climate change considering its impact on the environment during longer periods of occupation. Fundamental to this thesis, was to understand key elements of the dilapidation of the building envelope in dwellings over longer periods of occupation and how it could be measured as a recurrent factor affecting energy demand and consequently impacting on the environment. The recurrent envelope dilapidation factors, in combination with climate change future weather probabilistic external temperature shifts, was used to predict longitudinal energy demand. The resultant energy demand converted into CO_2 emissions led to tipping-points at which dwellings surpassed set government CO_2

emission targets. Presented as different dilapidation impact scenarios, produced tipping point time stamps that highlighted the risk of dwelling underperformance, occupant discomfort and a contributor to occupant fuel poverty and eventual global environmental risk.

Addressing the hypothesis and linking it to the research questions, are the estimation of tipping points and underperformance requiring interventions to avoid further environmental risk. The suggested periods and time stamps highlight the need for dwelling retrofit interventions ahead of time in order to avoid the associated risks. An estimated level of envelope underperformance informs the intensity of the intervention and retrofit required. This was achieved by creating a percentage reduction of air permeability and U-values that were re-inserted into the original compliance model of each dwelling, creating quasi-steady-state new heat loss coefficients or dwelling performance factors (DPF's). By analysing the results further, a linear correlation between them produced a regression formula that was extended to match the tipping point DPF's previously identified. This linked the DPF's with estimated air tightness and U-values that could be used to propose retrofit scenarios, hence reduce heat loss, energy demand and environmental impact. Such indicators are useful for industry relevant stakeholders in order to propose new standards of retrofit and improvements of existing dwelling design. The Industry needs to prepare for early retrofit, let it be due to dilapidation of the building envelope alone, or to adapt, optimise and avoid discomfort amid future weather shifts.

6.3. Contribution to knowledge

The research undertaken is an important first step towards predicting future energy demand and its corresponding environmental impacts by combining measured energy and building envelope performance results in combination with climate change impacts implanted into re-run steady state calculations and calibrated simulations. Throughout this research, the applied methodology including; the field study deployment to the simulations and statistical analysis, contributed to the understanding of how new dwellings perform over time. In this context, the following areas of new knowledge have been generated linked to the original research questions and objectives proposed.

6.3.1. Longitudinal evaluation of dwellings performance

Addressing research questions one and two discussed in chapter 1, is the work developed that took place over four years of monitoring whilst also extending that by applying climate change scenarios and calculating and applying a repeating dilapidation factor.

There is little evidence of building envelope evaluations taking place over long periods of occupation within the domestic sector. Most studies focus on the first and sometimes second year of early occupation period (Stevenson and Leaman, 2010). Longer tests are done at an early stage and then with extended intervals after 5 or 10 years, thus failing to reveal the real cyclical performance and morphological behaviour during occupied periods. This research has highlighted the importance of applying repeated longitudinal testing during occupation extending beyond the building structure settling period – usually the first year – whilst also bridging over the first and second years of the occupant realisation periods where the new home novelty wears off and rebound effect of energy use disperses. This research has identified that year three and four of occupancy reveals the true building energy demand and the ability to generate a comparable baseline, a mean between both years provides a better baseline and profile of demand (Bros-Williamson et al., 2017). The repeated monitoring involved yearly energy demand monitoring and bi-yearly building envelope testing, critical in identifying the displacement performance values between the testing intervals. Air permeability, wall U-value and dwelling performance factor intervals between tests were important in the understanding of the dwelling’s dilapidation. Although this research is based on a four-year period of testing, where early occupation dilapidation may have occurred more rapidly, it provides an appreciation of the extent that envelope dilapidation has, as analysed in the longitudinal analysis in Chapter 5. An additional but fundamental factor of this analysis over time was the realisation of a quantifiable energy performance gap between the as-designed and the as-built energy demand. In the case of two of the analysed dwellings this was documented in a journal publication in Energy and Buildings by Bros-Williamson et al. (2016).

6.3.2. Tipping points and Building retrofit

This research has identified three important factors which contribute to longitudinal analysis of dwellings energy and environmental performance. These include; gap in performance, the effects of future weather and climate change and the changes in the envelope performance by applying a DPF set of scenarios. Based on these and to answer research question three, this research devised tipping-points occurring at a moment in time with specific DPF's and corresponding air permeability and wall U-values. The tipping points and a time stamp when the dwellings exceeded environmental government targets and design predictions was thus calculated. At these points interventions are required to lower energy demands which can divert any net environmental impact, such as increased CO_2 emissions (that contribute to increased global temperatures) below targets and design standards. The predictions provide valuable resilience pathways that can help inform future building procurement, design, construction stages and maintenance plans.

Stakeholders involved in dwelling design and construction should consider such dwelling time stamps and tipping points for future-proofing and considering an adaptive dwelling design. These tipping points identify an estimated envelope performance level corresponding to the DPF at a specific time stamp. This is useful as it indicates a level of improvement that is needed, both in air permeability levels and wall U-value. A strategic approach can then be made to plan for a retrofit action that steers away from the estimated tipping points.

6.3.3. Links to maintenance of dwellings

An important outcome of this study and one that addresses research question four, is the identification of retrofit levels and interventions to the building fabric which are required to lower the dwellings environmental impact to the initial design standard or set CO_2 emission targets. It was found that some of these faults and incidents of dilapidation are unavoidable, however, many more are preventable through planned maintenance and inspection of building services. The dwelling performance factor (DPF) scenarios can help to act as a predictive, preventative and reliability-centred maintenance set of actions. A predictive maintenance method is regarded as a condition-based maintenance that requires investment in equipment monitoring and RSL staff training which has the potential to reduce labour costs and equipment downtime. Alternatively, a preventative method that proposes time-based maintenance can be applied; using the DPF and its estimated tipping points to plan for a maintenance action. This method can still suffer from unplanned failure and may lead to unnecessary maintenance, however, the probabilities are lowered. This planned approach is cost effective and can extend the service life of equipment and building envelope. Equally important is a reliability-centred method that combines both preventative and predictive methods with root cause failure analysis. It proposes to accurately define deviations from acceptable performance levels, to isolate the root causes of equipment failures, and to develop cost-effective corrective actions that prevent recurrence (Mobley, 1999). It is regarded as a reliable method as it has the potential to extend equipment life, however, it requires high initial cost for equipment and trained RSL staff to handle historical energy demand data.

The proposed scenarios of the DPF calculations in this research can be a good indicator for identifying service and envelope failures to implement maintenance actions. Although these maintenance checks can be programmed longitudinally over occupancy periods, it was found that it is during the early occupation services and envelope efficiency checks that largely contributed to the gap in performance. Poor building services commissioning prior to handover caused services to fail early on or operate badly; contributing to higher than anticipated energy use. Additionally, a lack in communication between the RSL and the residents on the responsibility of certain maintenance actions and checks produced uncertainty and a negative reaction against the dwelling operation and efficiency. Also unaccounted for was the impact of building services dilapidation and its performance, a fundamental element in the longitudinal environmental performance of dwellings which is beyond the scope of this research.

The proposed envelope maintenance linkage to the DPF and dilapidation scenarios in this research are a key contribution to knowledge.

6.3.4. Climate change probabilistic scenarios and the dilapidation factor

Research question five queries the impact climate change has on the longitudinal performance of dwellings. This section addresses the methodology applied and how weather patterns influenced energy demand over time.

Future probabilistic weather patterns obtained through the Prometheus project by Eames et al. (2010) and the UKCP09 (Murphy et al., 2009 and Jones et al., 2009) have been instrumental for the longitudinal prediction of energy demand and CO_2 emissions. The weather files obtained, from the nearest location to the dwellings, have produced probabilistic weather files for two CO_2 emission scenarios and three probabilistic percentiles for three timelines: the 2030's, 2050's and 2080's. However, the detailed analysis adopted the medium CO_2 emission scenario and a 50% probabilistic percentile, given the available computing power and time restrictions.

This research predicted dilapidation scenarios with effects caused by a changing weather profile. The applied external dry-bulb temperature shifts occurring over the decades leading to the 2080's impacted the simulated patterns of space and cooling energy demand. The use of such future weather predictions concluded that, although the requirements of space heating declined, and space cooling increased, the as-built DPF's used without shifts of envelope dilapidation showed a downward prediction of energy demand. However, by including varying intensities and scenarios of DPF's the results showed an increased energy demand; indicating that in this location the decline in envelope performance has a greater effect than that of climate change. This pattern was observed for the selected climate file (Edinburgh) which predicts mild external temperature increases, thus little demand of electrically powered cooling devices. If applied to southern locations closer to the Equator, with the corresponding future weather files, the requirements for cooling would be greater and its impact on energy demand and CO_2 emissions much higher.

This research demonstrates that future climate change weather files can be used not just for overheating predictions and energy demand, but also for heat loss calculations considering the dilapidation of the building envelope. The same methodology can be applied if test data is obtained from other dwelling performance factors, such as buildings services (heating, cooling and ventilation) that influence the building dilapidation. Together, a complete dilapidation of the dwelling can be devised using actual measured data. This research provides a set of dilapidation factor scenarios in combination with climate change predictions. However, further longitudinal testing would allow the refinement of the findings by pin-pointing a DPF trajectory that more closely fits the dwellings being analysed.

The calculations and results obtained from the impacts of climate change indicate that future weather will reduce the space heating of such dwellings, particularly as external temperatures increase and spread widely between spring, summer and autumn seasons. This results in lower energy use and CO_2 emissions associated with space heating, partially displaced over as cooling energy. Such use of cooling systems in most situations uses electrical energy which at first may have a large CO_2 emissions intensity (large factor kWh/kgCO_2) but as predictions of a decarbonised electrical grid this is expected to reduce making electrical fuel powered systems less environmentally harmful, however at a cost with an increased £/kWh used.

