What feasible macro-scale interventions could stimulate a sustainable growth in the UK housing retrofit industry? - An examination of the potential impact from supply-chain innovations on low energy retrofit of pre-1919 housing.

Submitted for the Degree of
Doctor of Philosophy
At the University of Northampton

Year
2019

Georgia Laganakou

Declaration

I, Georgia Laganakou, confirm that the work presented in this thesis is my own. When information has been derived from other sources, I confirm that this has been indicated in the thesis. None of the work has been submitted for another degree in this or any other University.

Date: 29/10/2019

Acknowledgements

This research was through funds made originally available from East Midlands Councils to the University of Northampton and CCBE for a funded studentship.

The research in this thesis would not have been possible without the support, patience and encouragement of many people. Foremost, I would like to thank my supervisory team: Dr Martin Field, Prof Andrew Pilkington, Prof John Horton and Dr Holger Siemons. I would also like to thank my family and friends for their encouragement, support and understanding.

Abstract

Understanding the context for encouraging new retrofit practices to be applied to domestic housing in the UK is of crucial importance to any consideration of what could impact on energy reduction and domestic housing costs within the wider UK housing market.

The thesis reviews attempts made to stimulate the retrofit market and the struggle of the industry to keep up with the stop/start UK legislation and changes of funding mechanisms on energy reduction policies.

It then focuses on the influence of voluntary standards such as Passive House and its Whole-House retrofit standard, EnerPHit along with current innovations incorporating offsite mechanisms in their retrofit delivery. Considering lessons learned from previous attempts, the thesis examines what outcomes these relatively recent approaches could have within the UK housing retrofit “evolution” and specifically when applied on the most challenging of the UK’s housing stock of the pre-1919 typologies. Wide research has been done on either housing retrofit or offsite construction in new-build but due to the relatively recent implementation of offsite in retrofit a research gap was identified considering their future applicability in the UK’s older stock and by extension on the retrofit market and regulation.

With a socio-technical methodology approach incorporating energy and cost modelling along with the uptake of a survey focusing on the construction industry’s representatives, the thesis examined the feasible complexities and opportunities of these approaches on pre-1919 typologies through the prism of regulation, technical complications, financial opportunities and social barriers and incentives.

The findings from this research showed that there is a variety of advantages and disadvantages in adopting deep retrofit with offsite mechanisms that stretch beyond straightforward energy and cost reductions and are dependable on typology, location and offsite measure applied. Equally important the research contributed on identifying how

these mechanisms could respond to the emerging regulations on quality control for retrofit delivery and provides an insight on of the policy and practical implications in the adoption of such measures.

Contents

List of Figures

Chapter 3

Chapter 4

<u>**Chapter 5**</u>

Chapter 6

Appendices

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Nomenclature

Abbreviations

AECB	Association for Environment Conscious Building
BEIS	Business, Energy and Industrial Strategy
BOS	Bristol Online Survey
BRE	Building Research Establishment
BSI	British Standards Institution
BSRIA	Building Services Research and Information Association
CCC	Committee on Climate Change
CERT	Carbon Emissions Reduction Target
CESP	Carbon Emissions Reduction Target
CIBSE	Chartered Institution of Building Services Engineers
CSH	Code of Sustainable Homes standard
DCLG	Department for Communities and Local Government
DECC	Department of Energy and Climate Change
ECO	Energy Company Obligations
EPBD	European Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EST	Energy Saving Trust
EWI	External Wall Insulation
FIT	Feed-In Tariff
GDFC	Green Deal Finance Company
IWI	Internal Wall Insulation
LEBD	Low Energy Building Database
MEV	Mechanical Extract Ventilation

MVHR	Mechanical Ventilation with Heat Recovery
NAO	National Audit Office
NEF	National Energy Foundation
NHBC	National House Building Council
NHS	National Health Service
NPV	Net Present Value
NZEBs	Nearly Zero Energy Buildings
ONS	Office of National Statistics
PAS	Publicly Available Specification
PHPP	Passive House Planning Package
RdSAP	Reduced data SAP
RftF	Retrofit for the Future
RHI	Renewable Heat Incentive
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
ROI	Return On Investment
SAP	Standard Assessment Procedure
SBRI	Small Business Research Initiative
SPSS	Statistical Package for the Social Sciences
TFA	Treated Floor Area
TPB	Theory of Planned Behaviour
TRA	Theory of Reasoned Action
TSB	Technology Strategy Board
UKGBC	UK Green Building Council
WHISCERS	Whole-House In-Situ Carbon and Energy Reduction Solution
WHO	The World Health Organisation
WRAP	Waste and Resources Action Programme

Definitions

kWh/m^2.a	Kilowatt-hours per square metre of area per year. It is used to express specific energy demand (heating or overall) when the m^2 refer to the floor area of a building. Also used to express heat loss when the m^2 refer to a building fabric element.
W/mK **(k-value)**	Thermal conductivity of a material expresses the heat transfer (Watts) per metre (m) per degree temperature (Kelvin or Celsius). In materials of low thermal conductivity the heat transfer occurs at a lower rate than materials of high thermal conductivity. Thus, the lower the value the better the material's ability to insulate.
W/(m^2 K) **(U-value)**	Thermal transmittance coefficient is the rate of heat transfer (Watts) through 1 m^2 of element (single material or a composite) with a 1^{0}C/K difference across it. Thus, the lower the U-value the better insulating it is.
m^3/(hr.m^2) **and ach^{-1}**	Airtightness or Air Permeability expresses the volume of air leakage that passes through the buildings envelope. m^3/(hr.m^2) (q50 measurement) is used in Building Regulations and translates to the volume of air (m^3) through the building envelope per hour(hr) per m^2 of building element at 50 Pascals differential pressure. The Passive House standard uses the number of times the volume of air within the building is changed in an hour- Air Changes per Hour (ACH) (n50 measurement) at 50 Pascals differential pressure
CO$_2$	Carbon dioxide relates to the "carbon footprint" or CO$_2$ pollution. In this thesis it is associated with the CO$_2$ emissions from fossil fuels required to generate energy (kWh) for heating.

Net Present Value	Is the value of all future “cash flows” (positive and negative) over the entire life of an investment discounted to the present. In this thesis it is translated to the capital cost required to retrofit a dwelling to the required energy standard (investment) and takes into account energy related bills (savings and payments), added comfort, added property value and cost related maintenance over the years (cash flows).
Return On Investment	Is the attempt to measure the amount of return on a particular investment, relative to the investment’s cost. It is expressed as a percentage or a ratio by dividing the benefit/return of an investment by the cost of the investment. In this thesis the term is used as the “payback” to demonstrate the return of investment (retrofit) after the assigned time period not as a percentage but as monetary value taking into account the Net Present Value.

1. Introduction

This chapter sets out the background, context, motivation, aim and scope of the research along with an overview of the thesis structure.

1.1. Context

According to the 2008 *Climate Change Act*, the UK has set a target of at least 80% reduction of greenhouse gas emissions by 2050, from 1990 levels (DECC, 2009). Currently 27 million existing houses in the UK have a combined energy use of 18% of the nation's total energy usage (DECC, 2013), while10% of English households fall within the "fuel poverty" category (DECC, 2015a) using too great a proportion of their income on energy costs. Since 80% of existing properties are likely to still be standing by 2050 (Boardman, 2007) on average 600,000 homes per year will need to be refurbished with energy saving and low carbon technologies in the next decades, to meet the 80% emissions target (EST, 2010). Nonetheless, it is estimated that only hundreds of energy refurbishments are carried out per year in the UK (Fawcett and Killip, 2014).

However, a range of previous studies show that even retrofitting to a modest standard of 'EPC C'[1] could reduce carbon emissions to 23.6mt CO_2, and create 180,000 new jobs; moreover for every £1 spent on reducing fuel poverty, at least 42 pence is also expected in National Health Service benefits (Washan, Stenning, and Goodman, 2014). Still, 75% of Great Britain's houses have an EPC rating below D (DECC and NAO, 2015).
On the other hand in order to help meet these targets, the UK government tightened energy efficiency standards for new buildings (Building Regulations and the now scrapped Zero Carbon[2]) and historically introduced a range of programmes for retrofit

---

[1] Energy Performance Certificates (EPCs) estimate a building's energy-efficiency from A (very efficient) to G (inefficient). http://www.energysavingtrust.org.uk/

[2] Building Regulations Approved Document Part L 2016 amendments link: www.planningportal.co.uk/info/200135/approved_documents/74/part_l_-_conservation_of_fuel_and_power and HM treasury and BIS policy paper scrapping Zero Carbon (HM Treasury and BIS, 2015) page 46.

such as: CERT (Carbon Emissions Reduction Target 2008-2012) and CESP (Community Energy Saving Programme 2009-2012), ECO1, ECO2, ECO2t and ECO3 (Energy Company Obligations 2013-2022), TSB's Retrofit for the Future (2009-2011), Green Deal (2013-2015), FIT (Feed-In Tariff) and RHI (Renewable Heat Incentive). Their aim was both to target the most vulnerable homes and create a sustainable market to foster change across the entire existing housing stock.

Whilst the UK has set a series of legislation and targets that aim for the reduction of domestic energy use and has initiated different programs to increase the aspiration of retrofit, survey and market data (ONS 2015 ; DECC, 2015b; Pettifor, Wilson and Chryssochoidis, 2015; Dowson *et al.*, 2012) reveal that the UK's different incentives for low energy housing retrofit have not yet generated significant market uptake or interest to carry out the retrofitting of domestic housing properties in large numbers.

Nonetheless, the lack of "anticipated success" of these programs and legislation brought in the forefront issues regarding the fragmented retrofit industry but also provided a number of valuable lessons for the future. Those are interconnected and include:

- The energy performance gap, i.e. the discrepancy between modelled energy pre-retrofit and the actual energy consumption, post-retrofit. This attributed to both user/resident and technical factors. The user/resident factor falls on what is called the "rebound effect", where energy improvements make energy services cheaper, and therefore encourage energy consumption increase (Sorrell, Dimitropoulos, and Sommerville, 2009; Galvin, 2014; Johnston *et al.,* 2016). The technical factor falls on the underperformance of retrofitted elements (Lomas, 2010) or the lack of technical skills in relation to both energy prediction and delivery within the industry (Jones, Lannon, and Patterson, 2013).
- Unintended consequences, i.e. outcomes that arise unintentionally as a result of either faulty installations due to the lack of skills within the industry (De-Selincourt, 2015; Banks and White, 2012) or even within policy failures to account

for complex systems in housing retrofit while focusing on single-minded objectives (Shrubsole *et al.,* 2014; Gupta *et al.,* 2015).

- The Whole-House versus incremental retrofit approach is the difference between targeting energy efficiency of a property as a whole rather than just the efficiency of a particular element (Waterson, 2005). This difference has an interconnected impact to the previous points made. The incremental approach is considered the reason of both energy performance gap and unintended consequence as for example if a single upgrade is made without considering the whole property could result amongst other things to: overheating, thermal bridging , consequent energy loss and even structural damage (NEF and EEPB, 2014b; BRE, 2015). Consequently, this is why to some extend where the energy efficiency programmes have been unsuccessful (i.e. Green Deal). On the other hand the Whole-House approach prevents separate aspects of retrofit being considered in isolation (Bonfield, 2016). Most importantly the Whole-House approach does not necessarily mean deep-retrofit but rather a holistic understanding of the building from the survey to impact of the installations.
- Even though the Whole-House approach and deep retrofit has been confirmed to have greater advantages versus the elemental approach, the typical greater up-front cost is still a barrier for an uptake on a bigger scale (Jones, Lannon and Patterson, 2013; NEF and EEPB, 2014b; Simpson *et al.*, 2015).
- Supply chain fragmentation and shortage in skills and knowledge in the industry has been recognised as a major barrier for the growth in the retrofit sector (NEF and EEPB, 2014b; Kenington *et al.*, 2014; Topouzi, Killip and Owen, 2017). This has a dirrect effect on the quality of retrofit and cosequent failures demonstrating that there is a need of coherant structure of delivery and even what the NEF and EEPB, (2014b) report identified as an “one stop shop” as means of supply coordination.

1.2. Research motivation

The Green Deal has been the latest national led programme targeting housing retrofit. It ended in 2015 with heavy criticism of its outcomes (Gardiner, 2015) while the same year the Zero Carbon for new build was scrapped before it even started. Both of those actions left the construction industry in dismay (Farah, 2015; Gardiner, 2015) due to the heavy investment already done and uncertainty about the future of low energy construction. Nonetheless, critical reviews of the "death" of Zero Carbon house standards indicate that it could mean could mean the "birth" of more substantial interest in voluntary standards such as Passive House[3] (Rickaby, 2015; Greenwood, Congreve and King, 2017) and its retrofit equivalent 'EnerPHit' due to its coherent and robust Whole-House approach. Additionally, in 2016 through the commission of Energy and Climate Change (DECC), now Energy and Industrial Strategy (BEIS), and the Department for Communities and Local Government (DCLG), published a report called *Each Home Counts* or as it commonly known the *Bonfield Review* (Bonfield, 2016). In summary, this in-depth report sets a framework of retrofit standards ensuring quality delivery, costumer protection and greater consistency across the industry, This has also led to the review of the building standards, PAS 2030:2017[4] (*Specification for the installation of energy efficiency measures in existing buildings)* and the introduction of PAS 2035[5] (*Specification for the energy retrofit of domestic buildings - Specification and guidance to support the Each Home Counts Quality Mark for domestic retrofit in the UK*) that will come into pass in 2019. The PAS 2035 standard will serve to reinforce ethos of retrofit quality centring amongst other things on Whole-House approaches with risk assessment from the installers to installations and customer feedback (Price, Rickaby, and Palmer, 2017).

---

[3] Passivhaus is the original German name of the standard. In this thesis the English translation equivalent is used, Passive House, when referring to the same standard.

[4] PAS 2030:2017 (BSI, 2017)

[5] PAS 2035 link to the BSI standard development site: https://standardsdevelopment.bsigroup.com/projects/2017-04146

These steps may suggest that even if previous programmes have failed to deliver retrofit in scale, the lessons learned may have initiated deeper awareness and soon to be legislation focusing on quality, while interest is also turning towards alternative approaches such as Passive House/EnerPHit as a better equivalent to previous standards (Zero Carbon).

In addition, relatively recent applications aiming to target retrofit at scale have been introduced by industry's "innovation intermediaries" (Brown *et al.,* 2018). These are industry led initiatives focusing in embedding offsite construction in retrofit applications where time and cost of construction can be reduced. Examples as such could be found in Energiesprong [6] that ensures net-zero energy and Beattie Passive TCosy[7] which ensures the EnerPHit standard. Those examples have focus on: a. reducing the cost of retrofit in economies of scale, b. targeting local authority/housing association led housing as those have the ability to retrofit properties simultaneously in numbers, c. retrofitting in volume in the social housing sector, meaning that there is also access to funding which is an understandable step on building a financial model before fully commercialising (Brown *et al.,* 2018) and d. consequently focusing on properties mainly built post 1950's in line with the ages of the majority of social housing in the UK (DECC and National Statistics, 2015). Those latter properties have evidently less planning restrictions to older ones and are typically "easier" to retrofit due to their simplified form. Nonetheless, as the English Housing Survey report (DECC and National Statistics, 2015) and the Fuel Poverty Statistics Report (Departament for Business, 2017) have shown the majority of the least efficient properties and those impacted by fuel poverty are within the pre-1919 stock.

Therefore if there is a transition to quality driven retrofit from steady legislation (PAS2030/2035) while innovative approaches using offsite are aiming to deliver quality and quantity how could this be adopted within the most challenging of the UK stock?

---

[6] Energiesprong official website:www.energiesprong.uk/

[7] Beattie Passive official website: www.beattiepassive.com/index.php

This PhD thesis aims to contribute to this area of research, as set out in more detail in the following section.

1.3. Research aim, objective and significance

The aim of this PhD research is to gain and add to the understanding of how supply chain innovations might support the low energy retrofit of the UK's challenging pre-1919 housing stock. It focuses on the most recent industry approaches of Whole-House retrofit standards such as EnerPHit along with offsite mechanisms applied.

Furthermore, it aims to evaluate the perceptions and experiences from the industry's representatives on retrofit approaches to date and analyse what could motivate the UK construction industry to adopt these standards and methods.

As previously identified, in the last two decades there have been policy interventions to tackle energy consumption in existing houses in the UK. Evidence suggests that the attempts so far have had mixed or limited outcomes and there are still no strong regulatory systems or incentives. Nonetheless, the lessons learned have been "stepping stones" for the evolution of large-scale interventions in addressing household energy consumption. The relatively recent offsite approaches have been latest endeavours in attempting to provide solutions where previous attempts have been unsuccessful: retrofit in volume, reduced cost and assurance of delivery (energy and quality). However, it is still important to understand how those approaches correspond in the older UK stock along with how the current industry perceives them.

In this context the research addresses the following questions:

RQ .1 *Can the cost of UK Whole-House retrofit to EnerPHit standard be reduced via current offsite mechanisms in pre 1919 UK house typologies?*

RQ .2 *Could the UK industry be confident in adopting this combination as common practice?*

RQ .3 What innovations are needed by the industry for ‘Whole-House’ retrofit practice to have a macro-scale effect in the UK?

As the following chapters explore, there has been significant research on housing retrofit and offsite as a mean to answer new-build housing challenges but there are still implications and possible benefits to consider when applied to older stock. This study builds on existing knowledge and research, and provides a new contribution by identifying complexities and future possibilities for these applications.

In addressing the research questions the objective of this PhD research through a socio-technical approach is to:

(RQ1): Through energy and cost modelling identify related implications within different typologies of the pre-1919 UK housing stock, with and without offsite measures applied and evaluate the impact retrofitted to higher standards such as EnerPHit

(*RQ2):* By focusing on “middle-actors”, construction industry’s professionals that have the ability to influence change in low energy design (Parag and Janda, 2014; Janda *et al.*, 2014), identify the industry’s perspectives on both energy standards, offsite mechanisms and their practical combination.

(RQ3): Analyse and compare these multi-disciplinary issues, to determine future impacts on the market, regulation and practical applications.

1.4. Thesis overview

This PhD thesis is presented in 7 chapters. Chapter 2 presents a literature review on the policies and national programmes on low energy housing and retrofit along with relevant existing research on the subjects. Likewise Chapter 3 presents a literature review on innovations and techniques specifically related to standards, approaches and offsite methods.

In Chapter 4 the research design and methodology are presented divided into six distinct parts: The first two review available research methods to answer the research questions identified in the preceding chapter and justify the socio-technical mix- methods chosen. In essence, the mixed-method approach chosen undertakes energy and cost modelling testing offsite approaches in pre-1919 UK typologies and also assesses industry representatives' perceptions via a survey uptake. The next five sections clarify how the mix-method approach is going to use the data collected and each section details a district relevant theme. These are:

- *Regulatory approach:* this section describes the energy standards used in the modelling of the typologies and their relevance to the research.
- *Technical approach:* details the data used for the energy modelling such as case study typologies, structure and build-ups along with the justification on the modelling software used.
- *Financial approach:* explains the model inputs of cost variations and determinants within the selected energy standards and constructions methods (onsite and offsite).
- *Social approach:* explains the survey justification, design and method of analysis.

Chapter 5 and 6 outline and discuss the individual and combined results based on the research methods along with their implications and significance.

- *Regulatory related outcomes:* this section presents the results on the applied energy standards modelled and discusses the heating energy demand differentials along with their impact.
- *Technical related outcomes:* presents and explains in more detail the resulting factors that influence the heating energy demand. It explores the technical elements influencing the heat loss/heat demand for each of the typologies explored. This provides an understanding of the technical implications and possibilities of different construction methods (onsite/offsite) and links to the feasible cost implications reviewed on the next section.

- *Financial related outcomes:* looks at the comparative results on the upfront cost of each scenario modelled (standard, typology, location and construction methods) along with the feasible payback opportunities. This allows for a clearer understanding of the limitations and prospects of the monetary complexities in both high energy efficient standards (EnerPHit) and offsite construction in retrofit.
- *Social related outcomes***:** presents the results from the survey and analyses them within research previously done on perceptions in either retrofit or offsite as well as with the technical results from this research. This allows a better understanding of barriers and incentives of the industry representatives on use of offsite in retrofit and by extension on their future macro-scale applicability.

Finally, Chapter 7 summarises the key research findings and draws them together through a discussion of the policy and practical implications along with reflections on further research.

2. Background context to UK housing retrofit

This section discusses the background context to housing retrofit in UK. Specifically, the UK housing condition, regulation and government led programmes aimed to stimulate the market and set standards along with existing research on outcomes and recommendations for the future of the retrofit sector.

2.1. Reducing energy use and CO_2 emissions

In UK around 67% of the total energy used per household is accounted for by space heating (DECC, 2016) and it comes directly from burning fossil fuels. The burning of fossil fuels releases CO_2 emissions in the atmosphere that cannot be absorbed by natural means, and create a thick “blanket” over the earth’s atmosphere resulting in global warming and climate change (Pelsmakers, 2015) with drier summers, wetter winters and more extreme winds and rainfall resulting to catastrophic flooding in the UK (Pelsmakers, 2015; Thompson *et al.*, 2015). The amount of emission savings related to the energy reductions from retrofit approaches differ depending on the amount of implementations but studies have shown savings from 23.6 $mtCO_2$ (Washan *et al.*, 2014) to 49$mtCO_2$ (Tahir, Walker, and Rivers, 2015). To understand the scale of retrofit needed and its impact, if UK wants to meet the legally bound targets set on the *Climate Change Act* of 80% CO_2 reduction by 2050, we will need to retrofit a house every minute for the next 35 years (Stafford, Gorse, and Shao, 2011).

2.2. Improving socio-economic conditions in the UK’s housing stock

In relation to their EU counterparts, the UK holds the oldest stock (Pre-1960) (Economidou *et al.,* 2011) a fact which places the UK retrofit industry at very challenging position: the old (‘heritage’) dwellings will in most cases be subject to rigid planning restrictions, while at the same time be the worst performing within the stock. According to the Annual Fuel Poverty Statistics Report (DECC, 2014a) the highest percentage of people living under the “fuel poverty” category are within the private rented sector with the highest percentage living in the oldest and least energy efficient properties and housing built pre-1919 and emitting double the amount of emissions on average compared to post-1990 homes (DECC and NAO, 2014). The older housing stock is the worst performing in terms of energy efficiency, as well as the most laborious and costly to improve (Deakin *et al.,* 2014).

There is also a clear association between *cold homes, fuel poverty and energy efficiency*, not least from individual responses to notions of their own ‘thermal comfort’ which will vary from person to person, in relation to ‘personal factors’, e.g. metabolic rate (level of activity), amount of clothing; and, environmental factors, e.g. air temperature, radiant temperature, air speed, and humidity.[8] Other studies have demonstrated the connections between cold homes and negative health impacts which lead to increased monetary demands on the NHS (AECB, 2014; DECC, 2014a; House, 2015; Royston, 2013). Yet despite contributing to many thousands of deaths each year, the health risks of cold homes receive only sporadic attention from the media and from policy-makers, while they are estimated to burden the NHS with costs of £1.36 billion per annum(DECC, 2015b). Shrubsole *et al.*, (2014) pointed out 119 unintended consequences of improving domestic energy efficiency through retrofit that stretches beyond the “clinical” health improvement of residents but has a wider impact in their wellbeing *“including the built environment, life style and activities, community, local economy, the natural environment and the wider global ecosystem” (page 343).*

---

[8] The World Health Organisation (WHO) and Public Health England recommends that indoor temperatures are maintained at 21°C in living rooms and 18°C in bedrooms for at least 9 hours a day and in general with temperatures below 18°C, negative health effects may occur, such as increases in blood pressure and the risk of blood clots which can lead to strokes and heart attacks (World Health Organization, 1987).
Relative humidity is measured as a percentage, and describes the ratio between the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature; the lower the percentage the “drier” the air is and vice versa. Within the threshold of 40%-70% is the acceptable to achieve thermal comfort. When relative humidity exceeds 70% for long periods it could increase impacts on health and trigger allergies and respiratory illnesses, particularly for asthma and rhinitis [CIBSE Guide A(CIBSE, 2015)]. Low relative humidity can also have health impact and it has been suggested that “low room moisture content increases evaporation from the mucosa and can produce micro-fissures in the upper respiratory tract which may act as sites for infection” (CIBSE Guide A).

At the same time a focus has to be given to ill-conceived installations of retrofit measures that could also lead to major health impacts. When for example new insulation has been applied without sufficient thought of the consequences of 'thermal bridging'[9], interstitial condensation has been found to occur within the building structure leading to damp and degradation of the structural elements, with structural defects and health risks increasing as a result of mould growth. In May 2016 Saint-Gobain commissioned a survey of over 3,000 UK homeowners and renters to explore issues in relation to 'health and wellbeing'(Saint-Gobain, 2016). The top three issues identified were: *the homes were too cold, too expensive to run and there was a lack of noise control,* with the highest levels of discomfort observed within the rented sector rather than with owner-occupiers. Additionally, the retrofit works, even if there are vulnerable customers who may need it the most, can be highly disruptive and be a major barrier to uptake retrofit measures (Brown *et al.*,2014; NEF, 2014; Dowson *et al.*,2012).

2.3. Household behaviour

Studies researching the impact of housing retrofit upon household behaviour have noted the potential for what is now commonly referred to as a *Rebound Effect*, where the energy improvements in a home somewhat counter-intuitively support subsequent higher levels of energy consumption from the resident household. The recognition that linked this effect directly to energy consumption is called the *Khazzoom-Brookes postulate* and was acknowledged first by economist William Jevons in the late 19th century (Madlener and Alcott, 2009). Influencing factors are considered 'direct' when the occupants utilize higher temperatures and 'indirect' when the occupants purchase high energy consuming products as a result of energy savings through reduced heating. The actual amount of any *increase* in energy use after the retrofit implementations can be difficult to quantify, but studies such Barker *et al.*, (2007) on the macro-economic 'rebound effect' on the UK

---

[9] Thermal bridging occurs when areas in parts of the building envelope have less reduced insulation, and the subsequently lower U-values allowing for result in significant localized heat losses, local surface condensation, air leakage and mould growth (CIBSE Guide A, Building regulations AD L andC).

economy, found that the post-retrofit levels of energy demand for 2010 were about 11% more than expected, due to direct and indirect rebound effects.

An additional factor recognised on influencing energy consumption post retrofit is the interaction of residents with the technologies and measures installed. Studies on Retrofit for the Future projects by Topouzi,(2013) and Topouzi,(2016) showed that there are various reasons influencing the impact of this interaction and most importantly those factors need to be addressed when retrofit measures are proposed. Notably, considering an occupant-centre approach i.e. lifestyle, needs and habits as well as better transfer of knowledge i.e. clear post-retrofit instructions/demonstration of new systems installed.

2.4. Addressing the ‘energy efficiency’ gap

A significant factor that impacts upon the actual energy savings achievable through housing retrofit is what is commonly known as the “energy efficiency gap” – the difference between what is predicted and modelled prior to the implementation of works on-site*,* against what is in reality saved. Studies have researched factors such as unexpected occupant behaviour (as noted above 2.3), and poor installation/construction quality (Tweed, 2013; Guerra-Santin *et al.*, 2013; Haas, Auer and Biermayr, 1998; Zero Carbon Hub, 2014). The energy efficiency gap due to poor installations is difficult to quantify since they are usually left undocumented, but an example of the effects of thermal bridging via inadequate or faulty external wall installations (De-Selincourt, 2015) resulting in an increase of heating energy demand by 40%. The ‘energy performance gap’ is challenging not least because there is more than one aspect of a building that determines final energy use. Monitoring results through UK and international dwellings (both retrofit and new build) the work on performance monitoring (Johnston *et al.*, 2016; Hopfe and Mcleod, 2015; Baeli, 2013) has pointed directly to how rigorous quality construction could be the key in ‘bridging the gap’. Additionally, non-technical causes on the energy performance gap were identified by Topouzi, Killip and Owen, (2017) as “*lack of technical knowledge; poor communication among project teams; unclear boundaries* *or roles and responsibilities*"(Page 552). The proposed solution of the study was the integration on the existing RIBA Plan of Work (RIBA, 2013) and Government Soft Landings (BSRIA, 2014) a series of "feedback loops" between stages providing learning outcomes that come from project experience and provide solutions consequently in future ones.

2.5. Legislation and regulations

Different types of legislation and regulatory initiatives have been introduced in UK to stimulate energy reduction in both new and retrofitted housing, and a critical review of their aims and outcomes is listed below.

2.5.1. The European Union's Energy Efficiency Directive

The European Union has set three climate change targets to be achieved by 2020 (http://ec.europa.eu): 20% reduction of greenhouse gas emissions, 20% of all energy to be delivered by renewables and 20% increase overall energy efficiency. Depending on country preferences, these targets can be based on primary or final energy consumption, or energy intensity**.** The Energy Efficiency Directive sets a number of binding measures for EU Countries to achieve the 20% targets and in regards to building efficiency the European Energy Performance of Buildings Directive (Directive 2002/92/EC - EPBD) sets the following requirements that have to be implemented by each EU country (under the principle of subsidiarity individual nations may decide for themselves the means by which they achieve this):

- Improve building regulations
- Introduce energy certification schemes for buildings
- Introduce schemes for inspection of boilers and air-conditioners

In 2010 the EPBD was 'recast' (Directive 2010/31/EU) with the key issues agreed as:

- The move towards new and retrofitted nearly-zero energy buildings by 2021 (2019 in the case of public buildings)

- The application of a cost-optimal methodology for setting energy-use requirements for both the external ‘envelope’ of buildings and the technical systems they contain.

In the UK the Green Deal and Zero Carbon policies were the Government “actions” to implement the EPBD yet both are now cancelled, raising the legitimate concern that if EU legislative drivers are proving to be an inadequate spur for a coherent strategy for building efficiency, what might be the building industry’s future if the UK is not an EU member state in the future?

2.5.2. The ‘Paris Agreement’

At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally-binding global climate deal, agreeing an aim to limit the rise in global temperature to well below 2°C, with efforts to hold it to 1.5°C (http://unfccc.int/).

2.5.3. The UK’s Climate Change Act

The Climate Change Act was passed in 2008 with the aim of reducing greenhouse gas emissions by 80% of 1990 levels by 2050. The Act requires the Government to set legally binding ‘carbon budgets’ - a cap on the amount of greenhouse gases to be emitted over a five-year period. The Committee on Climate Change (CCC) was set up to advise the Government on emissions targets, and report to Parliament on progress made in reducing greenhouse gas emissions. Its latest Progress Report (CCC, 2016) shows that emission levels have fallen by 38% below 1990 levels in 2015, but that this is primarily the result of reduced coal use in electricity generation. Alarmingly the CCC stated that “*any single sector, will not be enough to meet the fourth, or recommended fifth, carbon budgets or the 2050 target. Furthermore, current policies are not sufficient to continue the good progress to date or broaden it to other sectors”* (Page 11). As the building sector accounts for 18% of total and direct CO_2 building emissions are split between homes (75%), commercial buildings (15%) and the public sector (10%), the

Committee in its latest report underline the need for new legislation and incentives to increase the energy efficiency in the retrofit housing sector.