6.4. Discussion

6.4.1. Mechanisms of dilapidation of the envelope

The intensity of envelope dilapidation predicted in these dwellings can be difficult to accurately define and describe, hence the implementation of different levels of dwelling performance factors (10%, 50% 100%). The definition of these intensities requires further analysis; however, it is a good representation of three levels in which dilapidation can happen. A low dilapidation (10% DPF) is a slow and steady account for the envelope degrading and reacting to change in its capacity to thermally react to changing weather patterns. A 50% DPF accelerates this rate of dilapidation with a moderate effect. A worse case scenario would be experienced if the dwellings were subject to 100% DPF where a large detrimental cause for envelope degradation was experienced. One of the detrimental effects causing increase in ventilation heat loss is the degradation of the air tightness of envelopes after occupation. A study by Doebber and Ellis (2005) concluded that degradation of airtightness can be more effective to heat loss than insulation continuity or thermal mass. Evidence from the re-test of dwellings by the NHBC Foundation (2011) indicated that loss of airtightness in post construction can be due to structure settlement and gaps produced by envelope movement. The work by Asiz et al. (2008) showed that high energy loss in the form of infiltration was experienced mostly at clear joints between structures and adjacent shear wall panels. Further evidence of this came from work by Geissler (1996) who after conducting many air leakage tests after 15 years post construction found that only 5% of timber frame dwellings presented adequate levels of air tightness and with some to be four times higher than the design levels. Furthermore, it has been shown damaged air tight membranes of new dwellings after DIY and uncontrolled use of trades in work done in bathrooms and kitchens (Molin et al., 2011). Airtightness degradation was also evidenced by Reiss and Erhorn (2003) in a study of 31 dwellings airtightness where results of 20 of them presented issues of degradation with 9 of these presenting more than 50% air leakage. Similar evidence was obtained in a study by Love et al. (2017) where failure to remediate air leakage can affect the energy demand of the buildings and present thermal discomfort.

The above evidence shows that the dilapidation of the envelope, considering air tightness as a dominant factor, as explained in Chapter 5 of this research, has a detrimental effect over longer periods of occupation. Reasons for this decrease of the air tightness can be attributed to problems with seals detaching when exposed to moisture loads and continued solar radiation. Tapes sealing vapour control layers that create an airtight layer in modern new build dwellings can also suffer from delamination which creates uncontrolled infiltration often obscured from any survey unless exposed during large envelope upgrades. A cause of air tightness increase may also come with the increased wetting of renders and certain external boards creating cracks, crevices and fissures which in combination with the above delamination of layers can be detrimental to the performance.

Finally, reduction in settlement and movement in timber panel dwellings can be a cause for apertures in structure creating uncontrolled crevices into the dwelling, thus increasing air infiltration. Reducing the impact of this can be done by on-site construction supervision ensuring that concrete ground floors are level to avoid the use of packers and adjustment of wall panels positioned into place during erection.

6.4.2. Longitudinal measurements of HVAC performance

The measurement of the efficiency of building services has not been the focus of this study. As explained in chapter 3, in order to calculate the heat loss coefficient of dwellings the efficiency of ventilation and heating systems is required, despite this these were considered as stagnant, but it is well know that systems require planned maintenance schedules to maintain efficiency and avoid higher energy demand. Over time these systems will contribute equally as the envelope dilapidation and be integral to the dwelling performance factor calculation.

With the eminent move to electrical heating due to the decarbonisation of the electrical grid in the UK and with the slow-moving decarbonisation of the heating grid, certain other problems arise, particularly if dwellings are experiencing envelope dilapidation and impacts from climate change. Electric heating as a solution to reducing the dwellings large environmental impact can be considered a reasonable solution and retrofit option. However, such devices in the form of cheap heat pumps, can create other problems to households increasing energy demand through slow technological occupant adaptability and the increased fuel cost per unit consumed. If such technology is considered as a retrofit solution to lower the environmental impact, there needs to be bridge between occupant operation knowledge and heating schedules particularly as heat pump technology is more efficient over longer periods of operation and not as an instant heating source at impromptu uses, as gas central heating is often operated. For this to efficiently operate during long periods, there needs to be an efficient envelope that can maintain heated periods with minimal heat loss. If dilapidation is acting on these dwellings and little attention to maintenance or scheduled envelope retrofit remediation action is performed, the efficient and low carbon implementation of electric heating will not be the expected fail-safe solution.

In this study, the measurement of the efficiency and operation of all HVAC technology and building services equipment would contribute to strengthen the impact of the dwelling performance factors (DPF) proposed and to consider a fully as-built longitudinal analysis of dilapidation. A fully measured dwelling including all building envelope components and HVAC systems should performed.

6.4.3. Service life, replacement, maintenance of the building envelope

A mechanism of calculating retrospectively the service life of the dwellings using the DPF and dilapidation methodology, climate change, and gap in performance would propose a service life gap estimation against the commonly used 60-year service life of buildings but most importantly refine the estimated time stamp for replacement and retrofit. A life cycle analysis (LCA) would enhance the understanding of the actual service life of as-built occupied dwellings and the associated environmental impacts over time. However, how much maintenance schedules and its impact on envelope dilapidation is still to be analysed, with the expectation that it will ease the rate of dilapidation steering it back towards the often post gap in performance baseline or dictated standards at the time of designing the dwellings. The replacement of better performing systems and envelope components not functioning properly such as windows and doors or sealing up gaps, crevices and delaminated membranes would ease dilapidation rate and follow a minimal DPF percentage. This in turn would increase the service life of the dwelling and reduce energy demand and CO_2 emission impact.

Climate change would remain the determining factor to the decrease of service life below the expected 60 years. As it is difficult to accurately predict its intensity and effect on the climate these dwellings are susceptible to, the only solution is to adapt to the changing weather and to mitigate any eminent changes such as increased wetting of the envelope, longer hours of solar radiation and continued maintenance schedules. Designing resilient dwellings to resist climate change should be at the forefront of any building landlords as well as public buildings owned by local authorities.

This study has focused on a snapshot of the dwelling's life cycle through four years of measured performance. It is difficult to predict accurately the performance beyond a longitudinal timeline, particularly as it is difficult to predict the exact intensity of the effects simulated and extrapolated. Despite this, the study does take the four years as an early occupation period in which most of the large displacements are expected to happen, such as movement and settlement of the structure, impacting on air tightness. Also, the early adaptation of both landlords and tenants which also impact the efficient operation of the services and heating schedules. Of importance will be the real trajectory climate change and dilapidation will take, hence the assumed levels of intensity modelled as options and impacts. The results show that climate change on its own has a small impact to these dwellings over the next 60 years of predictive performance, even with the consideration of cooling and its environmental implications. However, it is dilapidation that could take a different posture; slow impact with a 10% DPF, where dilapidation will be minimal but consistent or where maintenance schedules are considered, and performance is maintained within the landlords capability. A medium dilapidation of 50% DPF will certainly increase the environmental impact, but it may be that dilapidation accelerates as a result of poor maintenance or major implications such as unattended water ingress wetting insulation, or larger unsealed apertures from DIY or poor workmanship service penetrations. A much larger impact, and one considered as worst-case-scenario would be the 100% DPF which yearly will increase dilapidation at an alarming rate, caused by envelope performance neglect and minimal repair or maintenance on the dwelling. What would be a determinant factor would be to understand where the predicted 60-year life cycle period is breached and at what point this would be considered a failed life cycle prediction.

6.4.4. Use of this study by industry professionals

Industry professionals can learn and adopt some of the methods and outcomes of this study during two critical stages; at the design stages and after occupation. As explained, there are two aspects that impact the environmental performance; the dwelling envelope dilapidation and the probabilistic effect of climate change on the demand of energy and increase CO_2 emissions.

Adopting a slower rate of envelope dilapidation must come in the shape of better design choices by architects and developers considering the effects of dilapidation to deliver a resilient envelope solution and one that can resist the passage of time better than conventional approaches. Architects are at the forefront and decision-making process to use this type of study to prepare a design that can be specified with more robust materials and fixing mechanisms, for example quality of seals, tapes between membranes. Additionally, industry professionals can use this study to plan better the location and selection of developments that can be less exposed to driving rain and potential flooding and manage better the solar exposure to harness energy considering high quality exterior cladding and render products. Also, within the realm of architects, is quality control during construction stages and before handover. There needs to be better supervision of work, particularly the positioning and fixing of exposed components (exterior) such as insulation products, membranes, tanking, windows and doors, as these are the weak points where envelope performance is at the risk of dilapidation.

Another design related aspect is designing for retrofit and thermal improvements that may be required in the future. These are design choices considering probable adaptation and improved thermal response required if the original envelope is not as expected or where remediation can be conducted easier particularly in areas that are prone to failure and typical replacement. Examples of this are roof eaves and soffit space for external insulation. Many dwellings are designed with reduced eaves space where the roof overhangs around the perimeter of the building are minimal in depth. Designing the eaves with a larger overhand gives the opportunity to apply external insulation when required without complicated detailing using flashings or changing roof structure (Bean et al., 2018; Cubasch et al., 2001; Wang et al., 2010). Also, for a much quicker and less destructive approach, access to services should be suitably placed with enough space for movement and when replacement or maintenance takes place, these can be worked on easily. For example, introducing ducting that can easily adapt to other devices and uses anticipating future interventions and replacement of more efficient systems.

After occupation this study provides an insight into areas where dilapidation and reduced envelope performance is occurring therefore can be easily remediated during planned maintenance schedules and other replacement works. A weak point is the quality of openings such as windows and doors where seals tend to degrade and cause small openings between frames, causing a reduction in air tightness. Schedule maintenance and the importance of persistent supervision of work performed by third party trades or DIY should be controlled, particularly by RSL landlords. One aspect that is often ignored is attention to tenant malfunction calls (services and envelope) which often if not dealt with can cause a larger impact over time. It was observed through some of the tenant engagement sessions and questionnaires issued, that the RSL ignored or disregarded many of the tenant dwelling issues such as MVHR filter maintenance and replacement, windows since construction phase not positioned accurately creating gas and cervices or traces of external render board moisture stains/ apertures as indicated in Chapter 5.