2.5.4. UK Building Regulations

The UK's Building Regulations set the minimum acceptable standards for the construction and refurbishment of all buildings. The document that is directly related to energy reduction is Part L and to domestic retrofit is the Approved Document PartL1B, "Conservation of Fuel and Power in Existing Dwellings", making a '*functional requirement*' to '*make reasonable provision for the conservation of fuel and power'*, with a simple approved document giving guidance on how to comply. The form that details the carbon and energy calculation required is the result of the Energy Efficiency Directive in 2002 - Wales, Northern Ireland and Scotland have subsequently developed their own similar standards. The evolution of Part L post-2013 was aiming to eventually adopt the Zero Carbon standard for new build in 2016 but is currently at a standstill. In the case of retrofit, the standard was not updated in 2013 and upgrades to buildings may not be mandatory if not "*technically, functionally and economically feasible*" (AD Part L1B, Regulation 23- HM Government, 2013).

2.5.5. Zero Carbon Homes

The Zero Carbon Homes policy, launched by the Labour government in 2007, would have required all new homes built from 2016 to meet the zero-carbon standard and would gradually be introduced through subsequent changes in the Building Regulations so the industry would be able to adapt. Its configuration derived from the Energy Efficiency Directive guidance (www.gov.uk) and the definition provided by the UK Green Building Council Zero Carbon Definition task group, based on three hierarchal principles (Zero carbon Hub:www.zerocarbonhub.org):

1. A high level of **energy efficiency** in the fabric and design of the dwelling
2. **'Carbon compliance'** – a minimum level of carbon reduction to be achieved from on-site technologies (including directly connected heat networks) and

3. **‘Allowable solutions’** – a range of measures available for achieving Zero Carbon beyond the minimum carbon compliance requirements.

For these three principles to be reflected in the construction industry two steps would be taken: an alignment within the Building Regulations and the adoption of a new-build Code of Sustainable Homes standard[10]. (In addition, CSH was aiming for a wider view of sustainability beyond energy and carbon reduction that included ecology, health and well-being.) This way the construction industry and consumers would have a clear guidance on how Zero Carbon should be achieved. *Table 2.1* shows a summary of what was scheduled for the Building Regulations in progression to Zero Carbon and what has been achieved to date, with a strong start in 2010 then not completely meeting the scheduled 2013 target and officially cancelled in 2016.

Year	**Scheduled % CO_2 reduction**	**Actual % CO_2 reduction**
2010	25	25
2013	44	31
2016	Zero Carbon	Cancelled

Table 2.1 *Yearly improvement over AD L1A 2006 (as a % of carbon reduction) (NHBC, BRE, Zero Carbon Hub, www.gov.uk)*

In July 2015 (*Deregulation Act 2015*, www.gov.uk) the Government decided to remove the Zero Carbon policy and the mandatory use of the Code for Sustainable Homes, with the justification that this should remove delays to the construction of new housing supply (HM Treasury and BIS, 2015). Of particular concern here is that even-though the Zero Carbon standard was designed mainly for new build properties, housebuilders could through the ‘Allowable Solutions’ turn the spotlight onto the existing housing stock which enabled housebuilders to argue that their developments could potentially contribute to

---

[10] The sustainability criteria of the Code included: energy, water, waste, pollution, management, ecology, health and materials. In the Code for Sustainable Homes, there are six levels of compliance, with level six meeting the energy definition of Zero Carbon.

the upgrade of nearby housing to similar energy efficient standards - if Zero Carbon homes would become the industry's norm then a wider momentum to retrofit activity could also be progressively influenced. The disheartening truth, however, is that the proposed stimulation of new-build housing supposedly at the heart of the cancellation of the Zero Carbon policy will have a direct regressive effect in the future, as all housing that is aimed to be built to only current construction standards will itself require retrofit in a future years (Mark, 2016) if its energy use is to be constrained : the funds initially "saved" from the Zero Carbon cancellation could turn to be higher when these homes need to be upgraded.

2.5.6. Code for Sustainable Homes and BREEAM

The Code for Sustainable Homes underpins the Building Regulations for new residential developments and is the successor of EcoHomes (2000-2010). It covers more than energy performance alone and its sustainability criteria include: Energy, Transport, Pollution, Materials, Water, Land Use and Ecology, Health and Wellbeing, using SAP for the energy performance calculation. It was launched in 2006 and was meant to become mandatory in 2016 but it was scrapped as in 2014 (Hartman, 2014) prior to the end of Zero Carbon. The Code for Sustainable Homes is still operational, but is now generally voluntary.

BREEAM (Building Research Establishment Environmental Assessment Method) is BRE's method for housing assessment (both new and refurbishments). Even though BREEAM is a "voluntary" sustainable assessment rating system, some UK local authorities may require BREEAM certification (or equivalent) either as part of a local plan, or as a planning condition for developments[11]. BREEAM has five categories for different types of development that include: BREEAM Communities for master planning, BREEAM Infrastructure for Civil Engineering and Public Realm, BREEAM Homes and

---

[11] City of London Local Plan Sustainable development planning requirements: www.cityoflondon.gov.uk/services/environment-and-planning/planning/design/sustainable-design/Pages/Sustainable-development-planning-requirements.aspx

Commercial Buildings, BREEAM In-Use for commercial Buildings and BREEAM Refurbishment and Fit-out for homes and commercial Buildings[12]. BREEAM Refurbishment replaced the EcoHomes (major refurbishment) and EcoHomes XB 2006 (minor interventions). The rating system is similar to the Code for Sustainable Homes that it includes the same categories and it is also uses SAP for its energy performance calculation.

2.5.7. Other UK policy drivers

Since the Energy Performance of Buildings Directive in 2002, a number of drivers and incentives were introduced aiming a. to reduce energy consumption in existing homes; and b. to stimulate the establishment of a strong UK retrofit industry.

2.5.7.1. FIT (Feed-In Tariff) and RHI (Renewable Heat Incentive)

These are specific incentives aimed at encouraging householders to retrofit renewables and other solar-generated energy (such as from Photo-Electric cells) in their properties and “sell” the energy created back to the grid. The Renewable Energy Strategy(HM Government, 2009) suggests that by 2020 over 30% of electricity should come from renewable sources including 2% from small-scale sources. Such ‘microgeneration’ is defined in Section 82 of the UK’s *Energy Act* (2004)[13] as the production of electricity or heat from a low-carbon source, at capacities of no more than 50 kWe or 45 kWth. Unfortunately in December 2015 the government revealed a 65% cut in subsidies regarding solar power putting, at risk 18,700 jobs (Macalister, 2015; DECC, 2015d) - in April 2016 small-scale solar power installations dropped by 74% compared to the previous year (Vaughan, 2016).

---

[12] BREEAM technical standards: www.breeam.com/discover/technical-standards/

[13] Energy Act 2004 Section 82: www.legislation.gov.uk/ukpga/2004/20/section/82

2.5.7.2. TSB's Retrofit for the Future

A Technology Strategy Board initiative, the Retrofit for The Future[14] programme spanned from 2009 to 2011 with £17m of funding through the Small Business Research Initiative (SBRI)[15]. The aim was to demonstrate how to achieve up to 80% energy reduction on UK's social housing stock through major retrofit implementations with grants up to £150,000 per property. An average 50% energy reduction was achieved, although the percentage target was criticized as the 80% reduction was not feasible especially in properties that were already performing better in relation to older constructions(Gupta et al., 2015). The high cost of retrofit (£150,000 including design and monitoring) showed the difficulty of "upscaling" this approach and cost to many properties - the cost analysis (The Technology Strategy Board, 2014)of the applications and reasons of the cost variations have been summarized principally as to: bespoke products affect the cost rise along with procuring form immature supply chains and poorly applied installations that require remedial work. The intent of the programme however was to "kick start" the retrofit market (Jones *et al.,* 2013) and make innovative solutions for energy reduction the norm, raising the hope that with supply chain innovation this cost could be made smaller (Gupta et al., 2015). Other findings showed that when the design team and residents were involved together with the delivery satisfaction was much higher (Institute for Sustainability, 2012).This could be taken as evidence of the importance of the occupier's involvement and choice throughout the retrofit procedures to achieve greater comfort and greater energy savings since the residents' have a greater understanding of how the systems operate in situ.

---

[14] Innovate UK is the new name for the Technology Strategy Board. Information about Retrofit for the Future can be found: https://retrofit.innovateuk.org/

[15] Information about BRSI:www.gov.uk/government/collections/sbri-the-small-business-research-initiative

2.5.7.3. Green Deal

Green Deal was a heavily criticized financing program (Gardiner, 2015) that ran between 2013 and 2015[16], its aim was the finance of housing retrofit measures through loans that would be repaid through the house utility bill savings designed around a 'Pay as You Save' model[17]. The Department of Energy and Climate Change was the generator of the program aiming at the reduction of energy carbon, to tackle fuel poverty and stimulate the market. The financing mechanism was led by the “golden rule” i.e. the energy and cost saving achieved from the retrofit upgrades in the property would have to be able to pay back the amount it was borrowed for the applications. The main reasons of its failure were its over-complexity and high loan interest rates that did not reflect the energy and cost payback from the retrofit upgrades (DECC and NAO, 2016; Pettifor, Wilson and Chryssochoidis, 2015; Washan and Cole, 2012). Even before it was lunched other research had already showed likely problems - a study made by Affinity Sutton exploring the feasibilities for retrofitting their stock showed a funding gap ranging from £3k-£10k depending on the level of the upgrade (Washan and Cole, 2012).The damage of the low Green Deal uptake and its subsequent closure was particularly reflected in the impact upon many supply chain companies as they had heavily invested in materials and employees and were eventually left with high financial damage and loss of jobs (Gardiner, 2015). The National Audit Office published a report (DECC and NAO, 2016) showing that only 1% of households took the “Green Loans” and that the Green Deal did not achieve “value for money” and delivered “negligible” carbon savings.

---

[16] The Green Deal (Qualifying Energy Improvements) Order 2012 link: http://www.legislation.gov.uk/ukdsi/2012/9780111525234/contents. Energy Saving Trust: Update (24 July 2015) The UK Government has decided to stop funding the Green Deal Finance Company (GDFC). The GDFC was set up to lend money to Green Deal providers. www.energysavingtrust.org.uk/scotland/grants-loans/green-deal

[17] UKGBC: www.ukgbc.org/resources/key-topics/new-build-and-retrofit/retrofit-domestic-buildings

2.5.7.4. ECO (Energy Company Obligations)

ECO was introduced in 2013, with equivalent previous schemes CERT (Carbon Emissions Reduction Target 2008-2012) and CESP(Community Energy Saving Programme 2009-2012)[18], aiming to reduce energy consumption and support people living in fuel poverty by funding energy efficiency improvements in homes. The installation funding of these measures are the obligation of big energy companies. The DECC aimed in the combination of Green Deal and ECO in cases where the measures where too expensive to meet the conditions for accessing Green Deal loans. Additionally, contributions from energy suppliers through ECO were expected and ECO installers were encouraged to promote the Green deal scheme. However, suppliers were rarely able to achieve this as very few households saw Green Deal finance as a sufficiently attractive proposition (DECC and NAO, 2016).

ECO has equally been under criticism as it has a regressive impact as the cost of installation reflects in the residents' bills, including those within the fuel poverty category and its predecessors (CERT and CESP) had achieved more than double the carbon savings in relation to the amount of funds dedicate to the scheme (DECC and NAO, 2016)but this is mainly due to the fact that ECO's aim was to tackle 'harder-to-treat' properties, which cost more and take longer to improve.

Since its introduction in 2013 there have been three updated amended versions (www.ofgem.gov.uk). The initial ECO1 ran from 2013 to 2015 similar to Green Deal, it was followed by ECO2 from 2015 to 2017 and extended to 2018 known as ECO2t. The current scheme, ECO3, began in 2018 and it is aimed to run up to 2022[19].

---

[18] OFGEM(The Office of Gas and Electricity Markets): www.ofgem.gov.uk/environmental-programmes/eco/overview-previous-schemes

[19] Department for Business, Energy and Industrial Strategy: https://www.gov.uk/government/consultations/energy-company-obligation-eco3-2018-to-2022

2.5.7.5. Bonfield Review PAS 2030 and PAS 2035

The Government in July 2015 commissioned Dr Peter Bonfield, Chief Executive of the Building Research Establishment (BRE) to lead an independent review of consumer protection, advice, standards and enforcement for UK home energy efficient and renewable energy measures. The review report titled Each Home Counts (Bonfield, 2016) proposed the introduction of a quality mark that brings together existing standards and quality assurance. The wider intention is the establishment of a quality mark for the retrofit industry sector. This is aimed to be established by focusing on three basic elements: *Code of Conduct;* a *Consumer Charter* and defined *Codes of Practice and standards*. The *Code of Conduct* will be a set of requirements on the companies' behaviour on operation and reporting in alignment with quality mark. The *Consumer Charter* will emphasize on the consumers journey with a focus on their rights under the *Code of Conduct* and responsibilities. Finally, the *Codes of Practice and standards* focuses on the quality of assessments and installations in accordance with existing and future updated standards. The Publicly Available Specification (PAS) is a specification for the installation of energy efficiency measures in existing buildings which is developed by the British Standards Institution (BSI). Due to the Each Home Counts review the PAS 2030 was revised in 2017 (2030: 2017 *Specification for the Installation of Energy Efficiency Measures*) (BSI, 2017) as the original standard was criticized as “not fit for purpose”(Rickaby, 2017a) and measures under the current ECO3 scheme require to be installed in accordance with PAS 2030:2017. There are three main updates on the specification (Rickaby, 2017a): a. the installers need to be involved in the site-specific design of the installation, b. the design has to take into account the “whole-dwelling” focus i.e. take into account interactions between measures installed and c. when insulation is proposed the existing ventilation system must be assessed and if necessary upgraded.

The Each Home Counts review also brought to the forefront additional need for further work on standards in retrofit and as a result a PAS 2035[20] specification is on development that includes all the stages of work from assessment to monitoring and evaluation (Price *et al.*, 2017).

Even though the ECO3 does not currently include the Each Home Counts quality mark (but intends to do so in late date) (DBEIS, 2018), it is evident that there is a shift on legislation to focus on holistic quality of delivery rather than just aim to achieve CO_2 or energy targets.

2.6. Concluding remarks

Although the various UK drivers introduced so far have not fully “succeeded” in meeting the desire to stimulate substantial retrofit activities very valuable lessons have been learned that the industry and market can utilise for its growth:

- As retrofit might not always increase the monetary value of the property improved the industry needs to explore alternative routes on educating both their workforce and homeowners with regards to other energy, comfort and health benefits.
- Retrofit is disruptive to residents and communities, so the industry has to explore mechanisms for the smooth delivery of the process via experienced teams.
- The approach used has to be cohesive: if measures are not comprehensive and are not working with each other, the results could be proven harmful and more costly in the long run.
- The complexity of previous schemes was the biggest drawback for their uptake and the need for clearer models of delivery is evident.
- The lack of regulatory coherence that has been proven extremely problematic for the industry supply chain. Programmes and incentives such as Green Deal and ECO were mainly focusing on stand-alone retrofit implementations, usually

---

[20] PAS 2035 link to the BSI standard development site: https://standardsdevelopment.bsigroup.com/projects/2017-04146

tackling the worst performing element(s) of the dwelling but without considering it as a whole. This, as discussed in section 2.5.7.5 is gradually changing and Whole-House approaches are becoming part of legislation in housing retrofit. Previous attempts or regulation focused on either energy/ carbon targets (TSB's Retrofit for the future, Zero Carbon) or elemental approaches to single elements without consideration to the whole dwelling (Green Deal/Building Regulations). Nonetheless, quality in assessment, design, installation and delivery and actual energy deduction go hand to hand (as explained in sections 2.1 to 2.4.).

3. Innovations in UK house improvement techniques

These sections purpose is to discuss and review the latest attitudes and approaches in the UK retrofit “evolution” and sets the initial contexts of the research rational.