Considering the role of climate change, whatever the intensity and impact it will have over the next 60 years, new and existing dwellings need to mitigate, adapt and be more resilient. Industry professionals need to use this study as a prompt to better dwelling design to avoid the effect of climate change both to stop the accelerated probability of dilapidation or increase electrical energy demand for cooling. Dwellings need to resist the longer periods of solar exposure and increased levels of precipitation, let alone the higher probability of flooding and other associated problems. The key is to understand that climate change effects will have a different impact on different households and designs, but prevention through conscientious design and adaptation by retrofitting existing dwellings (Harkin et al., 2019; Historic Environment Scotland, 2016; Leissner et al., 2015).

Lastly, better design and construction is justifiable considering the effects of dilapidation and climate change. This will not only reduce the risk of occupant's discomfort, future increased spending on adaptation and increased energy demand, let alone higher environmental impact; but also contribute bridging the gap between as-designed and as-built which has also a role to play in the focus around sustainability and meeting CO_2 emission targets for net zero buildings

(Committee on Climate Change, 2019, Gambhir et al., 2019; The Scottish Government, 2018; The Scottish Parliament, 2018).

6.5. Recommended improvements and identified limitations

The constraints and limitations of the study undertaken are outlined below.

6.5.1. Scope and reliability of heat meters and in-house-display units

The monitoring of energy demand relied on the data logged by installed heat meters attached to air source heat pumps and other technology. In-house-display units (IHD) showing real time delivered power consumption of natural gas and electricity were used throughout the monitoring period for recording delivered energy. Each dwelling had a different configuration recording consumption and generation according to the heating and ventilation technology employed.

Limitations were identified in the lack of sub-metering; with the installed logging equipment making it hard to differentiate between specific energy uses in each dwelling. Having a fully sub-metered set of dwellings, particularly the three dwellings analysed in detail, would have increased the accuracy and understanding of the consumption.

Issues with the heat meters installed on the air source heat pumps and solar water heaters were also identified in relation to the commissioning and calibration which was out with the scope of this research. Also identified, were the uncontrolled tampering of heat meters by residents in several of the selected dwellings, causing the heat meter to stop or wrongly record heat flows and its associated energy consumption. Two dwellings with such problems were taken out from the research and disregarded from the results and analysis. Other dwellings did not present this problem as consumption was recorded by appropriately commissioned utility metering-compliant gas and electrical meters, or by IHD’s in each properly.

Sub-metring, although intended at the start of the research, was deemed out of scope for its complexity, the permissions required from occupiers and RSL and the cost associated with purchasing and installing the equipment.

6.5.2. Occupant access, resident turnover and dwelling use awareness

Data acquisition from testing relies on continuous dwelling access where occupants can accept equipment being deployed in their dwelling during repeated visits from the research team at set periods of monitoring. This longitudinal study involved numerous visits to the dwellings for testing and energy meter readings. Most of the recruited residents were very amenable and happy to take part in the study. It was, however, noted that after the third and fourth year of the studies, residents were becoming anxious and repeatedly asked for the testing to cease. Various incentives were used to retain an amicable relationship and enable access to the deployed meters and to conduct any remaining tests. Luckily the resident turnover in the selected sample was minimal with only two of the families moving out of their dwellings replaced by two new ones during year four of the study.

Retaining access into the dwellings and having a low turnover of occupiers are important elements of a longitudinal study of this nature, particularly in domestic buildings where post occupancy and building performance evaluations are conducted. Occupant turnover can be high in many RSL stock, particularly social housing that has many tenures and vulnerable occupants, and hence why studies such as these are rarely conducted.

It was also identified that often residents are alienated from the technology installed, as information on its adequate operation and control is often written for a more technologically knowledgeable audience, or for installers and maintenance contractors. The performance of dwellings cannot be entirely blamed on occupant behaviour, the more likely culprit is often the inefficiency of systems and the inadequate commissioning of them. This misguidance and gap in knowledge resulted in increased occupant complaints, maintenance and replacement calls and early occupation snagging which overloads RSL staff.

6.5.3. Probabilistic future weather climate change files

In this research the use of future weather projections played an important role in the longitudinal approach and the established impacts of a changing climate. The climate change projections proposed by the UKCP09 probabilistic scenarios and carbon emission intensities over set timelines were used to understand how the selected dwellings could perform, considering heating and cooling energy demands and the corresponding operational CO_2 emissions. Although the use of probabilistic weather files into dynamic building software has been prolifically researched, limitations are found in the sourcing of exact location weather files. The adopted methodology used site-specific weather station data to generate actual weather files recorded during the monitored period of study. This allowed a full calibration of the dwelling models and a closer estimation to actual energy demand for space heating. Future projections considering probabilistic climate change shifts in weather applied the nearest baseline weather files to the site, however, the weather station weather file was not able to be converted into future weather files. Obtaining site specific future weather through the Department for Environment, Food & Rural Affairs (Defra) Weather Generator tool was laborious tasks and beyond the scope of the research, requiring more time, computing power and unreliable if generated wrongly.

At the time of writing this thesis, the UK Government reviewed the methodology for probabilistic future weather projections and created new guidelines to generate them. The UKCP18 proposed methodology seeks to provide robustness of UK climate projections (Herrera et al., 2017). The methodology uses new distributions of possible future changes in weather variables, new spatially coherent projections of climate and downscaled simulations of future climate. It is also likely that the spatial resolution will be lower than 5 km (Fung and Gawith, 2018). It is hoped that the process of obtaining building simulation files using the UKCP18 projections can be available for the building industry, particularly for a broader set of locations.

6.6. Opportunities for future research

The work described in this thesis has provided a platform for future research to refine the integration between longitudinal building envelope performance testing, climate change and estimated account of environmental tipping points based on envelope dilapidation and Government CO_2 emission targets.

Through undertaking this research, areas for further research, beyond the scope and time availability were thus identified:

- **Could the future predictions of the dwelling performance be used by others?**

The predictions from this study can help the RSL to plan their maintenance schedules and act on the potential risks that climate change can impose. The study can benefit from the integration of services performance dilapidation which can be included to the dilapidation predictions and at design stage compare service life calculation against dilapidation tipping points. The timelines and tipping points provide and anticipate a cause for action in the improvement of the dwelling's performance considering the gap in performance, climate change probabilistic future weather patterns and dilapidation of the envelope therefore cover important aspects of the continuing use of buildings. It provides architects developers and landlords an opportunity to plan and design for a resilient domestic portfolio of buildings (van den Brom et al., 2018).

- **The roles of thermal mass in further simulations**

Thermal mass plays an important factor in the thermal performance of dwellings as it can balance temperatures and contribute to internal thermal comfort (Hacker et al., 2008; Holmes and Hacker, 2007; Latif et al., 2016; Paolini et al., 2017). Additionally, it harnesses heat otherwise lost through the building envelope saving energy in heating. However, it is important to plan adequately the placement of high inertia materials to avoid overheating, particularly with the risks of climate change and increased dry-bulb temperatures. In the calculations where degree day data are needed, the dwelling thermal inertia and absorption coefficient is applied, implying that it is an important element for the calculation of energy demand. The study performed used dynamic thermal modelling that considers the thermal inertia of materials and components, therefor is already applied in the calculations and results; however, further study could analyse the impact thermal mas has on the calculations in order to apply design scenarios to minimise the impact of climate change or envelope dilapidation within the proposed time stamps and tipping points (Morgan et al., 2017).

- **Modelling of other systems with DPF and CC**

The focus of this study has been the impact of energy demand for heating and cooling with the assumptions made over envelope dilapidation (DPF) and climate change. However, beyond this study has been the considerations and impact of other systems and technology used such as ventilation systems with heat recovery (MVHR) which contribute to internal temperatures and can lower energy demand for heating. Finding a correlation between poor indoor air quality due to diminishing efficiency of ventilation systems and the longitudinal lowering or increasing levels of air permeability levels of dwellings would certainly enhance this study considering the role of climate change and envelope dilapidation. The efficiency of installed renewable systems was also beyond the scope of this study; however, the link between electricity energy demand and renewable energy performance considering climate change and the probabilistic increasing levels of solar radiation would enhance and prolong the study (Bel and Joseph, 2018; Daggash and MacDowell, 2019; Pfenninger and Keirstead, 2015).

- **Validating the tipping points and estimated performance values**

The four-year testing provided vital building envelope performance linked with energy demand that was used to calibrate building models and estimate longitudinal environmental impact and potential tipping-points. However, further testing beyond the early occupation periods, and beyond the four years is required to understand the dilapidation of the building envelope and refine the assumptions.

- **Effects of market value on the homes due to poor performance**

This research showed that expenditure for fuel represents a large proportion of spend for households. Not analysed here is how this compares against the cost of rent for such dwellings belonging to the RSL's mid-market rent (MMR) category which have a higher monthly cost than social rented properties but are still lower than private sector rents in the area (Bros-Williamson et al., 2014). The rent for one of the 2 bed dwellings is approximately £420 per month nearly £5,000 per/yr.

This study would benefit by performing a full longitudinal economic analysis. It could consider projections using outcomes of the research, retail fuel prices over the timelines, alongside inflation and occupant's income trends, to perform an affordability study that predicts tipping points and the relationship between dilapidation of the building envelope against capital or rental value.

Appendices

Appendix 1a

Appendix 1a: Housing Innovation Showcase (HIS) selected dwellings codes

The Housing Innovation Showcase (HIS), developed by Kingdom Housing Association (KHA) comprised of twenty-seven dwellings of varying size and form, using ten different construction techniques; twelve flats with communal gardens, three terraced houses, eight semi-detached and four bungalows, all with private gardens. This research analysed 13 of the 27 dwellings in the development.

Location of analysed dwellings in the development

Figure 1a-1: Site plan of the HIS development. Dash lines indicate selected dwellings for tests

Dwelling Code	Type of dwelling	Method of Const.
F.1.4	2 bedroom Flat	Volumetric - Offsite
TFA	**LZCT**	**Construction system**
77.62 m^2	-	Steel Frame
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		Powerwall Ltd

Dwelling Code	Type of dwelling	Method of Const.
F.2.5	2 bedroom Flat	Offsite panels
TFA	**LZCT**	**Construction system**
78.14 m^2	ASHP	Timber closed panel
Building Standard - Compliance		**Manufacturer/ system**
2010 Building regulations SAP2009		ScotFrame Val-U-Therm

Dwelling Code	Type of dwelling	Method of Const.
F.3.12	2 bedroom Flat	Offsite panels
TFA	**LZCT**	**Construction system**
77.9 m^2	mCHP boiler	Timber closed panel
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		Stewart Milne - Sigma II panel

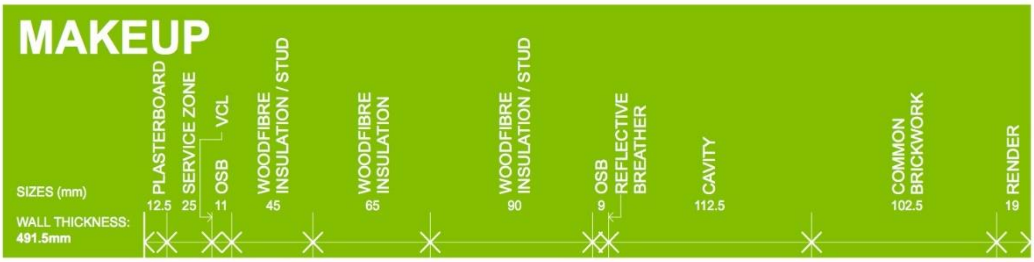
Dwelling Code	Type of dwelling	Method of Const.
B.4.14	Bungalow/ cottage	Onsite
TFA	**LZCT**	**Construction system**
78.67 m^2	Solar Thermal	Insulated clay block
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		Campion/ Porotherm

Dwelling Code	Type of dwelling	Method of Const.
B.5.16	Bungalow/ cottage	Offsite
TFA	**LZCT**	**Construction system**
78.67 m^2	1kWp Solar PV	SIP's
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		CUBE RE:Treat

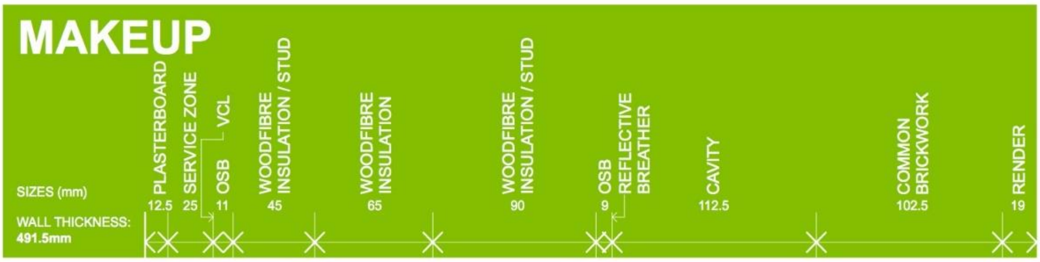
Dwelling Code	Type of dwelling	Method of Const.
SD.6.17	Semi-detached	Offsite panels
TFA	**LZCT**	**Construction system**
96.92 m^2	-	Timber closed panel
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		ScotFrame Val-U-Therm

Dwelling Code	Type of dwelling	Method of Const.
SD.6.18	Semi-detached	Offsite panels
TFA	**LZCT**	**Construction system**
93.96 m^2	-	Timber closed panel
Building Standard		**Manufacturer**
2010 Building regulations Passivhaus - PHPP		ScotFrame Val-U-Therm

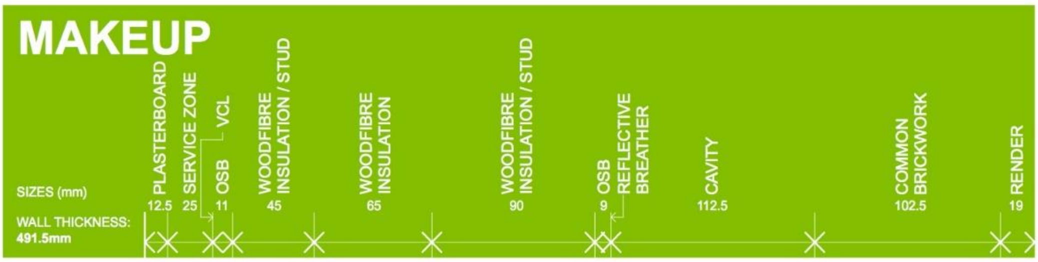
Dwelling Code	Type of dwelling	Method of Const.
T.7.19	Terraced	Offsite panels
TFA	**LZCT**	**Construction system**
83.2 m^2	Solar PV slates	Timber closed panel
Building Standard - Compliance		**Manufacturer/ system**
2010 Building regulations Section 7 (Gold)		e.CORE pods, CCG panels



Dwelling Code	Type of dwelling	Method of Const.
T.7.20	Terraced	Offsite panels
TFA	**LZCT**	**Construction system**
83.2 m^2	Solar PV slates	Timber closed panel
Building Standard - Compliance		**Manufacturer/ system**
2010 Building regulations Section 7 (Silver)		e.CORE pods, CCG panels



Dwelling Code	Type of dwelling	Method of Const.
T.7.21	Terraced	Offsite panels
TFA	**LZCT**	**Construction system**
83.2 m^2	-	Timber closed panel
Building Standard - Compliance		**Manufacturer/ system**
2010 Building regulations Section 7 (Bronze)		e.CORE pods, CCG panels



Dwelling Code	Type of dwelling	Method of Const.
SD.8.23	Semi-detached	Offsite
TFA	**LZCT**	**Construction system**
95.76 m^2	Solar PV	Timber closed panel
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		Lomond Homes, Breathing wall

Dwelling Code	Type of dwelling	Method of Const.
SD.9.24	Semi-detached	Offsite panels
TFA	**LZCT**	**Construction system**
95.8 m^2	Hybrid Solar PV	Timber closed panel
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		CCG IQ system

Dwelling Code	Type of dwelling	Method of Const.
SD.10.33	Semi-detached	Onsite
TFA	**LZCT**	**Construction system**
83.42 m^2	-	Concrete wall form
Building Standard - Compliance		**Manufacturer**
2010 Building regulations SAP2009		Becowall/ Bobin Dev.

Appendix 2a

Appendix 2a: Cooling baseline temperature step-by-step calculation

Step 1: calculation of heat carrying capacity of air, and the building time constant, τ using Equation 1a.

$$Q_{air} = mC_p \quad \text{Equation 1a}$$

Where:

Q_{air}: heat carrying capacity of air (kW/K)

m: Mass flow rate of air (kg/s)

C_p: Specific heat of air is set at, 1.02 kJ/kg/K

Step 2: Heat imparted to the air by the fan is considered using Equation 2a.

$$Q_{fan} = \frac{V\Delta P}{mC_p\,\eta_{fan}} \quad \text{Equation 2a}$$

Where:

Q_{fan}: Temperature raise imparted to the air by the fan (K)

V: Volume flow rate of air (m^3/s)

ΔP: pressure rise across the fan (kPa)

η_{fan}: fan efficiency (% fraction)

mC_p: heat carrying capacity of air (kW/K)

Step 3: Calculation of temperature rise due to sensible gains to the space (solar, people, lights and machines).

$$Q_G = \frac{Q_S}{mC_p} \quad \text{Equation 3a}$$

Where:

Q_G: Temperature rise due to sensible gains (K)

Q_S: Monthly average sensible gains (kW)

mC_p: heat carrying capacity of air (kW/K)

Step 4: Temperature rise due to daytime fabric gain due to thermal mass using Equation 4a:

$$Q_{envelope} = \frac{U\prime}{mC_p}\,(\theta'_{ao} - \theta_{ai}) \qquad \text{Equation 4a}$$

Where:

$Q_{envelope}$: temperature rise due to fabric gain (K)

U': heat loss coefficient (kW/K)

mC_p: heat carrying capacity of air (kW/K)

$\theta' ao$: Monthly mean outside temperature (day) (˚C)

θ_{ai}: Indoor air temperature set point (˚C)

Step 5; Calculation of temperature rise due to the notional latent component using Equation 5a:

$$\Delta\theta'_L = 2400\ x\ \frac{g_O - g_S}{1 - e^{-k(g_O - g_S)}} \qquad \text{Equation 5a}$$

Where:

$\Delta\theta'_L$: Notional latent component (K)

go: Monthly mean outside moisture (kg/kg)

gs: Monthly Supply moisture content (kg/kg)

k: Constant factor for moisture (0.71)

Step 6: Calculation considering the mitigation due to overnight cooling using Equation 6a:

$$\frac{Q_c}{mC_p} = -\ \frac{C}{mC_p\ x\ 24\ x\ 3600}\ x\ e^{\frac{t_3 - t_1}{\tau}}\ \text{-}\left(\theta'_{sp} - \theta_{ao,night}\right) \qquad \text{Equation 6a}$$

Where:

$\frac{Q_c}{mC_p}$: Average rate of gain that will be absorbed by the structure overheating carrying capacity of air (K)

C: Building thermal capacity (kJ/K)

mC_p: heat carrying capacity of air (kW/K)

$(t_3 - t_1)$: Length of unoccupied period (hours)

τ : building time constant

Building time constant is calculated using Equation 7a:

$$\tau = \frac{C}{(3600\ x\ U')} \qquad \text{Equation 7a}$$

Where:

C: Fabric thermal capacity (kJ/K)

U': Heat loss coefficient (kW/K)

In order to get the final baseline for cooling, Equation 8a is used:

$$\theta_b = \theta_{ai} - Q_{fan} - Q_G - Q_{envelope} - (\Delta\theta'_L) + Q_{overheating} \qquad \text{Equation 8a}$$

Where:

θ_b: Base temperature (˚C)

θ_{ai}: Indoor air temperature set point (˚C)

Q_{fan}: Temperature raise imparted to the air by the fan (K)

Q_G: Temperature rise due to sensible gains (K)

$Q_{envelope}$: Temperature rise due to fabric gain (K)

$\Delta\theta'_L$: Notional latent component (K)

$(\frac{Q_c}{mC_p})\ Q_{overheating}$: Average rate of gain that will be absorbed by the structure overheating carrying capacity of air (K).