3.1. Current attitudes of the UK retrofit industry

3.1.1. Brexit and the construction industry’s future

The results of the June 2016 referendum for UK to leave the EU have left the many key actors in the construction industry feeling very vulnerable to uncertainty about what the future could hold: speculations are already being made of the potential impact (McLeod and Milne, 2016; AECB, 2016; Cross, 2016; Simpson, 2016) that the UK could repeal its obligations the European Energy Performance of Buildings Directive. The latest CCC Progress report (CCC, 2016) notes the uncertainty regarding future regulation: *“The vote to leave the EU may have an impact on how emission reduction is delivered in the buildings sector. A number of EU policies currently contribute to cost-effective emission reduction. To meet the UK's domestic emission reduction commitment, it will be necessary to agree new arrangements or adapt existing arrangements, as appropriate. It is too early for the Committee to assess the precise balance under the new arrangements*” (Page 83).

The construction industry also relies heavily on foreign skilled and un-skilled workers and the potential curtailment of free movement of persons following Brexit is another key concern. The 2015 RICS UK Construction Survey showed that 66% of firms reported having turned down work due to a lack of staff as a result of the skills shortage but with UK unemployment at a low of about 5.1% (McLeod and Milne, 2016) it may be reasonable to assume that the labour and skills shortage in the construction industry cannot be resolved domestically. Similarly, while the materials used in the UK construction industry are largely domestically produced, there is a large market of imports especially from Germany, China, Italy and Sweden (McLeod and Milne, 2016): with three of those countries being part of the EU, any future UK restriction on the free movement of goods and workers could lead to costs being increased, making the demand for retrofit works even more challenging.

The retrofit industry's immediate response to the Brexit referendum was one of enormous concern given the years preparing for the implementation of Zero Carbon standards, including public and private investments in projects like the AIMC4 project (www.aimc4.com) a partnership of companies, created to research, develop and pioneer the volume production of the low carbon homes for the future. The housebuilding firm-Stewart Milne estimated it had already invested £1million into the research and development of Zero Carbon homes (Thorpe, 2016).

3.1.2. Grenfell Tower fire tragedy

The fire in Grenfell Tower in west London on 14th of June 2017 is considered the worst experienced during peacetime since the 19th century and has resulted to 72 casualties along with 70 physically injured (MacLeod, 2018). The inquiry on the fire examining the circumstance leading to the catastrophe is still ongoing (www.grenfelltowerinquiry.org.uk) but reports from experts (part of the inquiry) have stated that "*evidence "strongly supports" the theory that the polyethylene material in the cladding was the primary cause of the fire's spread*" (Professor Luke Bisby,(BBC, 2018). The decisions leading to the cladding fitting and eventual disaster have brought in the forefront issues with social injustice, the culture of deregulation and the construction industry's fragmentation.

Grenfell Tower is mainly social housing and home to predominantly lower and modest income, working class residents while it sits in the north of Kensington and Chelsea surrounded by more affluent neighbourhoods. Thus, the questions quickly rose whether an equivalent incident would be feasible in one of building of the wealthier residents. This was brought in the forefront as Grenfell Tower residents had since 2013 raised serious concerns about fire safety with the Kensington and Chelsea Tenant Management Organisation (KCTMO) (MacLeod, 2018).

The outer rainscreen cladding at Grenfell Tower was a Reynobond PE composite panel made of an unmodified polyethylene core sandwiched between two layers of aluminium and set 25 to 50mm away from the PIR insulation fixed on the existing wall (Odell and O'Murchu, 2017). Similar cladding insulant tested in BRE had showed their "unacceptable" flammability (De-Selincourt, 2017) and the question was raised on how was it possible to be applied in this occasion.

The deregulation as part of a war on "red tape" meant that reforms on Build Regulations Part B (Fire safety) were not made to include provision for automatic sprinklers and revisiting fire standards for cladding (De-Selincourt, 2017). Adding to this the KCTMO for cost cutting reason contracted the installed cladding rather than that previously recommended and approved by the residents, architects and engineers ; zinc composite with a fire-retardant core while at least eight sub-contractor firms part of the refurbishment questioning the level the levels of expertise and the degree of oversight of the project (MacLeod, 2018).

The Grenfell Tower fire will undoubtedly have a wider impact on how the external wall insulation retrofit is perceived from now on even if the measures or materials are up to higher standards. Rickaby, (2017b) appropriately stated on the future outcome in the sector by the Grenfell Tower fire:

"It may mark the end of any external wall insulation on residential towers, leaving us little option but to leave residents in cold, hard-to-heat, mouldy homes, or to demolish and rebuild. It may delay retrofit in social housing for a while, because scarce resources will be diverted to improving fire safety and installing sprinkler systems. The social, economic and environmental repercussions will last for many years" (page 8).

3.1.3. 'Elemental' versus 'Whole-House' retrofit

There are fundamentally two different approaches to housing retrofit that deliver different results: *elemental measures* focusing on single component upgrades and piecemeal energy savings, and *Whole-House* retrofit referring to a combination of measures aiming to reduce overall energy demand to a minimum.

The ‘elemental’ approach to domestic retrofit focuses on upgrading or replacing the worst performing element of the structure (such as single-pane glazing) and is a method used in many large scale projects aiming to include large numbers of properties with the finance available at the time (Jones *et al.,* 2013; NEF and EEPB, 2014b). This is the “method” supported by programmes like the Green Deal (www.gov.uk/green-deal-energy-saving-measures/overview), previous ECO programmes (www.ofgem.gov.uk) and by region specific programmes such Warm Wales (www.warmwales.org.uk). In practice there have been well-documented catastrophic results when the single element upgrades do not take in to account “misapplied” cavity and external wall insulation or other works that have been inadequately installed. BRE research (BRE, 2015) demonstrated that the cost of extracting faulty insulation is five times higher than the original installation, along with introducing further structural problems. A consultation report made by CoRE (Centre of Retrofit Excellence)[21] in 2015 for the Green Construction Board (De-Selincourt, 2015), explored the complications faced specifically in solid wall insulation applications through a series of responses from across different disciples of the industry. The root of the problem lays in the uncoordinated installation of individual measures by separate installers who have not been trained appropriately in regards to how their work relates to what the next installer may be doing (PAS 2030; Green Deal / ECO) but as discussed in sections 2.5.7.4 and 2.5.7.5 these methods are beginning to change.

‘Whole-House’ retrofit refers to a retrofit method that integrates a series of improvement-measures tailored for the specific property, either at a single point in time or applied incrementally in stages. The usual process for implementing the Whole-House method

---

[21] The Centre of Retrofit Excellence (CoRE) has since 2016 been closed. Many of the previous trainers and industry representatives are now behind The Retrofit Academy with the same ethos and goals, link: www.retrofitacademy.org

will be to commence with a ‘fabric first’ approach, meaning upgrades are first applied to the built structure of the dwelling prior to implementing upgrades to services and other energy uses within a building, and to subsequent ventilation strategies, heating systems and lighting. Research into retrofit drivers introduced to date (Green Deal, ECO, RftF), academic research (Jones, Lannon and Patterson, 2013; Simpson *et al.*, 2015; Baeli, 2013) and industry representative organisations (NEF, 2014; De-Selincourt, 2015; BRE, 2016) have concurred in their conclusions that that the Whole-House approach in retrofit is the most beneficial *in the long term* for the following reasons:

- Higher energy reduction and lower cost of bills
- Minimized risk of faulty installations and increase the building’s durability
- Increased comfort and wellbeing through indoor environmental quality

Notwithstanding the basic principle that higher capital outlay can lead to increased reductions in energy use and thereby also in CO_2 emissions (see the schematic summary in *Figure 3.1* below), in the *short term*, there remains concern that ‘Whole-House’ retrofit still requires higher outlay of capital costs to bring about a large scale uptake, as examples from Retrofit for the Future showed.

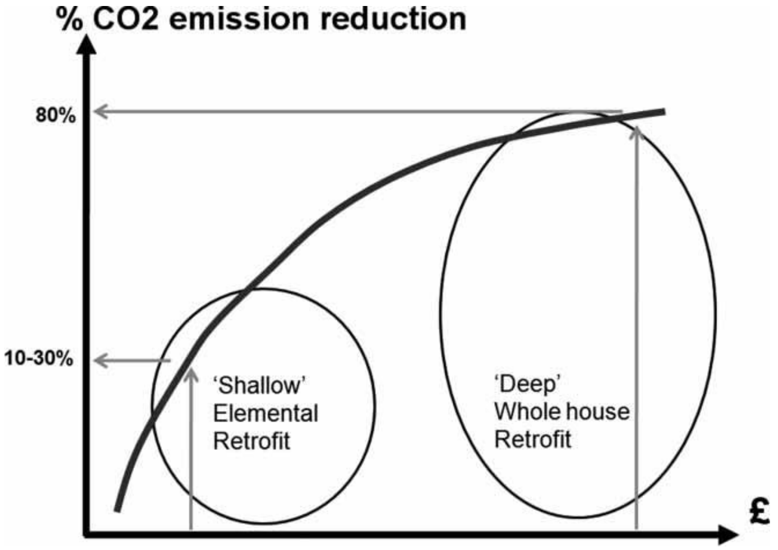


***Figure 3.1** Retrofit cost relative to CO_2 emissions reduction*
Figure taken from (Jones et al., 2013)*, page 536.*

A study made by Jones, Lannon and Patterson, (2013) also raised the question of whether the large scale impact of stand-alone (‘elemental’) measures, upgrading the worst performing elements of buildings, has a greater impact in energy and cost reduction in total, as it could be applied to a high number of properties: a challenge to this can be found in the BRE (BRE, 2015) monitoring of elementally-improved properties that argued such approaches would be unlikely to achieve substantial energy reductions, and that they could also lead to unintended consequences with high risk (structural and on residents’ health).

Some “responses” from the industry are beginning to form the aim to minimize the cost gap of Whole-House deep retrofit these include –the ‘step-by-step’ approach[22] (EuroPHit and Simpson *et al.*, 2015) and the introduction of offsite manufacturing (Energiesprong and Beattie Passive). Supporters of both Passive House and Energiesprong trust that the quality of their delivery of Whole-House retrofit is their “strong card” for subsequent growth in the industry.

3.1.4. Use of Passive House / EnerPHit standards

Adamson (1987) and Feist (1988) the creators of Passive House (PassivHaus, is the original German name) defined it on the Passive House Institute website, as ‘*a building in which the comfortable interior climate can be maintained without the need for active heating and cooling systems’* (*Passive House Institute - What is a Passive House?* www.passivehouse.com). The basic idea is that if the building is super-insulated and adequately ventilated conventional heating will not be required. The space is heated via the occupants’ activities and through passive solar warmth, and the highly insulated fabric would retain that heat in the space. The ‘EnerPHit’[23] standard applies these

---

[22] Step-by-step retrofit refers to the Whole-House retrofit approach that is done in stages through a span of years but prior to the commencement of any work an overall plan has been made to ensure that as a whole all steps will work together(http://europhit.eu)

[23] The Passive House standard was initially designed for new-build and in 2010 the Passive House institute published the first EnerPHit criteria (https://passipedia.org/)

principles to existing properties and even though the targets are more relaxed the same approach applies with a design focus based on five straightforward principles (http://www.passivhaustrust.org.uk/):

- very high levels of insulation
- extremely high performance windows with insulated frames
- airtight building fabric
- 'thermal bridge free' construction
- a mechanical ventilation system with highly efficient heat recovery
- accurate design using the Passive House Planning Package (PHPP).

The levels of energy use that need to be met for a Passive House to be certified are (www.passivhaus.org.uk) shown in *Table 3.1*:

Criteria	Passive House	EnerPHit
Specific Heat Demand (SHD)	≤ 15 kWh/m².yr	≤ 25 kWh/m^2.a
Primary Energy Demand (PE)	≤ 120 kWh/m².yr	≤ 120 kWh/m^2.a *
Limiting Value	n_{50} ≤0.6^{-1}	n_{50} ≤1.0^{-1}
** PE ≤ 120 kWh/m^2.a + ((SHD - 15 kWh/m^2.a) x1.2)*		

Table 3.1 *Passive House and EnerPHit criteria comparison*

At present, a dwelling in the UK can achieve Passive House certification and achieve regulatory compliance but SAP (Standard Assessment Procedure) is the most commonly used and accepted. SAP is a tool to show compliance with the required regulations and not to be used as design tool (Powell, *et. all* , 2015). The equivalent SAP for retrofit is RdSAP (Reduced Data SAP) that requires even less “detailed” entries for an assessment (www.bre.co.uk).

A comparison of PHPP and SAP suggests:

- SAP “needs” less data entry so is easier to use but less accurate and detailed
- SAP may underestimate heating load for low energy buildings.
- PHPP entails more data entries taking longer to create models and requires more experience and knowledge

- PHPP delivers more accurate results with clear distinctions between final to primary energy
- SAP has become more CO_2 focussed to “prove” compliance and fabric efficiency is of “less importance”

The Passive House standard, as applied both to domestic and non-domestic buildings, is the fastest-growing energy performance standard and there are around 50,000 certified buildings around the world (Hopfe and Mcleod, 2015)- in Ireland Dun Laoghaire-Rathdown County Council has made Passive House mandatory for all new buildings in 2015 “*All new buildings will be required to meet the passive house standard or equivalent, where reasonably practicable”* (www.phai.ie). Certified Passive House buildings have proven through monitoring that they have been able to minimize the ‘energy performance gap’ i.e. the buildings operate as designed (Johnston *et al.*, 2016; Hopfe and Mcleod, 2015; Baeli, 2013).

3.1.5. Supply chain issues in retrofit

The retrofit supply chain is diverse made up from different sub-sectors. When whole house retrofit activity occurs, each sub-sector is brought together and managed by a central project or contract manager. Nonetheless, supply chain fragmentation and shortage in skills and knowledge has been an issue faced in retrofit programmes and analysed in proceeding research (NEF and EEPB, 2014b; Kenington *et al.*, 2014; Topouzi, Killip, and Owen, 2017; Gupta et al., 2015). In the Retrofit for the Future programme (2.5.7.2) for example this was an issue that contributed to cost increase and brought the supply chain “inadequacies” in the forefront (The Technology Strategy Board, 2013; Gupta et al., 2015; Baeli, 2013). The Green Deal programme (2.5.7.3) emphasised those issues even further with elemental approaches from different supply chain trades that resulted to unrealistic cost payback from the retrofit upgrades (DECC and NAO, 2016; Pettifor, Wilson and Chryssochoidis, 2015; Washan and Cole, 2012) and even unintended consequences to the building’s structure (De-Selincourt, 2015).

Finally, the gravest illustration of the supply chain issues is reflected in the Grenfell Tower fire tragedy (3.1.2) where it resulted in the loss of human life and possible future mistrust in the retrofit applications (Rickaby, 2017b) .

Therefore, those examples presents that accountability, supply coordination along with developed skills and knowledge are the identified improvements the supply chain has to adopt moving forward (Topouzi *et al.,* 2017; Bonfield, 2016; NEF and EEPB, 2014b).

3.2. Offsite approaches in retrofit

The following sections are reviewing f offsite measures examples in retrofit that have been applied in the UK housing stock.

3.2.1. Energiesprong

A Dutch government-supported refurbishment approach - Energiesprong (broadly translated as 'Energy Leap') - is an innovative Whole-House initiative that is seen as a possible solution to retrofit on a large scale and to minimising the 'energy gap' (Gupta and Gregg, 2016) involving wrapping an existing dwelling in a customized, offsite prefabricated system of wall and roof panels to achieve ambitious energy improvements (Transition Zero: www.energiesprong.eu/). Its central concept works by replacing household energy bills with an energy plan that is paid to the provider of the house improvements (www.energiesprong.eu/) that are themselves governed by principles of:

- Quality (the refurbishment including long-term energy performance warranty - up to 30 years - on the house)
- Affordability (no additional cost to the household, financed by the resulting energy cost savings)
- Desirability (improving the look and feel of the house)
- Non-intrusiveness of the entire refurbishment (on-site refurbishment is within one week, and residents live in the house during installation.

The UK's Energy Saving Trust is involved in exploring integration of the programme into the UK housing market along with partners from all spectrums of the industry, house providers, construction sector and policy experts. In early June 2016 they secured €5.4m (£4.23m) of European funding through the Interreg NWE programme (www.nweurope.eu/ andwww.nef.org.uk/) to be used co-funding early market Energiesprong retrofits and allow the independent Energiesprong market development teams in the UK, France and the Netherlands.


.

***Figure 3.2** Energiesprong Nottingham retrofit*

(Image credit: Energiesprong, http://transition-zero.eu/index.php/2018/09/27/ccc-2018-progress-report-energiesprong/)

This will aim to put in place the right market conditions for these net-zero energy refurbishments to take place at scale but once again it is unsure how the UK's position in EU will influence, if at all the programme. The Nottingham City Homes are the first to adopt the Energiesprong approach with the first properties already retrofitted (*Figure 3.2*) (UK Green Building Council, 2018) and won the Housing Award for Innovation in 2018 (Energiesprong UK, 2018)

3.2.2. Beattie Passive

Beattie Passive is the first UK Certified Passive House building system[24] . The system uses timber frame structure and introduces continuous insulation around its core with the airtightness layer is applied internally. The levels of thermal insulation and airtightness are up to Passive House standards or better with equal levels of quality in fire resistance and acoustics with regards to Building Regulation standards. Offsite construction is used

---

[24] Beattie Passive web page: http://www.beattiepassive.com/index.php

where feasible and a "flying factory" where the offsite construction is made local to the project utilising local labour and reducing cost of transport. Even though the high volume of construction is currently in new-build, Beattie Passive has introduced their Whole-House retrofit version called TCosy™[25] with the same principles in their delivery of standards and in principle the timber structure becomes an external cell to the existing property (*Figure 3.3*).

Figure 3.3 *Beattie Passive Birmingham retrofit*

Left before and Right after retrofit

(Image credit: Beattie Passive, https://beattiepassiveblog.wordpress.com/category/birmingham-tcosy-blog/)

The retrofit approach is similar to Energiesprong in regards to the offsite element, the External Wall Insulation/structure measures and the fact that the delivery comes from the "particular co-ordinator/contractor". The main difference is on the type of "delivery assurance/guarantee" they provide. For example, Energiesprong guarantees zero bills for 30 years with the combination of upgrading the existing building fabric and the addition of renewables with no specific "claim" on energy target per say. On the other hand, Beattie Passive TCosy guarantees the delivery of the equivalent Passive House standard for retrofit, EnerPHit by ensuring through detailed checks (i.e. thermal imaging/airtightness tests) the required criteria are met as shown in *Table 3.1*. For obvious transparency reasons any Passive House or EnerPHit certification is given by a third body, a Passive House Institute accredited Building Certifier (http://passivhaustrust.org.uk/certification.php).

---

[25] Beattie Passive web page in retrofit: http://www.beattiepassiveretrofit.com/

As discussed in section 3.1.4 Passive House has been proven though exiting monitoring data from previous projects to deliver the energy designed thus this is Beattie Passive's "guarantee". Similarly, providing access and transparency in the delivery data provides an assurance for clients, legislation and even research.

3.2.3. Retrofit for the Future offsite examples

There are three projects in TSB's Retrofit for the Future that used different offsite mechanisms in their retrofit delivery: The Walker Garden Suburb in Newcastle upon Tyne, Cottesmore in Leicester and Bertram Street London. The Walker Garden Suburb[26] project is a 1940's semi-detached with brick cavity construction. The strategy comprised of External Wall Insulation to Passive House standards and the replacement of the existing 2-storey bay-windows with a modular off-site equivalent. The main strategy for the bay-window replacement was the eliminate the existing thermal bridging as it was identified though thermal imaging as one of the worst areas within the building (Crilly *et al.*, 2012).

Figure 3.4 *Walker Garden Suburb retrofit*
Left before and Right after retrofit
(Image credit: Low Energy Building Database, www.lowenergybuildings.org.uk/viewproject.php?id=157)

The new modular bay-window in combination with External Wall Insulation alter significantly the existing façade (*Figure 3.4*) of the building but it is safe to assume that

---

[26] Low Energy Building Database Walker Garden Suburb project page: www.lowenergybuildings.org.uk/viewproject.php?id=157

there would be any planning restriction to that extend as the building does not seem to have any heritage or streetscape “significance”.

In contrast, Cottesmore[27] a much older property (pre-1919) located in a conservation area the retrofit approach was quite different. The wall insulation was implemented internally and the entire roof was replaced with a prefabricated modular “loft pod” (*Figure 3.5*) that introduced 10 to 15% additional living area (Crilly *et al.,* 2012, Baeli, 2013).

Figure 3.5 *Cottesmore retrofit*

Left street view, middle “Loft pod” being fitted and right new roof view showing no height deference with adjacent properties (Image credit: Crilly and Lemon, (2012).

This is great example of how potentially offsite mechanisms could be implemented in older properties without having an external visual impact on the existing building or area. Additionally, the prefabricated “Loft pod” is fitted within a day (Baeli, 2013) and the additional living area compensates for any internal area lost from the Internal Wall Insulation applied.

The third project, Bertram Street[28] to some extent is similar, a pre-1919 terrace with the equally feasible planning restrictions to the alteration of its façade as it also locate in a conservation area (Baeli, 2013).

---

[27] Low Energy Building Database Cottesmore project page: www.lowenergybuildings.org.uk/viewproject.php?id=152

[28] Low Energy Building Database Bertram Street project page: www.lowenergybuildings.org.uk/viewproject.php?id=24#images

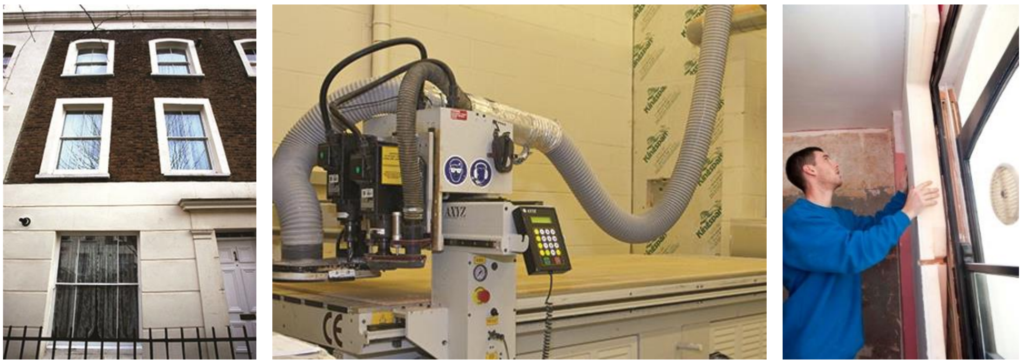


Figure 3.6 *Bertram Street retrofit*
Left street view, middle offsite laser cut of the insulation and right pre-cut insulation fitted.
(Image credit: NEF, www.nef.org.uk/service/search/result/whiscers & Baeli, (2013))

The retrofit approach was to insulate the existing wall internally using the WHISCERS™[29] (Whole-House In-Situ Carbon and Energy Reduction Solution) process which comprises in three basic steps. First a laser scanner is used to take accurate measures of the rooms, then the data are downloaded to a factory-based offsite cutting machine where the insulation boards are cut to the exact required measurements and finally the boards are fitted onsite (NEF, 2015) with the whole process reducing the waste by 10-15% in comparison to onsite cutting (Wrap, 2016). Equally important is that usually the Internal Wall Insulation application can be very disruptive as occupants require moving out of the property while work is being done but with this approach the residents can be on site when the survey and installation is taking place (NEF, 2015).

3.2.4. The potential of ‘offsite’ manufacture

Gibb, (1999) defined the concept of offsite as “*a process which incorporates prefabrication and pre-assembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site. In its fullest sense, off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation*” (Page 2). Nonetheless, the concept of offsite

---

[29] National Energy Foundation WHISCERS™ page: www.nef.org.uk/service/search/result/whiscers

manufacturing in construction is mainly known in the UK as a post-war solution that answered the need for mass construction of buildings. The criticism that the architecture of that period eventually received made ‘offsite’ a synonym to that era and unfortunately offsite-manufacture of building components is still viewed with general suspicion in UK (Pan *et al.*, 2004). Several studies have nevertheless revealed the benefits of prefabrication and offsite manufacturing (Gaze *et al.*, 2007; Monahan and Powell, 2011; NHBC, 2016; Zimmermann, 2012; Krug and Miles, 2013; Hairstans, 2014):

- Minimising construction time
- Efficient use of materials along with almost zero waste, having a significant reduction to their embodied energy
- Cost reduction due to the above along with reduced snagging and defects
- Light-weight structures when timber is used
- High safety controls as construction happens largely in a controlled environment

The actual process of offsite manufacturing can be classified under different principal methods (Pan et al., 2004a; Venables *et al.*, 2004; Ross, Cartwright and Novakovic, 2006; Hairstans, 2014):

- **Components:** Non-structural elements assembled offsite;
- **Subassemblies**: Key building elements manufactured offsite, or basic services provided in ‘cassette panels’;
- **Hybrid systems:** A mixture of volumetric and panelised structures;
- **Open panel systems**: Usually delivered to the site as a structural element with services, insulation, cladding while the internal finishes are installed onsite;
- **Closed panel systems**: Are have more factory-based construction such as lining and insulation and may include cladding, internal finishes, services and plumbing, or even doors and windows;
- **Volumetric systems:** Three-dimensional modules that can be used in isolation or in multiples to form the structure of the building and have the most factory base production

In UK, examples of offsite manufacturing in retrofit have been explored as discussed in the previous sections (3.2.1. to 3.2.3) with different approaches on the concept. The Energiesprong and Beattie Passive are using closed and open panel systems as their approach is the “wrapping” of the existing building fabric. The retrofit for the Future projects, Walker Garden Suburb and Cottesmore used volumetric systems to replace specific elements of the building with better equivalents and Bertram Street with its WHISCERS process using to some extend the component method.

The Energiesprong and Beattie Passive projects may offer as good examples of the industry’s potential, achieving maximum energy reduction while providing an accessible and desirable product, but it is not an idea without limitations; their applications so far in the Netherlands (Energiesprong) and the initial aims for UK applications are for its use in the social housing sector, where the stock is mainly post-1950’s structures and are, by its “structural form” (less exposed external envelop, flat facades, usually no planning application restrictions) reasonably straightforward to retrofit. The transition to the private market with more varied and complex structures and a different set of issues for potential funding mechanisms could be challenging. Beattie Passive to date of this thesis has at least one homeowner’s retrofit project that applied their TCosy system[30] and Energiesprong’s intention is that after establishing the industry with the social sector stock, the transition to the private sector will become easier with potentially similar financing mechanisms - a financier providing homeowners with finance for the refurbishment package and instead of paying their previous level of energy bill the homeowners pay instalments on the refurbishment loan (Energiesprong, 2015).

3.2.5. Supply chain issues in retrofit with offsite

Offsite construction offers a controlled supply chain management equally when used in new build or retrofit. For this reason Energiesprong and Beattie Passive (3.2.1. to 3.2.3) are able to guarantee their respective energy standards and similarly WHISCERS (3.2.3)

---

[30] Beattie Passive homeowner retrofit project: http://beattiepassiveprojects.com/woodstock/

has their own team to even include the removal and re-instalment of services in their application. In the Retrofit for the Future projects (Walker Garden Suburb in Newcastle upon Tyne and Cottesmore in Leicester 3.2.3) it was recognised that for the offsite construction in retrofit to have a macro scale effect in the market, close collaboration with the extended supply and fabrication chain is needed (Crilly and Lemon, 2012a). Those are concepts that both Energiesprong and Beattie Passive use with either local/national contractors (Energiesprong) or the utilisation of local labour (Beattie Passive). Additionally, the flexibility that the technology offers with BIM and laser scanning the offsite supply chains can make “economies of scope” (Venables *et al.,* 2004) possible for retrofit that requires more “bespoke” approaches in their application.

Offsite construction in new build is experiencing a momentum to deliver both quality and quantity of homes in UK and even favoured in publicly funded project (HM Treasury, 2017). This could be a drive to see more examples of supply driven offsite innovations applied on housing retrofit. Nonetheless, perceptions on offsite construction could have a major effect on their adoption and the next section reviews examples of those from existing research and projects.

3.2.6. Perceptions on retrofit and offsite construction

Understanding the perceptions of the stakeholders of the construction industry is of vital importance to recognise beyond just technical drivers and barriers for retrofit or offsite and previous research has provided insight in understanding various influencing factors. As the combination of housing retrofit with offsite mechanisms is relatively recent in UK there is limited research into how the combination of these two is perceived and derive mainly from the projects reviewed in previous sections (3.2.1 to 3.2.3).

In terms of the occupants' perceptions, apart from Cottesmore where the property was empty, the feedback was positive[31] due to the minimisation of disruption (speed delivery and no relocation). In regards to the actors involved in delivering these projects some very interesting findings were made. In the cases such as Beattie Passive and WHISCERS the delivery team is trained and works under the same contractor. Still Beattie Passive for example in its projects establishes "flying factories" that utilise and train local labour. This could presumably have an effect on how local labour and residents perceive the notion of offsite and possibly by example replicate those mechanisms. Similarly Energiesprong's contractor for their Nottingham project has *"adopted an Energiesprong-style energy performance guarantee as part of their holistic retrofit offer"*(Energiesprong, 2018). This a reflection on what Killip, (2013b) compares to innovation in construction from (Foxon, 2003) as three categories of learning: *"Learning by doing (experimentation); learning by using (familiarisation); learning by interacting (collaboration)"* (page 882). The question though rises on what the wider industry's perceptions are.

In retrofit, the sector on one hand has experienced resistance from tenants that consider the works not only disruptive but also "suspicious" of both "getting something for nothing" (when works are offered by Social Landlords or utility companies) along with bad experiences with maintenance builders (Brown *et al.*, 2014; Boardman, 2007; EST, 2011). On the other hand resistance in market has come from both SME's perceiving accreditation requirements (i.e. PAS 2030) onerous and bureaucratic or expecting demand (from client or regulation) to rise before taking action (Janda *et al.*, 2014; Killip,

---

[31] Occupant feedback from interviews or reference to :

Beattie Passive: https://beattiepassiveblog.wordpress.com/category/birmingham-tcosy-blog/

Energiesprong: www.energiesprong.uk/newspage/new-pilot-helps-optimise-the-energiesprong-solution-for-nottingham-rollout-to-155-homes

Bertram Street: www.superhomes.org.uk/superhomes/london-camden-bertram-street/

2013a; Kenington *et al.*, 2014) and private landlords perceiving no real monetary benefit from undertaking energy efficiency measures (Hope and Booth, 2014).

In the case of offsite construction, previous research suggests that the perceptions of the housebuilding industry focus on issues related to: perceived increased up-front cost, lack of suppliers, lack of suitability and reduced flexibility for the specific project or site along with perceptions grounded in the historical failings (Goodier and Gibb, 2005;Pan *et al.,* 2004a; NHBC, 2016). Even though the technical aspects have been "disproven" though research and actual projects, they are considered majors increased use of offsite in the UK.