Appendix 3a

Appendix 3a: Air tightness apparatus and calculation

- **Apparatus**

UKAS calibrated test equipment was used for to obtain air permeability results. The equipment used for the field tests is summarised in Table 3a-1 below.

Table 3a-1: Field tests equipment

Test equipment	Make	Model	Calibration type	Accuracy	Resolution
Blower Door Fan	Energy Conservation	Minneapolis – Model 3	UKAS (Yearly)	-	-
Micro-manometer	Energy Conservation	DG-700	UKAS (Yearly)	± 0.15 Pa	0.1 Pa
Thermometer	Testo	110	UKAS (Yearly)	± 1°C	0.1°C
Barometer	Druck	DPI 705	UKAS (Yearly)	± 0.02%	0.01 mbar
Anemometer	Skywatch	Xplorer 2	-	<20m/s ±3%	0.1/ unit

The equipment is set up in such a way that the air-moving equipment (blower door fan) is freely attached to the door with a tightly fitted door frame and canvas. The pressure and flow measuring gauge (Micro-manometer) and the blower door are connected to a power source (110v) and by clear flexible tubing. The tubing also connects the manometer to the outside of the dwelling and the lowest part of the inside of the dwelling. The blower door fan has various interchangeable ring sizes (A to C) that will limit the amount of air passing through the dwelling to obtain the required building and fan pressure readings. Prior and after testing, meteorological conditions were taken with the above equipment. Figure 3a-1 below shows the equipment and an example set-up.

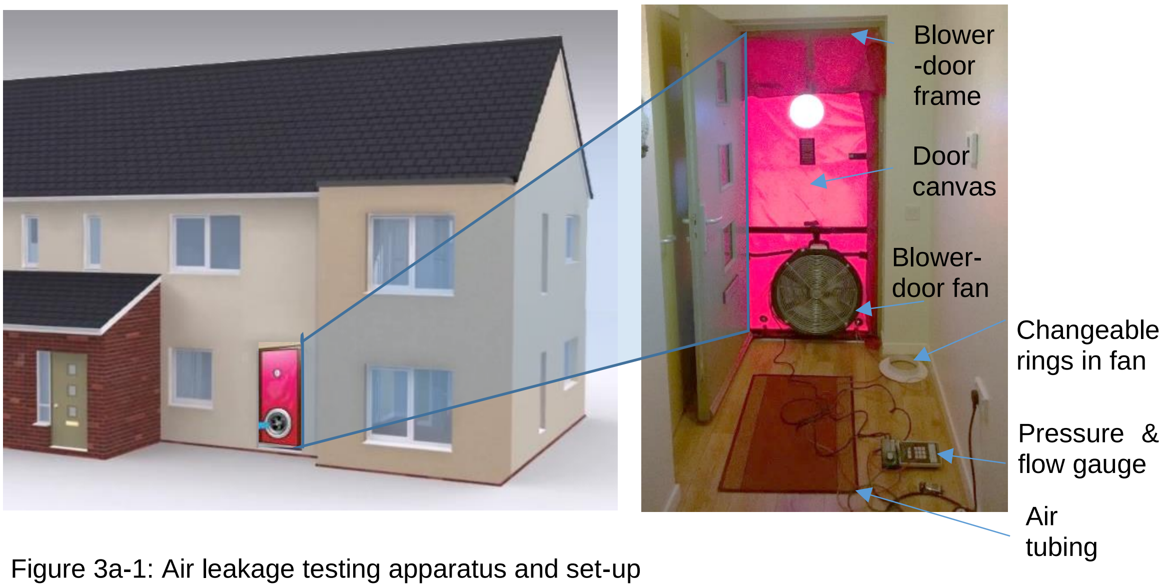


Figure 3a-1: Air leakage testing apparatus and set-up

- **Expression of results and data analysis**

The preferred method of expressing ventilation heat loss through the dwellings envelope was air permeability as used throughout the UK (ATTMA, 2010). This method considers the volume flow of air passing through each square metre of building envelope. Equation 9a expresses this calculation by dividing the air flow rate (*Q50*) across the envelope at a pressure difference of 50 Pa and dividing it by the building envelope area A_E (m^2), expressed as m^3/hr.m^2.

$$q50 = \frac{Q50}{AE} \qquad \text{Equation 9a}$$

In this research, the *In-situ* tests applied the power law equation and least square technique developed by ATTMA (2010) and BS EN (2001). It establishes the relationship between the fan flow (Q) and the building pressure step-increases to 50 Pa (Δ_p) as stated in Equation 10a below.

$$Q = C(\Delta p)^n \qquad \text{Equation 10a}$$

Where Q is the leakage air volume flow rate in (m^3/hr), C is the flow coefficient that relates to the aperture size and Δ_p gives the pressure difference across the envelope, *n* are the flow exponent characterising the flow regime (Sinnott and Dyer, 2012).

Appendix 3b

Appendix 3b: In-situ U-value equipment used, specifications, calculations and error analysis

- **Apparatus**

Calibrated equipment was used throughout the tests during all the years of monitoring. Table 3b-1 below shows information on the equipment used and its specifications.

During the fieldwork the installed monitoring equipment obtained datasets that later used in calculations set by the ISO and British Standard 9869-1 (BSI, 2014), adopted as the preferred methodology and calculation process in this research.

Table 3b-1: In-situ U-value list of equipment used in field monitoring.

Test equipment	Make	Model	Intervals & Setting	Accuracy	Resolution
Data logger 24 bit	Grant Squirrel	SQ2020 & SQ2010	5 minute intervals	± 0.05% & 0.1%	-
Heat flux plates	Hukseflux	HFP01	Voltage differential	+3 /-3%	60 x 10-6 V/(W/m)2
Thermo-couples	RS Components	Chromel – alumel - 41 µV/°C	K-type Single ended	± 1.5°C	0.5°C
Temperature & Humidity logger	Gemini	Tinytag Ultra TGU-4017 (indoor & outdoor)	5 minute intervals	± 0.5 to 0.4°C, ±3%	0.1°C,0.5%

- **Expression of results and data analysis**

Throughout the field tests, the heat flux plates record a voltage differential, later calibrated to provide the heat flow. Internal (T_i) and external (T_e) ambient temperatures of the analysed element and surrounding air are taken. For the purposes of this research, the average method was used in accordance to ISO 9869 (BSI, 2014, p8). Equation 11a results in a U-value which derives from the mean (time averaged) heat flow in Watts per meter squared (W/m^2) divided by the mean difference between the inside and outside temperatures (Li et al., 2015).

$$\boldsymbol{U} = \frac{\sum_{i=1}^{n} \boldsymbol{Q}_{in.i}}{\sum_{i=1}^{n}(\boldsymbol{T}_{in.i} - \boldsymbol{T}_{ext.i})} \quad \text{Equation 11a}$$

Baker, (2011) argues that there are drawbacks to using internal and external air temperatures and recommends using surface temperatures in conjunction with external (r_{ext}=0.04 m^{2}k/W) and internal (r_{int}=0.13m^{2}k/W) surface resistances as shown in Equation 12a.

$$U_i = \frac{1}{\frac{\sum_0^{i=t} T_{si} - T_{se}}{\sum_0^{i=t} Q_i} + r_{int} + r_{ext}} \quad \text{Equation 12a}$$

In some cases the external surface temperature (T_{se}) is not possible to obtain, therefore it is substituted by the external ambient temperature (T_{ext}) and removing r_{ext} as shown in Equation 13a.

$$U_i = \frac{1}{\frac{\sum_0^{i=t} T_{si} - T_{ext}}{\sum_0^{i=t} Q_i} + r_{int}} \quad \text{Equation 13a}$$

In order to account for the heat flux sensor’s thermal resistance, a correction factor is applied to the calculation of <6.25x10^3 m^{2}k/W.

The above calculation process was performed in a simple spread sheet where the monitored data at 5-minute intervals was placed alongside the recorded heat flux and surface and ambient temperatures. Likewise, the application of the HFM’s calibration factor and error analysis. Accuracy, uncertainty and error analysis

The measurement of in-situ U-values, although a simple test, is a dynamic method subject to meteorological and practical issues that will contribute to significant errors and uncertainties, Ficco et al., (2015) explains that it includes:

- Un-homogeneity of materials

- Uncertain geometric gaps
- Assumptions in the one-dimensional heat flow
- Fluctuations of temperature and moisture
- Measurement uncertainties
- Influence of climate

The ISO 9869 (BSI, 2014) summarises expected values for uncertainty of the measurements. Table 3b-2 below quotes these estimations which can be applied as a quadrature sum and arithmetic sum.