Goodier and Gibb's, (2005) research on offsite barriers and opportunities suggested that: "*The preferred method used by suppliers to overcome the resistance of their client to the use of offsite was the provision of examples and case studies of previous successful uses of offsite*"(page 157). While research done by Berry *et al.*,(2014) on the influence of 'Eco open home' events showcasing environmentally sustainable home renovations and retrofits showed that it had a positive impact on the attendees and a great majority followed up with their own low energy renovations. These examples thus raise the question whether the inspiration of precedent projects could also have an influence of the uptake in the combination of the two measures (retrofit and offsite) in the wider sector.

3.3. Perceptions of comfort within retrofit

Comfort in relation to retrofit could be defined within different aspects. In this section three factors are reviewed, a. Indoor comfort as a result of retrofit, b. comfort on reduced disruption during retrofit works and c. guarantee on delivery and performance.

The predominant one is *indoor comfort* which can also have a direct impact in the residents' health as described in section 2.2. Indoor comfort is influenced by temperature (°C), relative humidity (%) and CO_2 levels (ppm). According to CIBSE A (CIBSE, 2015) and the World Health Organisation (World Health Organization, 1987) the recommended indoor temperatures are 21°C in living rooms and 18°C in bedrooms with summer comfort benchmarks 25°C and 21°C in respectively. Even so, temperature comfort may also vary from person to person depending on age, gender and state of health along with the direction of heating/cooling in the space such as cold drafts, cold spots etc. (CIBSE, 2015) . The levels of relative humidity also have an impact on thermal comfort and the recommended levels are between 40% to 70% where levels below or above those benchmarks can cause discomfort and health issues if sustain for long periods of time (BS 5250, 2011). Finally CO_2 levels of 800 to 1000ppm is often used as a good indicator of an adequate ventilation rate in a building that can be achieved with 8 l/s per person (0.5–1 air changes per hour rate (ACH) (CIBSE, 2005). Those factors are guidelines in whole house retrofit design. The Passive House/EnerPHit for example requires internal design temperature of 20ºC, frequency of overheating of hours in a given year ≤10% at 25°C and air humidity levels above 12 g/kg (~60% RH) for ≤ 20% (Passive House Institute, 2016). Additionally, MVHR system provides a steady stream of fresh air and heating designed for 20-30 m^3/h per person and the filters remove airborne pollutants reducing respiratory issues.

The *disruption of construction* works to residents has been a barrier for retrofit uptake identified in previous research (NEF & EEPB, 2014b; Pettifor, Wilson and Chryssochoidis, 2015; UKGBC, 2013; Loveday & Vadodaria, 2013; Britnell & Dixon, 2011). This is translated in the anticipated 'hassle factor' of having home life disrupted while retrofit works are taking place. This is closely connected with the aspect of "comfort" in relation to *guarantee on delivery and performance*, as the renovation sector has been associated in one hand with "cowboy builders" that could problems with the installations along with the uncertainty between predicted and actual performance (NEF & EEPB, 2014b; De-Selincourt, 2015). The offsite measures reviewed in sections 3.2.1 to 3.2.3 are approaching these issues aiming minimising the time of retrofit delivery and by extension disruption along with assuring performance.

3.4. UK housing retrofit overview to date

As outlined in the literature review (Chapter 2) there is a clear economic, health and environmental necessity of a major uptake in housing retrofit in UK. Since the *Climate Change Act* in 2008, research has been done on the role housing retrofit can have in the reduction of carbon use and CO_2 emissions accompanied with clear studies on economic and health benefits (Washan *et al*., 2014; NICE, 2016; DECC, 2015a; Association for the Conservation of Energy, 2015; Royston, 2013). The steps the UK government has taken so far have evidently yet to result in a vibrant retrofit industry and the market has not delivered the desired outcome, while in the name of "housing supply" demand has down-sized legislation 10 years in the making (Zero Carbon). The evidence suggests that even though the current regulatory demands, Building Regulations and minimum EPC bands, are still setting inadequate standards for real energy improvements there is a gradual change in the implementation quality installations in retrofit with the current *PAS 2030:2017* and the future *PAS: 2035 (2019)* signifying the acknowledgment in the *quality* of application and its correlation to energy reduction.

In the face of this, the previous attempts to spark a macro-scale effect of a sustainable retrofit market (RftF/Green Deal) have "taught" lessons that are invaluable for any viable future. The 'Whole-House' retrofit approach such as the EnerPHit standard has been confirmed to offer clear advantages over the "piecemeal incremental" approach, but still the greater up-front cost limits its uptake on a bigger scale (Jones, Lannon and Patterson, 2013; NEF and EEPB, 2014b; Simpson *et al*., 2015). However, in the exploration of innovative mechanisms to reduce the cost of works while achieving the EnerPHit standard, the Passive House Institute with project partners from 11 EU countries[32] undertook a project called EuroPHit spanning from 2013 to 2016 demonstrating the possibilities for step-by-step retrofit and strengthen the industry on achieving the eventual target on NZEBS (Nearly Zero Energy) by 2020. With the loss of

---

[32] Co-funded by the Intelligent Energy Europe Programme of the European Union. (http://ec.europa.eu/).

the UK's Zero Carbon policy and its EU referendum result the future of a concept such as EuroPHit is uncertain. Additionally, its long time-spanning installation of measures could probably not sustain an incentive desirable enough in a UK housing market where "property ladder" is the norm. The quality assurance that a certified Passive House provides could however offer the means of a formal evaluation of the creditworthiness of investments into energy efficiency in buildings. So in this context, the research focused on investigating the next step of innovative opportunities for housing retrofit and evaluates their applicability in the UK context

3.5. Innovation opportunities and research gaps

In theory, offsite manufacturing of prebuild elements could reduce the cost and improve the quality of installation as research has already shown for new-build construction (Gaze *et al.*, 2007; Monahan and Powell, 2011; Krug and Miles, 2013; Hairstans, 2014) yet there is still research to be done on the wider application and feasibility of such an approach being central to UK retrofit works. The current retrofit companies that utilize offsite manufacture in the delivery of "Whole-House" retrofit in UK such as Energiesprong and Beattie Passive aim to "challenge" what the previous retrofit attempts have failed; they guarantee energy reduction assurance whether with the Zero Bills guarantee for 30 years in the case of Energiesprong and certified EnerPHit standard in the case of Beattie Passive. However they are both currently focusing on post 1950's properties that are usually easier to retrofit and less energy demanding to begin with. As recorded by the English Housing Survey (DECC and National Statistics, 2015) the least efficient age typologies in UK are the pre-1919 and except for selective pilot projects the research behind wider feasible approaches on the offsite combination of measures is yet to be done. If the offsite approach is the next step to "retrofit evolution" its barriers and opportunities need to be explored in the dwellings that are most in need of energy reduction. The current housing retrofit barriers as outlined in the literature review (Chapter 2 and 3) could be summarized as lack of regulatory coherence, unintended consequences from incremental approaches, high upfront cost and works being disruptive to residents. Thus the thesis contribution stands on identifying whether the offsite mechanisms could be the instrumental in providing answers to those barriers specifically to the most challenging UK typologies.

3.6. Research aims and fundamental questions

The research aim to explore how this "evolution" in the retrofit industry of both high energy efficient standards (EnerPHit) and construction innovations (offsite) can be applied to the UK's diverse housing, including some of the UK's most common, but challenging, housing types. The objective is to identify the limitations and opportunities within regulatory, technical, economic and social aspects and review whether these applications can have a macroscale effect in the UK housing retrofit market leading to research outcomes that are relevant to industry practice, policy and academia. In particular it aims to answer the following research questions:

RQ .1 *Can the cost of UK Whole-House retrofit to EnerPHit standard be reduced via current offsite mechanisms in pre 1919 UK house typologies?*

RQ .2 Could the UK industry be confident in adopting this combination as common practice?

RQ .3 What innovations are needed by the industry for 'Whole-House' retrofit practice to have a macro-scale effect in the UK?

3.7. Concluding remarks

While the wider construction industry in UK has been criticised for its lack of innovation and decision making unless driven by required legislation (Rickaby, 2015), there has been a more precise identification of the kinds of constraints here when compared with other industries and Piroozfar and Piller, (2013) noted the areas in which innovation is particularly required : the 'size' of the product (house improvements), customers' dimensional interaction with the product, product flexibility, concept of variation, lifecycle, cost, economies of scale, costumers' needs and expectations, ownership (current vs future owners) and supply chain dynamics. So how can the housing retrofit industry adopt to overcome such constraints and could 'offsite' mechanisms along with stronger standards offer an alternative?

4 Research design and methodology

4.1. Introduction

The purpose of this chapter is to give an overview of the research design and methodology, supporting research questions and objectives that have been identified in the literature review.

4.2. Methodology

The research is conducted using a concurrent mixed-method methodology i.e. *explanatory* and parallel *quantitative* and *qualitative.* The *explanatory* and *quantitative* method is used to answer the first question - *Can the cost of UK Whole-House retrofit to EnerPHit standard be reduced via current offsite mechanisms in pre 1919 UK house typologies?* - via energy and cost modelling. As Fellows and Liu, (2015) have explained, "*explanatory* research aims *to "answer a particular question or explain a specific issue/phenomenon. As in exploratory studies, hypotheses are used but here, as the situation is known better (or is defined more clearly), the theory etc. can be used to develop the <u>hypothesis which the research will test</u>…"*: given that we already "know" that the initial upfront cost of EnerPHit is higher than 'elemental' retrofit (due to a higher up-front amount of materials and labour), the basic hypothesis to test is whether the use of offsite construction techniques to provide EnerPHit-standard outcomes; will be less costly than attempting to achieve EnerPHit solely through onsite construction processes. The model method ranges beyond just confirming whether there is an economic benefit or not and dives into the exploration of technical variables. In this respect the method contribution falls into a. extending from selective pilot projects and reviews a range of typologies and b. providing valuable information on future retrofit approaches.

Following the modelling the next stage focuses on the use of survey techniques of both *quantitative* and *qualitative* nature to provide an insight on the industry's knowledge, perception and reaction in combining EnerPHit standard and offsite construction, aiming to answer the next question of the research - *Could the UK industry be confident in* *adopting this combination as common practice?* In this respect the method expands beyond technical variables and focuses on the social aspect. The survey's contribution stands on the novel uptake of the construction industry's perspectives on the combination of deep housing retrofit and offsite. While previous research has dived in to exploring one of these aspects, opinions on the combination of these two are still to be explored.

Finally, this mix of *explanatory, quantitative* and *qualitative* methods are cross tabulated into a thorough analysis that address the final question of the research - *What innovations are needed by the industry for 'Whole-House' retrofit practice to have a macro-scale effect in the UK?* – and will look to focus on feasible policy, financial and technological innovations that could stimulate the dynamics of the retrofit industry. The overall contribution of the mix-method approach and conceptual framework exists in linking both technical and non-technical aspects

4.3. Research Structure

This section explains the research structure discussing the different analytical methods and techniques applied for each phase. The first phase describes the methodology rational behind the modelling, while the second phase outlines the methodology behind the survey uptake and finally the rationale behind the mixed method approach is explained.

4.3.1 Phase 1: Explanatory and Indicative Modelling

An example of examining a scientific approach could consist of inductive discovery (induction) and deductive proof (deduction) (Gray, 2014).The inductive discovery uses a "bottom-up" approach (Trochim, 2016) i.e. collection of data and/or observations that lead to a theory while the deductive proof tests a theory by collecting data. In this phase of the research the method of *deduction* will be applied as shown on *Figure 4.1* as the aim is to establish a hypothesis by using theory, variety of data and collection of information.

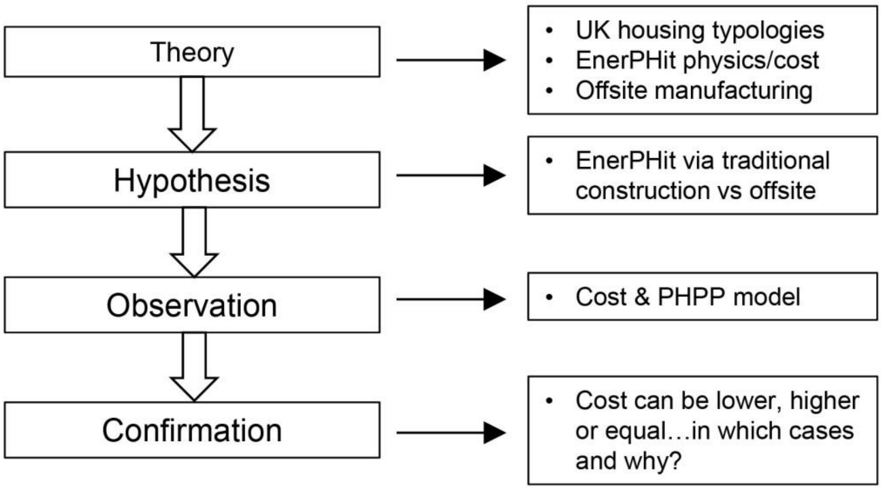


Figure 4.1 *Deductive reasoning method used in the research approach*
(Adapted from, (Trochim, 2016))

Theory:

The Theory consists on what is already known: a. need to retrofit the UK housing stock has been demonstrated by previous research and reviewed in the literature review (Chapters 2 and 3). b. the UK housing stock that is the most energy inefficient is the pre-1919. c. Whole-House retrofit is the most beneficial approach in the long term. d. the EnerPHit standard is based on the principle of Whole-House retrofit and is established for quality deliverance. e. offsite construction has demonstrated, in new build, quality of construction and cost reduction.

Hypothesis:

The hypothesis that is tested on this phase is whether by applying EnerPHit as the preeminent retrofit energy standard in these UK housing typologies the cost of construction will be reduced if offsite mechanisms are applied.

Observation:

The hypothesis is tested by conducting a series of energy and cost modelling using the required software on selected case studies of pre 1919 typical house typologies.

Confirmation:

The results of the modelling clarify the accuracy hypothesis and provide information to assess whether and in which cases a cost reduction is applicable.

4.3.2 Phase 2: Quantitative and Qualitative (Questionnaire/survey)

The aim for this research phase is the construction of a survey to understand the level of knowledge of the construction practices and standards discussed (EnerPHit, offsite etc.). The objective is not only to see the response on the applicability of the offsite manufacturing implementation in the housing retrofit but also receive feedback on existing perceptions on Passive House standard or similar and receive suggestions for future variations and research. A combination Likert scale was used as it is the procedure still most frequently used in attitude assessment (Corbetta, 2003) while ensuring that the questionnaire would not take up too much of the respondents' time. The questionnaire investigates stated intent and desire of the industry stakeholders to adapt to emerging standards and innovations in construction. Additionally, by allowing the submission of free text answers where appropriate, the responders elaborated on their answer decisions in further detail. This allowed a qualitative thematic analysis on issues that a. might not have been anticipated and b. providing an input of in depth qualitative investigation on the subject matters.

The questionnaire design although not formally applied is influenced by the Theory of Reasoned Action (TRA) and Theory of planned behaviour (TPB), which both suggest that the level of 'intentions' shown by an individual is the best predictor of their behaviour (Jackson, 2005; Kaiser, *et.al*, 1999; Kalafatis *et al.*, 1999).TRA was developed by Fishbein and Ajzen (Ajzen, 1991) in the late 1970s as a model which assumes that people behave according to their beliefs about the outcomes of their behaviour, and the values they attach to those outcomes. In the context of this research *Figure 4.2* demonstrates how the TPB has influenced the survey construction.