Table 3b-2: Accuracy of the tests, conditions and equipment

Description	**Uncertainty value**
Calibration of the HFM and temperature sensors	5%
Variations of thermal contact between sensors – reduced if more than 1 HFP's are used	5%
Operational error of the HFP caused by isotherms around it,	2 to 3%
Variations over time of temperatures and heat flow. Can be reduced if tests are done over long periods.	±10%
Ambient air and surface temperature variations	5%

Quadrature sum:

$$\left(\sqrt{5^2} + 5^2 + 3^2 + 10^2 + 5^2\right)\% = 14\% \qquad \text{Equation 14a}$$

To account for an error analysis, it is derived from individual measurement of uncertainties and the standard deviation (s.d) of the average value calculation (Baker, 2011). The U-value calculation is repeated with each measured error parameter applied. The principal errors calculated are:

- Heat flux error: U_{errQ}
- Internal temperatures: U_{err_Ti}
- External temperatures: U_{err_Te}
- Internal surface temperatures: U_{err_Tsi}
- External surface temperatures: U_{err_Tse}

For example error on internal surface temperature (δT_{si}) is applied to calculate U_{err_Tsi}, as shown in Equation 15b.

$$Q_{err\_Tsi} = \frac{1}{\sum_{0}^{i=t}\frac{T_{si}+\delta T_{si}-T_{se}}{Q_i}+r_{int}+r_{ext}}$$ Equation 15a

Once all errors are applied accordingly, an overall uncertainty on the U-value is estimated, δU. Equation 16a, applies the root mean square value (RMS) of the deviations of each error case from the baseline U-value.

$$\delta U = \sqrt{[\left(U - U_{errQ}\right)^2 + (U - U_{errTi})^2 + (U - U_{errTe})^2 + \ (s.d.)^2\ ]}$$ Equation 16a

Appendix 3c

Appendix 3c: Weather station specifications

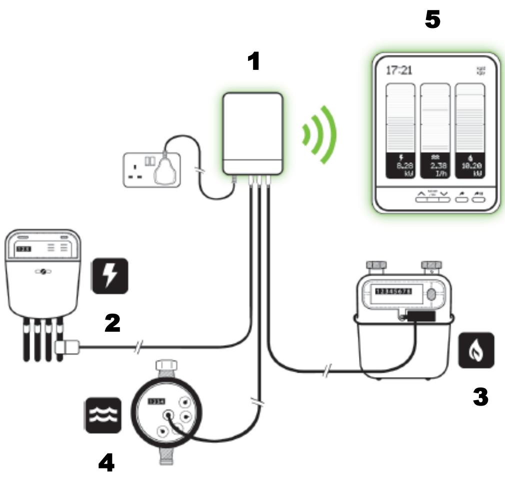
Table 3c-1: Weather station specifications

Sensor Name	Measurements	Make	Model	Accuracy
Temperature probe (in radiation shield)	Dry bulb temperature (°C)	Davis instruments	Vantage Pro2	±0.5°C typical
Barometric pressure	Atmospheric pressure (mbar)	Davis instruments	Vantage Pro2	±0.03 in Hg (1.0 mbar)
Humidity	Relative humidity (RH%)	Davis instruments	Vantage Pro2	±3%
Solar radiation	(W/m^2)	Davis instruments	Vantage Pro2 6450	±5%
Anemometer & Wind vane	Wind speed and direction (° from north and m/s)	Davis instruments	Vantage Pro2	Wind direction: ±3° Wind speed: ±2 mph (1m/s)

Appendix 3d

Appendix 3d: Specifications on the EWGECO IHD device

IHD devices such as the EWGECO are a multi utility display unit linked using a clamp transducer for electrical demand and a pulse block for natural gas meter, connected through a wireless Zigbee 2.4GHz communication (BEAMA, 2010). The data is displayed instantaneously “real time” as power demand (W) during hourly cumulative periods and the IHD stores the data in the internal memory, however some devices can connect to a wireless internet device storing and displaying their consumption in a web portal service called “My Ewgeco”. See Figure 3d-1 and 3d-2 below for the device breakdown.



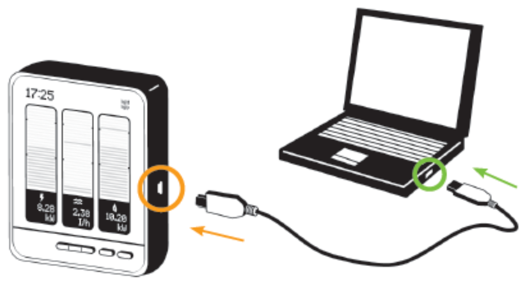


Figure 3d-1 (a): Connection diagrams for the IHD installed. [1] Transmitter. [2] CT clamp in live cable of electrical meter. [3] Pulse block in gas meter. [4] Pulse block in water and heat meters. [5] Traffic light display unit – 3 channels. Source: (Ewgeco 2011)

Figure 3d-2 (b): In-situ download of stored data via lap-top computer and cable into traffic light display device.

Appendix 3e

Appendix 3e: Hot water per shower as per Table V1

Table 3e-1: Hot water used for showers, Source: BRE (2014)

Shower type(s)	Hot water used per shower (litres)
None	0
Mixer (not combi)*	28.8
Mixer (not combi)* and electric	14.4
Mixer (combi)*	44.4
Mixer (combi)* and electric	22.2
Pumped	43.5
Pumped and electric	21.8
Electric	0

Shower type(s)	Hot water used per shower (litres)
Unknown	18.7

* Combi applies when the water is heated by a combi boiler.
Not combi applies in all other cases.
Unknown based on shower ownership of 27.2% mixer (not combi), 9.8% mixer (combi), 15.1% pumped, 47.9% electric

Appendix 3f

Appendix 3f: Table 1d from SAP2009 Hot water calculation

Table 3f-1: Temperature rise of hot water drawn off (ΔT_m, in K)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	annual
41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9	37.0

Appendix 3g

Appendix 3g: Sample survey given to occupants

Section 1: Household questions – people

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Please complete as much of the questionnaire as possible. If you have any issues relating to the questionnaire please inform the named researcher.

1.1 Starting with the lead householder, list the names of people who stay in the house. Include babies and children.

No.	Name of occupant	Age	Daily activity	Relation to the lead occupant
Example	*John* [First name is enough]	12	*Secondary school 5 days a week 09-15*	[make gender clear] i.e. *Partner (male)*
1[you]				
2				
3				
4				
5				
6				

1.2 For the people listed above, please indicate how long they spend **awake inside** the house. This excludes normal sleeping times. Please **tick** ✓only one option for each person in each section. **Tick** ✓ one set for weekday and one set for weekend day:

No.	Weekday				Weekend day (Saturday and Sunday)			
	Less than 4hrs	Between 4 & 8hrs	Between 8 & 12hrs	More than 12hrs	Less than 4hrs	Between 4 & 8hrs	Between 8 & 12hrs	More than 12hrs
example		✓						✓
1[you]								
2								
3								
4								
5								
6								

Section 2: Building performance – personal comfort

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In relation to your own experience, please **tick** ✓one number on each scale according to how you felt in the house during summer. **This is between June and August:**

2.1 **Temperature** (last summer): Please **tick** ✓

Uncomfortable	1	2	3	4	5	6	7	Comfortable
Too hot	1	2	3	4	5	6	7	Too cold
Stable	1	2	3	4	5	6	7	Fluctuates a lot during the day

2.2 **Air movement** (last summer): Please **tick** ✓

Still	1	2	3	4	5	6	7	Draughty
Dry	1	2	3	4	5	6	7	Humid (condensation)
Fresh	1	2	3	4	5	6	7	Stuff

How would you describe the level of lighting in your home? (last summer): Please **tick** ✓

2.3 **Natural light levels:**

Too little	1	2	3	4	5	6	7	Too much

2.4 **Artificial light levels**

Too little	1	2	3	4	5	6	7	Too much

2.5 **Overall lighting levels**

Unsatisfactory	1	2	3	4	5	6	7	Satisfactory

How would you describe the level of sound proofing in your home? (last summer): Please **tick** ✓

2.6 **Noise levels coming from outside** into your home?

Very quiet	1	2	3	4	5	6	7	Very noisy

2.7 **Noise levels coming from your nearest neighbour** into your home?

Very quiet	1	2	3	4	5	6	7	Very noisy

2.8 **Noise levels from your ventilation systems** at your home?

Very quiet	1	2	3	4	5	6	7	Very noisy

Section 3: Energy efficiency - you and your house

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3.1 The following are a list of common energy reducing habits; please **tick ✓**one for each habit that best describes how often you would do it. If you do not have the appliance listed in the habits, put a line through all 4 boxes. Please answer these in relation to your habits over the period of last summer.

	always	**some-times**	**rarely**	**never**
Close windows / put on more clothing before putting the heating on				
Keep time in the shower to a minimum				
Boil and cook using the minimum amount of water				
Hang clothes out to dry rather than use the tumble drier (weather permitting)				
Use the lowest temperature setting on the washing machine				
Switch off electrical appliances rather than stand-by				
Switch off the light(s) when leaving a room				
Draw curtains as sun goes down				
Open and close the trickle vents				

3.2 In your opinion, and relating to energy use in the home, how energy efficient is your <u>family</u>? Please **tick ✓**

Very energy inefficient	1	2	3	4	5	6	7	Very energy efficient

3.3 In your opinion, how energy efficient is your <u>house</u>? Please **tick ✓**

Very energy inefficient	1	2	3	4	5	6	7	Very energy efficient

Section 4: Energy use – appliances

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4.1 Please indicate which of the following appliances/ services you have in your home, and state the number of times you would use this item a day

Tick ✓ the items/ services you have		State the number of times this item is in use a day (complete if applicable)
Cooker oven (electric)		
Cooker oven (gas)		
Washing machine		
Tumble dryer		
Baths		
Shower		

4.2 Which of the following appliances do you have in your home? **Tick ✓** all that apply

Household appliances

Fridge and Freezer combined		Hob (electric)	
Fridge separate freezer		Hob (gas)	
Microwave		Toaster	
Vacuum cleaner		Other that you use often:	

4.3 Please indicate how many of the following equipment you have in your home. **Do this by stating the number of each you have in your home. Enter 0 if you do not have this item**

Entertainment – only state a number if the item has been used in the past 6 months

	How many of this item do you have		How many of this item do you have
LCD TV		Plasma TV	
CRT TV (not flat screen)		DVD player	
Set top box (e.g. SKY)		Radio	
Games console (used through the TV)		Laptop	
Tablet (e.g. ipad)		Smart phone	