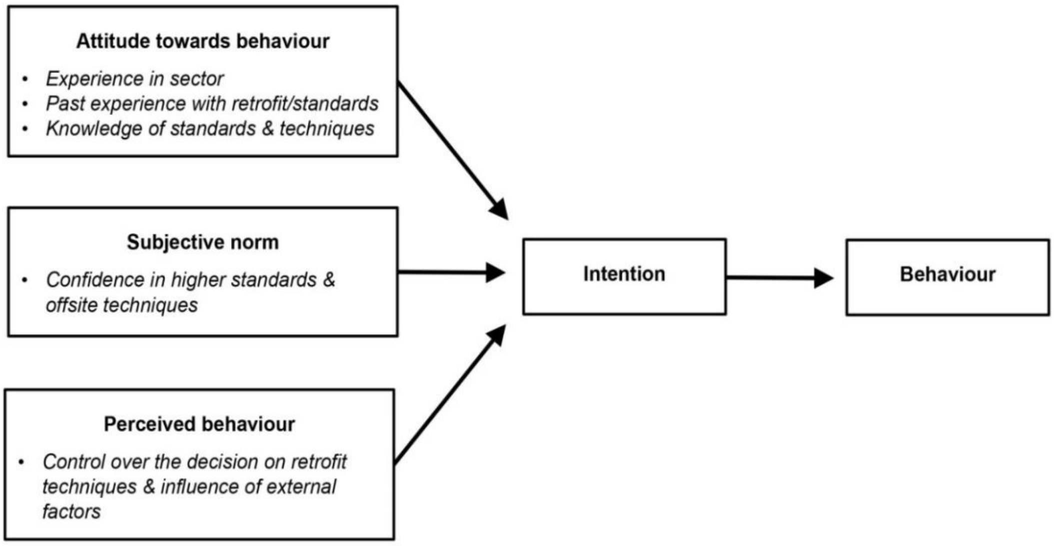


Figure 4.2 *Theory of Planned Behaviour in relation to the research*
(Adapted from (Ajzen, 1991)

Attitudes are formed from an individual's belief about the behaviour which in this research was explored by investigating the participants' background and knowledge on current energy standards. The subjective norm is the perceived social pressure to engage or not to engage in behaviour but in this research it is examined in relation to the participants' background. For example, an energy consultant with experience in dealing with low energy design might have more confidence in low energy techniques. Perceived behaviour falls within the perceived control of the individual which consists of the resources and opportunities available to them. In this research it is translated in recognising the incentives and barriers on choosing EnerPHit and offsite techniques. Ultimately the above method used in the survey aims to interpret the intension parameters that influence current perceptions and behaviours to understand what the potentials are for the connection of retrofit with offsite measures.

4.3.3 Rationale mixed-method approach

The emphasis of using mixed methods is to expend further understanding from one to another, thereby combining findings from a variety of data sources. Consequently, it is important to consider what data are required and alternative sources for data collection during the design and planning stage (Fellows and Liu, 2015).The UK housing retrofit industry is a complex system involving multidisciplinary sectors with knowledge and techniques from several disciplines (i.e. **Regulatory**: legislation / standards, **Technical**: engineering/ physics, **Financial**: economics, **Social**: social science) and it would not have been an in-depth approach to examine with simplified methods. The study's approach was structured in such a way that the methods and techniques were able to answer specific research questions. The central premise of mixed-method research is that combined qualitative and quantitative approaches can provide more comprehensive evidence and a better understanding of the research problem than either approach alone (Creswell and Clark, 2007). As *Figure 4.3* demonstrates, the backbone of the research rationale stands on its interdisciplinary subject approach.

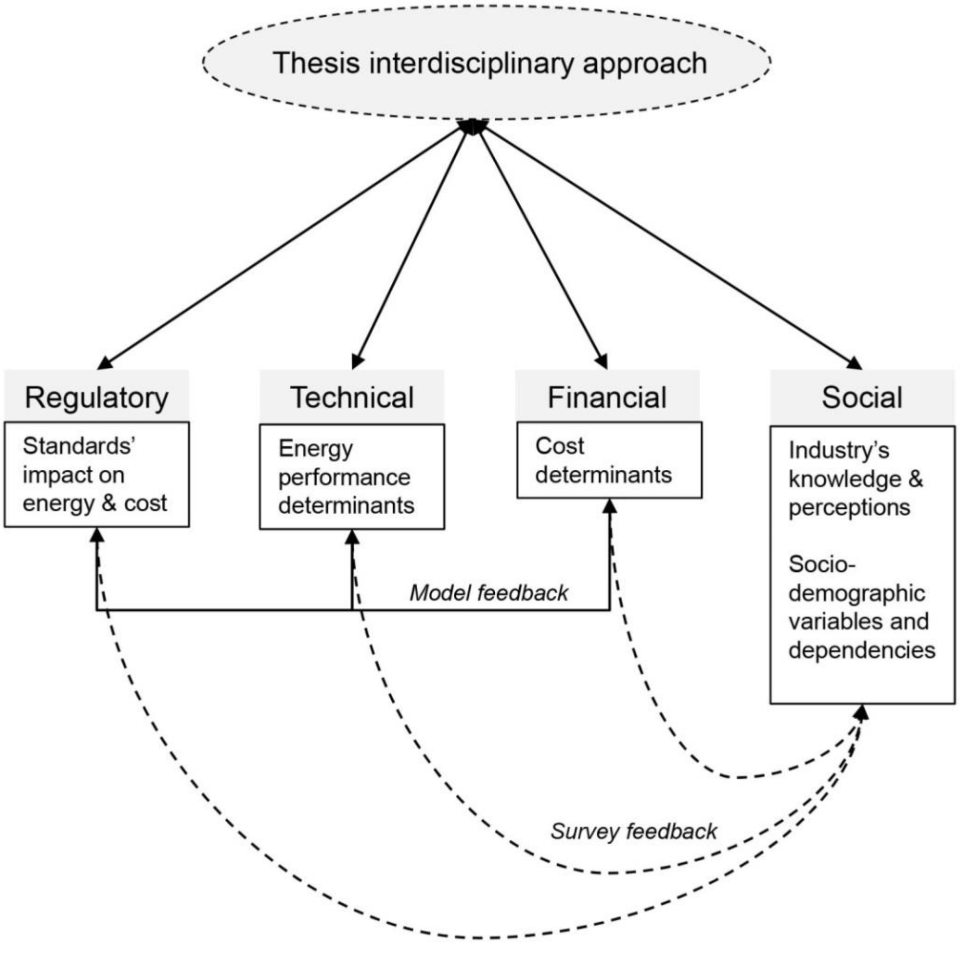


***Figure 4.3** Interdisciplinary approach of the thesis*

There has been significant research with socio-technical approach in retrofit (Chiu *et al.*, 2014; Tweed, 2013; Topouzi, 2015; Pelenur, 2013a) but with the main focus on occupant energy consumption interaction. The novel contribution falls on the use of a socio-technical approach that considers both social and cultural retrofit factors from the industry's perspective alongside innovative technical and econometric measures that take into account retrofit specific parameters (offsite).

The **Regulatory** approach focuses on the relevant standards applied in the model which by extend have an impact and are interconnected with the **Technical** and **Financial** approaches/results/feedback. For example when a same typology is retrofitted to EnerPHit standard it will have a different energy demand to a Building Regulations equivalent. The **Technical** determinants of (shape of dwelling, amount of materials, labour onsite or offsite) along with the energy demand will have an impact on **Financial** outcomes of either upfront cost or energy reduction translated to bills. The **Social** approach applied within the survey feedback becomes the human factor input in the equation and questions what the dependencies of those technical aspects future uptake are. The descriptions of relevant inputs assigned to each approach are detailed in the following sections.

4.3.4 Outline research design

The research design is outlined in the following sections with the equivalent actions, methodology and inputs reflecting the thesis' interdisciplinary approach. The methods applied are discussed, providing an understanding of the aspects considered in the study's research inquiry. *Figure 4.4* sets the outline of the research methods and how they triangulate with each other. The thematic approaches/ disciplines (Regulatory, Technical, Financial & Social) were interdependent starting from the data collection to the results analysis as demonstrated in *Figure 4.4*.

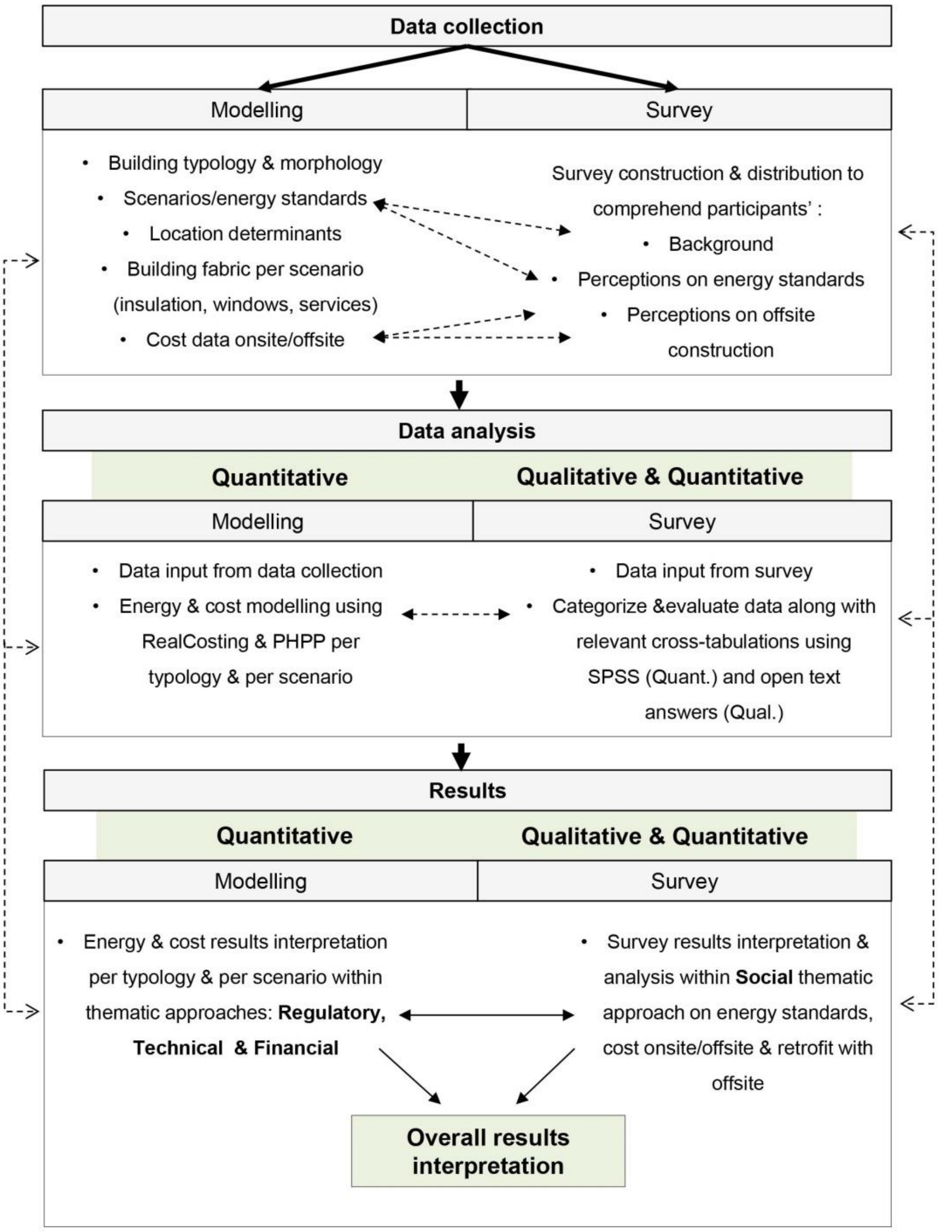


Figure 4.4 *Outline of the research design & methods*

4.4. Regulatory approach

The regulatory approach of the research looks at the current standards (mandatory or not) in relation to energy saving criteria. It should be acknowledged though that in reality there are unpredictable regulatory implications, especially in relation to planning. Ever since the introduction of the *Civic Amenities Act* (1967) the notion of conservation has developed amongst the local authorities and consequently the construction industry. The energy retrofit and specifically "Whole-House" on the other hand being relatively recent in

UK does not present enough precedents to inform on how best to address the complexities on the combination of heritage conservation and energy efficiency through retrofit measures. Additionally, due to the typologies age unexpected obstacles on site are high likely to arise even with extensive survey prior to works. The research therefore recognises that even though actual parameters are considered on the energy and cost modelling a project delivery usually presents unforeseen complexities that cannot be quantified in the model.

With this in mind, three types of energy modelling and four cost modelling scenarios were tested; *Base Case* where no retrofit is taken place, *Building Regulations* where minimum standards are applied and finally the *EnerPHit* standard. The *EnerPHit* scenario cost related retrofit measures are then compared with onsite to offsite construction.

4.4.1 Base Case

The Base Case refers to the un-retrofitted/existing typology and it is an obvious start point to the model. This enables the research to quantify the feasible energy reductions and associated cost (upfront capital and bill reduction) when the retrofit measures are applied. The analysis on the existing dwelling also offers a central review on each typology's existing advantages or disadvantages (i.e. shape, percent of external walls, windows etc.). Subsequently, those elements become informative on the feasible offsite applicability in each typology and test its technical limitations. The pre/post-retrofit comparison is the apparent method that any retrofit research or case study uses to argue the energy demand reduction or set target such as witnessed in the TSB's Retrofit for the Future. In this thesis however, even though the target is set to limiting energy heat demand in the case of EnerPHit, the existing case studies are also at the forefront of the research objective. Instead of evaluating a singular or selective number of case studies a wider analysis is made within each group of most commonly found pre-1919 typologies.

This way each typology's most common determinants were identified and potential tailored offsite macro-scale possibilities could be examined.

Since in UK energy improvements when retrofit is taking place are mostly voluntary, it is assumed that the case study dwellings have not been upgraded and are on their original construction; apart from reasonable upgrades regarding, the heating systems (boiler) and partial roof insulation. This offers a clear assessment on the energy and cost impact the equivalent retrofit standards have.

4.4.2 Building Regulations

When a building undergoes any type of retrofit the Building Regulations have to be followed for the design, construction and alterations to meet the required standards. In terms of energy conservation in existing buildings (retrofit) the Approved Document PartL1B, Conservation of Fuel and Power in Existing Dwellings sets the minimum standards. In theory, with the exception of extensions where new thermal elements and services have to follow limiting compliance, the mandatory energy upgrade is "triggered" when >25% of the building's envelope undergoes renovation or >50% of an individual thermal element (AD Part L1B, Paragraph 5.8, HM Government, 2013).

Even so, upgrades to buildings in principle may not be obligatory if not "*technically, functionally and economically feasible"* (AD Part L1B, Regulation 23, HM Government, 2013). Thus, the energy and cost model in this case takes the minimum acceptable standards into account as set out in *Table 4.1*. The *Base Case* it is used as an "intermediate" comparison to what is the "worst case" of the un-retrofitted existing stock to the "best case" EnerPHit standard. The inclusion of Building Regulation scenario has been of particular importance and has a bi-fold objective. It allows a comparative assessment of current legislation in regards to housing retrofit and the demonstration of cost and payback differences between minimum and high energy efficient standards.