Appendix 4a

Appendix 4a: Monthly data averages from weather station, 2016

Period		Month/ year	Temperature (°C)	Humidity (%RH)	Pressure (mBar)	Solar Radiation (W/m2)	Wind Direction (degrees)	Wind Speed (m/s)
Year 4 (2016) - Site Weather Station	1	Jan	4.71	77.81	994	25.81	143	2.52
	2	Feb	4.06	71.20	987	87.21	199	2.26
	3	Mar	6.43	63.42	1010	112.69	180	1.67
	4	Apr	7.31	61.40	1012	151.13	151	1.77
	5	May	11.66	55.65	1012	163.75	122	2.11
	6	Jun	13.62	50.77	1017	148.07	124	1.65
	7	Jul	15.64	53.58	1015	146.08	223	2.10
	8	Aug	15.74	79.74	1008	150.97	167	2.13
	9	Sep	14.96	83.57	1020	112.88	200	2.17
	10	Oct	10.50	85.10	1000	93.62	111	1.65
	11	Nov	5.13	91.90	999	83.23	200	1.34
	12	Dec	7.13	88.70	1006	29.11	204	2.37
		Mean	**9.74**	**81.44**	**1011**	**108.71**	**169**	**1.98**

Appendix 4b

Appendix 4b: Full water heating calculation example

Table 1a: Number of days in month n_m													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
m	1	2	3	4	5	6	7	8	9	10	11	12	
nm	31	28	31	30	31	30	31	31	30	31	30	31	
Table 1c. Monthly factors for hot water use													
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual	
1.1	1.06	1.02	0.98	0.94	0.9	0.9	0.94	0.98	1.02	1.06	1.1	1	
Table 1d Temperature rise of hot water drawn off (ΔT_m, in K)													
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual	
41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9	37	
# of occupants (N)=			2	Input	[42]								
Actual occupancy, N												2	(42)
Daily hot water requirement for:													
Baths (litres/da	Vd,bat	= Baths per day × 50.8										51.3	(42a)
							number of baths per day (shower also					0.45	
If the number of baths per day is unknown then:													
(no shower present, i.e. "None" selected in Table V1) (42a)= 0.35 ×(42)+0.50													
(shower also present)(42a)= 0.13 ×(42)+0.19													
Showers (litres/day)			Vd,sho	= Showers per day × hot water per shower from Table V1								34.4	(42b)
If showers per day is unknown then (42b) = 0.45 × (42)+0.65										=	1.55		
Other (litres/day)			Other (litres/day)									33.6	(42c)
a. Average daily water use (litres/day)							Vd,average=(42a)+(42b)+(42c)					119	(43)
b. Formula=		(25*N)+36											
$V_{d,\ average}$		**a.**	119.3	[43]	**b.**	86.00	[43]						
$V_{d,month=}$													
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual	
131.19	126.42	121.65	116.87	112.10	107.33	107.33	112.10	116.87	121.65	126.42	131.19		[44]
V=													
195.01	170.56	176.00	153.44	147.23	127.05	117.73	135.10	136.71	159.32	173.91	188.86	1881	[45]
								Distribution loss (0.15 times):					282.13699
												Total	**2163.0502**
								< 125L/per/day (-5%):					**2060.0478**
4. Water heating energy requirements													
											kWh/year		
Energy content of hot water used from above												1880.91	(45)
Distribution loss from Table 1 column (c)													
	If instantaneous water heating at point of use, enter '0' in boxes (46) to (61)												
	For community heating use Table 1 (c) whether or not hot water tank is present												
	29.25	25.6	26.4	23	22.1	19.1	17.7	20.3	20.5	23.9	26.1	28.3	
Water storage loss:				56.7								282.14	(46)

	a)	If manufacturer's declared loss factor is known (kWh/day):										1.1	(47)
		Temperature factor from Table 2b										0.721	(48)
		Energy lost from water storage, kWh/year							(41) × (41a) × 365=			0.79	(49)
	b)	If manufacturer's declared cylinder loss factor is not known :											
Cylinder volume (litres) including any solar storage within same cylinder												0	(50)
If community heating and no tank in dwelling, enter 110 litres in box (50)													
Otherwise if no stored hot water (this includes instantaneous combi boilers) enter '0' in box (50)													
Hot water storage loss factor from Table 2 (kWh/litre/day)												0	(51)
If community heating and no tank in dwelling, use cylinder loss from Table 2 for 50 mm													
factory insulation in box (50)													
		Volume factor from Table 2a										0	(52)
		Temperature factor from Table 2b										0	(53)
		Energy lost from water storage, kWh/year						(50) × (51) × (52) × (53)=				0	(54)
Enter (49) or (54) in box (55)												0.79	(55)
Water storage loss for each month (56) = (55) x (41)m													
	24.58	22.2	24.6	23.8	24.6	23.8	24.6	24.6	23.8	24.6	23.8	24.6	
											289.44		(56)
If cylinder contains dedicated solar storage, box (57) = (56)m × [(50) – (H11)] / (50), else (57) = (56)													
where H11 is from Appendix H													
	24.58	22.2	24.6	23.8	24.6	23.8	24.6	24.6	23.8	24.6	23.8	24.6	
H11	0	Dedicated solar storage volume V, litres (volume of pre-heat store,										0	(57)
		or dedicated solar volume of a combined cylinder)											
	0	0	0	0	0	0	0	0	0	0	0	0	
Primary circuit loss from Table 3												0	(58)
Primary circuit loss for each month (59)m = (58) ÷ 365 × (41)m (modified by factor from													
Table H5 if there is solar water heating and a cylinder thermostat)													
	0	0	0	0	0	0	0	0	0	0	0	0	
Combi loss from Table 3a, 3b,3c (enter '0' if not a combi boiler)													
	0	0	0	0	0	0	0	0	0	0	0	0	
Total heat required for water heating calcu						(62)m = 0.85 × (45)m + (46)m + (57)m + (59)m + (61)m							
	219.59	204.47	213.83	190.43	185.71	164.63	156.87	173.85	174.08	197.53	210.44	226.40	(62)
Solar DHW input calculated using Appendix G or Appendix H (negative quantity) (enter "0" if no solar													
contribution to water heating) (add additional lines if FGHRS and/or WWHRS applies, see Appendix G)													
													[63]
Output from water heater, kWh/month													
	219.6	204	214	190	186	165	157	174	174	198	210	226	
	if (64)m < 0 then set to 0									=	2317.82		(64)
Heat gains from water heating, kWh/year													
	84.51	74.5	78.2	70.1	68.6	61.3	58.8	64.6	64.5	72.6	76.9	82.5	
Include (57) in calculation of (65)m only if cylinder is in the dwelling or hot water is from													
community heating													
0.25 × [0.85 × (45)m + (61)m] + 0.8 × [(46)m + (57)m + (59)m]=											856.96		(65)
Water heating													
Output from water heater (calculated above)													
	219.6	204	214	190	186	165	157	174	174	198	210	226	
										=	2317.82		(216)
Efficiency of water heater, %													
	85.63	85.4	84.9	84.4	83.2	79.5	79.5	79.5	79.5	83.8	85.1	85.6	
											996		(217)
(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency													
adjustment' column of Table 4c)													
Fuel for water heating Energy required for water heating, kWh/month													
	256.4	239.4	251.7	225.7	223.3	207.1	197.3	218.7	219	235.8	247.3	264.4	
							(64)m × 100 / (217)m=				2786.04		(219)

Appendix 4c

Appendix 4c: Dwelling characteristics and variables under a correlation and error analysis

	Variables	*N*	Actual space heating all years (kWh/m²/yr)				Design space heating (kWh/m²/yr)				DBDA
			Mean	Median	SD	Standard error	Mean	Median	SD	Standard error	(kWh/m²/yr)
Building standard	SBS 2010	9	62.37	66.28	23.29	7.76	28.04	28.61	7.38	2.46	34.32
	SBS 2010 & Section 7	3	34.05	28.03	10.24	5.91	11.32	7.06	8.05	4.65	22.73
	SBS 2010 & Passivhaus	1	24.98	-	-	-	21.59	-	-	-	3.39
Construction type	Off-ste	8	42.97	38.25	17.93	6.34	20.20	22.09	9.19	3.25	22.77
	On-site	4	70.57	81.90	25.52	12.76	29.57	32.07	9.15	4.57	41.00
Dwelling type	Flats	2	42.05	-	17.36	12.27	27.25	-	6.32	4.47	14.80
	Bungalows	2	78.05	-	13.39	9.47	28.61	-	2.25	1.59	49.43
	Terrace	3	34.05	28.03	10.24	5.91	11.32	7.06	10.2	5.91	22.73
	Semi-Detached	5	56.75	67.90	25.69	11.49	26.84	25.22	8.70	3.89	29.90
Heating type	Combi gas boiler	11	54.58	59.41	24.20	7.30	25.05	25.22	8.79	2.65	29.53
	Gas boiler η ≥90%	7	54.06	53.94	22.99	8.69	22.02	21.76	9.48	3.58	32.05
	Gas boiler η ≤90%	5	55.21	64.66	25.57	11.43	28.70	26.36	6.14	2.75	26.51
	ASHP/ electric	1	25.66	-	-		4.31	-	-	-	21.35
Ventilation type	MVHR	10	53.96	56.56	25.49	8.06	21.95	23.91	9.79	3.10	32.01
	ME only	2	43.24	-	16.17	11.44	30.19	-	9.26	6.55	13.05
Household Composition	With children	6	54.46	53.94	22.50	9.18	23.00	21.76	10.8	4.42	31.46
	Without children	6	49.89	45.16	26.17	10.69	23.65	25.79	9.47	3.87	26.23
Occupancy	Mostly occupied	4	66.73	74.90	25.69	12.85	23.70	28.61	11.5	5.73	43.02
	Early mornings/ evenings	3	62.18	59.41	12.47	7.20	19.40	20.93	3.40	1.97	42.77
	Mixed	5	34.53	27.06	16.73	7.48	25.38	25.22	11.1	4.96	9.16

*DBDA= Difference between design and actual

Appendix 4d

Appendix 4d: HDD normalised delivered energy for space heating of all thirteen dwellings using the three baselines

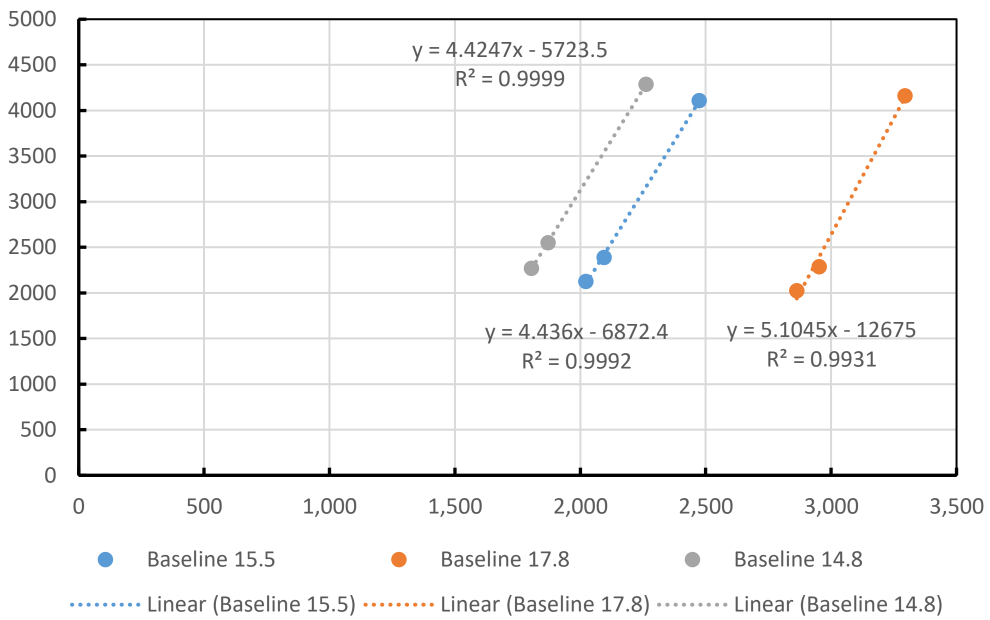
				Normalisation Year 1				Normalisation Year 2				Normalisation Year 3				Normalisation Year 4		
Dwelling Code	Mean internal temperature	Delta t	Actual Year 1	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C	Actual Yea 2	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C	Actual Year 3	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C	Actual Year 4	Baseline 15.5˚C	Baseline 17.8˚C	Baseline 14.8˚C
F.1.4	21.9	12.3	4554.03	4533.78	4592.74	4731.20	4512.65	5496.86	5236.12	5875.19	4747.72	5581.69	5342.79	5960.01	4630.35	5433.33	5223.10	5711.98
F.3.12	20.3	10.7	2312.92	2302.63	2332.58	2402.90	1670.79	2035.19	1938.65	2175.26	2212.34	2600.95	2489.63	2777.24	1586.31	1861.40	1789.38	1956.86
B.4.14	22.3	12.7	9056.31	9016.04	9133.29	9408.63	7080.45	8624.70	8215.60	9218.31	6178.02	7263.23	6952.37	7755.53	6458.37	7578.35	7285.13	7967.02
B.5.16	22.0	12.4	6344.71	6316.50	6398.64	6591.55	5905.01	7192.90	6851.71	7687.97	7298.33	8580.33	8213.10	9161.90	5518.49	6475.49	6224.94	6807.59
SD.6.17	21.1	11.5	4125.75	4107.41	4160.82	4286.26	1743.62	2123.91	2023.16	2270.09	2032.17	2389.14	2286.88	2551.07	2269.77	2663.39	2560.34	2799.98
SD.6.18	21.9	12.3	1652.53	1645.18	1666.58	1716.82	2516.30	3065.11	2919.72	3276.07	2003.16	2355.03	2254.24	2514.65	2142.35	2513.87	2416.60	2642.80
T.7.19	21.2	11.6	2284.46	2274.31	2303.88	2373.34	1833.06	2232.86	2126.94	2386.54	1972.76	2319.29	2220.03	2476.49	2450.52	2875.48	2764.22	3022.96
T.7.20	23.4	13.8	2533.81	2522.54	2555.34	2632.38	2713.30	3305.07	3148.30	3532.55	1724.47	2027.38	1940.61	2164.80	2355.19	2763.61	2656.68	2905.35
T.7.21	20.1	10.5	4439.94	4420.20	4477.68	4612.67	4319.79	5261.94	5012.34	5624.10	4641.70	5457.04	5223.48	5826.92	5164.84	6060.50	5826.01	6371.32
SD.8.23	22.4	12.8	8153.21	8116.96	8222.52	8470.40	6426.00	7827.52	7456.23	8366.26	10159.59	11944.19	11432.98	12753.76	7890.38	9258.70	8900.46	9733.54
SD.9.24	18.9	9.3	7030.13	6998.88	7089.89	7303.63	6713.79	8178.08	7790.16	8740.95	5625.59	6613.76	6330.70	7062.04	6637.91	7789.03	7487.66	8188.50
SD.10.33	21.9	12.3	6535.63	6506.58	6591.19	6789.89	6263.30	7629.34	7267.45	8154.44	7873.95	9257.06	8860.87	9884.50	9452.11	11091.26	10662.11	11660.09
CV				9%	50%	50%		49%	49%	49%		60%	60%	60%		55%	55%	55%
SD				2365.77	2396.54	2468.79		2481.10	2363.41	2651.86		3157.34	3022.21	3371.35		2898.09	2785.95	3046.72
Mean				4896.75	4960.43	5109.97		5247.79	4998.86	5608.98		5532.42	5295.64	5907.41		5530.37	5316.38	5814.00
Median				4476.99	4535.21	4671.93		5379.40	5124.23	5749.65		5519.36	5283.14	5893.46		5746.91	5524.55	6041.65

Appendix 4e

Appendix 4e: Baseline correlation analysis and test of an example dwelling

Dwelling Code: SD.6.17

		Baseline 15.5	Baseline 17.8	Baseline 14.8	15.5 HDD	17.8 HDD	14.8 HDD
Year 1	Actual	4107.41	4160.82	4286.26	2,474	3,294	2,262
Year 2	Actual	2123.91	2023.16	2270.09	2,022	2,863	1,805
Year 3	Actual	2389.14	2286.88	2551.07	2,095	2,952	1,872
Year 4a	Formula	**2438.76**	**2357.75**	**2705.55**	2,099	2,945	1,905
Year 4	Actual	2663.39	2560.34	2799.98			
% difference		-8%	-7.91%	-3%			



Appendix 5a

Appendix 5a: Comparative analysis of relative impacts

	Heat energy demand (kWh/m2/yr)				Carbon emissions (kgCO2/m2/yr)			
SD.6.17	Baseline	2030	2050	2080	Baseline	2030	2050	2080
100% DPF	38.3	52.66	88.45	180.16	7.05	9.69	16.27	33.15
50% DPF	38.3	44.35	57.57	82.15	7.05	8.16	10.59	15.12
10% DPF	38.3	38.60	40.67	43.52	7.05	7.10	7.48	8.01
SD.6.18								
100% DPF	29.21	41.01	76.30	178.99	5.37	7.55	14.04	32.93
50% DPF	29.21	33.40	45.66	70.00	5.37	6.15	8.40	12.88
10% DPF	29.21	28.28	30.11	32.70	5.37	5.20	5.54	6.02
SD.7.19								
100% DPF	71.15	91.96	154.45	314.88	19.85	10.48	4.32	8.82
50% DPF	71.15	77.44	100.53	143.58	19.85	8.83	2.81	4.02
10% DPF	71.15	67.40	71.02	76.07	19.85	7.68	1.99	2.13

Table 5a: Performance overtime - dilapidation of envelope

	Heat energy demand (kWh/m2/yr)				Carbon emissions (kgCO2/m2/yr)			
SD.6.17	Baseline	2030	2050	2080	Baseline	2030	2050	2080
100% DPF	38.3	37.84	55.60	101.03	7.05	6.96	10.23	18.59
50% DPF	38.3	31.87	36.19	46.07	7.05	5.86	6.66	8.48
10% DPF	38.3	27.73	25.57	24.41	7.05	5.10	4.70	4.49
SD.6.18								
100% DPF	29.21	30.98	51.84	108.57	5.37	5.70	9.54	19.98
50% DPF	29.21	25.23	31.02	42.46	5.37	4.64	5.71	7.81
10% DPF	29.21	21.36	20.46	19.83	5.37	3.93	3.76	3.65
SD.7.19								
100% DPF	71.15	75.89	118.07	218.76	19.85	8.65	3.31	6.13
50% DPF	71.15	63.91	76.85	99.75	19.85	7.29	2.15	2.79
10% DPF	71.15	55.62	54.30	52.85	19.85	6.34	1.52	1.48

Table 5b: Performance overtime - dilapidation of envelope and climate change without cooling

	Heat energy demand (kWh/m2/yr)				Carbon emissions (kgCO2/m2/yr)			
SD.6.17	Baseline	2030	2050	2080	Baseline	2030	2050	2080
100% DPF	38.3	41.46	59.88	106.39	7.05	7.38	10.35	18.74
50% DPF	38.3	35.49	40.47	51.43	7.05	6.28	6.78	8.63
10% DPF	38.3	31.36	29.85	29.77	7.05	5.52	4.82	4.64
SD.6.18								
100% DPF	29.21	36.92	58.89	117.69	5.37	6.38	9.74	20.23
50% DPF	29.21	31.17	38.07	51.58	5.37	5.32	5.91	8.07
10% DPF	29.21	27.30	27.51	28.95	5.37	4.61	3.96	3.90
SD.7.19								
100% DPF	71.15	81.17	124.34	226.87	19.85	9.25	3.48	6.35
50% DPF	71.15	69.19	83.11	107.86	19.85	7.89	2.33	3.02
10% DPF	71.15	60.90	60.56	60.96	19.85	6.94	1.70	1.71

Table 5c: Performance overtime - dilapidation of envelope and climate change with cooling

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