4.4.3 EnerPHit

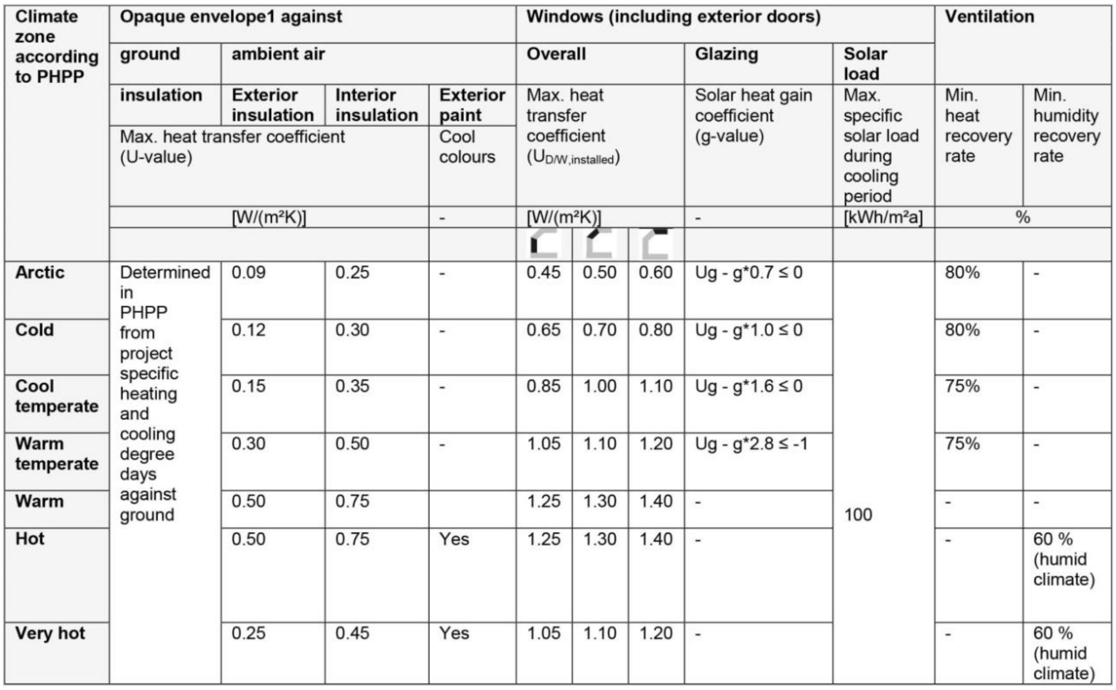
EnerPHit is the Passive House equivalent for existing buildings. The justification behind choosing EnerPHit as the main standard to explore in the research stems from the fact that (Passive House) is the fastest-growing energy performance standard (Hopfe and Mcleod, 2015) and is the most recognized alternative to the “scrapped” LZC (Greenwood *et al.,* 2017) and thus in essence making it the most “reliable” standard to use for the Whole-House retrofit argument of this thesis. This argument can also be supported by the fact that a property retrofitted to EnerPHit standard can be eligible for a mortgage discount from the Ecology Building Society of 2 to 5 greater than one with an EPC improvement certificate (Ecology Building Society, 2017).

The EnerPHit standard similarly to the Building Regulations for existing buildings is more “relaxed” in relation to new build (Passive House), recognising the feasible complexity and restrictions of older buildings. The EnerPHit standard can be achieved through compliance with the criteria of the *component method* or alternatively through compliance with the criteria of the *energy demand method* (Passive House Institute, 2016). The component method (*Table 4.2*) focuses on the overall heat transfer coefficient of the element (U-value) as an average for the entire building allowing for certain elements/areas to have higher values as long as this is compensated for by means of better thermal protection in other areas. This way flexibility is provided in buildings where restrictions, technical or regulatory would make compliance with the energy demand method unattainable or “damaging” to the existing building.

The heating energy demand compliance method is more “straightforward” and is met by achieving the limiting values of ≤ 20-25 kWh/m^2.a (*Table 4.3*). In both cases the airtightness and Primary Energy Demand must be met as shown in *Table 4.1*. In this thesis the energy and cost modelling is using the energy demand method for two main reasons. First, the component method would apply generally to challenging “site specific” case studies that would not otherwise be able to achieve certification. Even though this could be a realistic option to many retrofit projects aiming for EnerPHit, the thesis objective is to draw similarities within each group of the pre-1919 typologies as a method to unravel novel macro-scale opportunities in retrofit innovations (EnerPHit and Offsite). Secondly, adding to the first reason is the investigation into the relationship of the physical shape impact (form factor of the typologies) to the amount of measures (onsite or offsite) that are needed to achieve the EnerPHit standard. The level of importance into this uptake also stands on the fact that the physical shape of the existing buildings is predetermined, thus the form factor cannot be changed in favour of energy efficiency as done in new-build construction.

Limiting criteria per standard/scenario modelled			
Criteria	**Base case**	**Building Regulations**	**EnerPHit**
Specific Heat Demand kWh/m^2.a	-	-	≤ 25 (Cool Climate) ≤ 20 (Warm Climate)
Primary Energy Demand kWh/m^2.a	-	-	≤ 120
Air tightness	10 m^3/(m^2.hr)@50Pa	10 m^3/(m^2.hr)@50Pa ** 5 m^3/(m^2.hr)@50Pa (used in the modelling)*	n_{50} ≤ 1.0 h^{-1} @ 50Pa
U-values			
Wall	1.7	0.30	≤ 0.15-0.30
Floor	2	0.25	≤ 0.15-0.30
Pitched roof Insulation at rafter level	0.35	0.18	≤ 0.15-0.30
Pitched roof Insulation at ceiling level	0.35	0.16	≤ 0.15-0.30
Flat roof	0.35	0.18	≤ 0.15-0.30
Windows	4.8	1.6	≤ 0.85-1.2
Doors	5	1.8	≤ 0.85-1.2
**The limiting value in the Building regulations for airtightness is 10 m^3/(m^2.hr)@50Pa but is assumed that the retrofit applications will improve the existing condition to 5m^3/(m^2.hr)@50Pa.*			

Table 4.1 *Limiting Criteria of modelled standards used in the energy modelling for each scenario*



Climate zone according to PHPP	Opaque envelope1 against				Windows (including exterior doors)					Ventilation	
	ground	ambient air			Overall			Glazing	Solar load		
	insulation	Exterior insulation	Interior insulation	Exterior paint	Max. heat transfer coefficient ($U_{D/W,installed}$)			Solar heat gain coefficient (g-value)	Max. specific solar load during cooling period	Min. heat recovery rate	Min. humidity recovery rate
	Max. heat transfer coefficient (U-value)			Cool colours							
	[W/(m²K)]			-	[W/(m²K)]			-	[kWh/m²a]	%	
Arctic	Determined in PHPP from project specific heating and cooling degree days against ground	0.09	0.25	-	0.45	0.50	0.60	Ug - g*0.7 ≤ 0	100	80%	-
Cold		0.12	0.30	-	0.65	0.70	0.80	Ug - g*1.0 ≤ 0		80%	-
Cool temperate		0.15	0.35	-	0.85	1.00	1.10	Ug - g*1.6 ≤ 0		75%	-
Warm temperate		0.30	0.50	-	1.05	1.10	1.20	Ug - g*2.8 ≤ -1		75%	-
Warm		0.50	0.75		1.25	1.30	1.40	-		-	-
Hot		0.50	0.75	Yes	1.25	1.30	1.40	-		-	60 % (humid climate)
Very hot		0.25	0.45	Yes	1.05	1.10	1.20	-		-	60 % (humid climate)

**Note: The data on the table are for reference only and are not used in the energy modelling of this thesis.*

***Table 4.2** EnerPHit criteria for the building component method* (Passive House Institute, 2016)

Climate zone according to PHPP	**Heating**	**Cooling**
	Max. heating demand	Max. cooling and dehumidification demand
	kWh/m^2.a	kWh/m^2.a
Arctic	35	Equal to Passive House requirement
Cold	30	
Cool temperate	25	
Warm temperate	20	
Warm	15	
Hot	-	
Very hot	-	

***Table 4.3** EnerPHit criteria for the energy demand method Institute*
(Passive House Institute, 2016)

4.5. Technical approach

In this section the technical determinates and inputs are explained. These include: a. the rationale behind the typology range along with relevant descriptions of their morphology, b. justification of the dataset and software used in the modelling and finally, c. recognising and understanding the technical limitations of the modelling process.

4.5.1 Typologies

The UK housing stock is one of the oldest in Europe (Economidou *et al.,* 2011). It includes almost 13 million dwellings built before 1960, including 4.7 million built before 1919; this is the least energy-efficient housing type in comparison. These pre-1919 homes have a staggering average mean energy use (heating and lighting) of 480 kWh/m^2.a (emitting 9 t CO2/year), while the more recent post-1990 dwellings' mean energy use is little more than half of this Figure at 270 kWh/m^2.a (emitting 4.5 t CO2/year).[33] Initially, the research was aiming to review all the categorized age typologies from DECC (Department of Energy and Climate Change) but it recognised the significance of focusing on the pre-1919 that are the majority of the hard to treat homes (in relation to the other age groups)(Thorpe, 2010). This understanding brought into focus the importance of researching this age group's retrofit with offsite mechanisms possibilities that contrasts with current offsite applications centring mostly to post 1950's (Energiesprong / Beattie Passive).

4.5.2 Typical structure and building fabric

There are common structural and building fabric elements found in all typologies; that have been used in the modelling and upgraded accordingly to the required standard tested. The roof is traditional timber with some insulation presumed applied much later (mineral wool). The walls are solid brick (lime mortar) and the floor on shallow stepped

---

[33] English Housing Survey (www.gov.uk) , the Office of National Statistics (www.ons.gov.uk) and BRE (Building Research Establishment, www.**bre**.co.uk)

brick footings ventilated suspended timber with no insulation. Finally, the windows are timber sash, single glazed (NHBC, 2015; Episcope, 2014).

4.5.3 Typology characteristics

The typologies used in the energy and cost modelling with relevant morphologies are categorized below and are the most common found in UK[34] namely: Detached, Semi-Detached, End Terrace, Terrace-Bay (windows) and Terrace-Flat (elevations). Relevant case studies where used for the research and their characteristics described have a direct impact on the feasible energy and cost implications.

4.5.4 Detached

The Detached dwelling is considered a single unit that does not share a wall with another structure and usually has a good form factor[35] but the extensive external walls result to high heat loss.

Figure 4.5 *Examples of Detached houses*
Left to right, a and b photos taken by the researcher, c, The Nook, Lover's Lane, Brighton, RftF programme
*(*Image credit: Low Energy Building Database, *www.lowenergybuildings.org.uk)*

The amount and shape of bay windows usually differ and the dwelling consists of two to three floors. This typology usually has the most different variations where original bay

---

[34] Ibid.

[35] Passive House Designers Guide, PHT 2011, p2 Form factor: *"A useful variant of the A/V ratio known as the 'Form Factor' describes the relationship between the external surface area (A) and the internal Treated Floor Area (TFA). This allows useful comparisons of the efficiency of the building form relative to the useful floor area. Achieving a heat loss Form Factors of ≤ 3 is a useful bench mark guide when designing small Passive House buildings".*

windows or extensions have been added along with ornamental features. The variations on the morphology have an impact on the energy as more or less external wall is present and the ornamental features have an impact on whether internal or external insulation is used upon retrofitting. A good example of “balance” is shown on *Figure 4.5* (c). The Nook, Lover’s Lane, Brighton a Retrofit For the Future project that used a combination of external wall insulation front elevation and internal wall insulation on the front due to planning restrictions and the plaster exterior made that feasible as the external wall insulation is not visible. This demonstrates an example of achieving the building fabric upgrade in line with the planning requirements. In many cases extremal wall insulation would not be applicable on this typology due to the visibility of all or most its elevations to a streetscape and the covering or replication of brick/ ornamental features would not be acceptable by most planning authorities.

4.5.5 Semi-Detached

The Semi-Detached dwelling is a single unit that shares a single party wall with a “mirrored” neighbour property. Its form factor is usually slightly worse than a Detached but in comparison has less exposed external wall area.

Figure 4.6 *Examples of Semi-Detached elevations*
*Left photo by the researcher, right Clapham Retrofit, Arboreal Architecture (*Image credit: Low Energy Building Database, *www.lowenergybuildings.org.uk)*

The original construction does not usually have a back extension and the front elevation is most commonly “flat-faced” or with a ground floor bay window (*Figure 4.6*). It consists normally of two to three floors. The Semi-Detached usually has fewer implications in comparison to the Detached due to its better “compact” design along with a smaller amount of external wall area. In regards to feasible planning restrictions on this case the external wall insulation might not be feasible not only due to the façade alteration but also due to the visual impact in relation to the neighbour property.

4.5.6 End-Terrace

The End-Terrace dwelling is the last or first unit in a row of houses and similarly to the Semi-Detached the End-terrace shares one party wall including a rear extension and is two floors high. The front elevation bay windows are usually 45/35 or 90 degree angle as in most Terraced houses.

Figure 4.7 *Examples of front (left) and back (right) End-Terrace elevations. Photos by the researcher*

The form factor is significantly worse than the other typologies and the combination of the extensive external envelope and wall connections (*Figure 4.7*) results in high thermal bridging[36] connections and a higher heat loss. Consequently, the application of external wall insulation could result in technical implications on the wall/ roof /ridge connections. These are usually difficult to successfully insulate without having a thermal bridge impact. Similarly, the front elevation of the bay windows could also prove challenging and

---

[36] BRE The importance of thermal bridging: www.bre.co.uk/certifiedthermalproducts/page.jsp?id=3073: *”A thermal bridge, also called a cold bridge, is an area of a building construction which has a significantly higher heat transfer than the surrounding materials. This is typically where there is either a break in the insulation, less insulation or the insulation is penetrated by an element with a higher thermal conductivity.”*

usually expensive to effectively insulate (extensive detailing to avoid thermal bridge implications). This typology has the disadvantage of both being the “least efficient”, thus in more need for retrofit but at the same time the most challenging relating to technical implications.

4.5.7 Terrace – Bay window

The Terraced dwelling sits in the middle of a row of houses and has the same characteristics (form factor, thermal bridges and shape) to the End-terrace and is one the most common typologies found in UK. The main difference to the End-terrace is that it shares two party walls which in comparison have a great impact on the dwelling’s heat loss.

Figure 4.8 *Examples of Terrace houses with bay windows*
*Clock wise, a, b and c photos taken by the researcher, d, Brent, London, RftF programme project (*Image credit: Low Energy Building Database, *www.lowenergybuildings.org.uk)*

The application of external wall insulation largely depends on the existing streetscape. As seen from *Figure 4.8* (c) when the rows of houses are homogeneous and have the same external finish (i.e. exposed brick) the application of external wall insulation would probably not be acceptable. On the other hand, there are examples where this would be accepted where the streetscape is more “diverse”. A very good example is was demonstrated in one of the Retrofit for the Future projects *Figure 4.8* (d) where external wall insulation was installed along with timber cladding and did not have a negative visual impact on the consistency on the neighbour row of houses.

4.5.8 Terrace – Flat face

This type of Terraced dwelling has significant differences that influence the heat loss. The “flat faced” front and back elevations consist of less thermal bridges and has a very good form factor. It usually consists of two to three floors.

Figure 4.9 *Examples of Terrace Flat-face houses*
*Clock wise, a,b, c photos taken by the researcher, d, Cottesmore, Leicester, RftF programme project (*Image credit: Low Energy Building Database, *www.lowenergybuildings.org.uk)*

Similarly to the Terrace-Bay the application of any retrofit measures that would alter the front elevation of the property depends on the existing streetscape as seen from *Figure 4.9*. A good example of using offsite measures to completely replace an existing element with better equivelent without compromising the external aesthetics is seen on one of the Retrofit for the Future projects in Highfields, Leicester *Figure 4.9*(d). The entire roof was replaced with no evident visual impact (height/materials) to the existing and the neighbouring properties.

4.5.9 Case studies

The case studies collected for the energy and cost modelling were retrieved from a combination of different council Planning Portals in UK and the researcher’s own existing involvement to some of the properties refurbishment.

The public access to planning applications allowed collecting drawings of existing houses but with no personal data used. Drawing examples for each typology used can be viewed in Appendix A – Typology Examples. The scaled drawings were downloaded in pdf format and imported to AutoCAD were the accurate area measurements took place. In total 25 dwelling were analysed corresponding to 5 case studies per typology.

The case studies are representative to the typologies reviewed providing an overview of the implications and possibilities a Whole-House retrofit has with or without current offsite mechanisms. In *Table 4.4* the list of the average areas that were measured are presented per element of each typology.

Average areas in m^2 of the case studies measured and recorded.					
	Detached	**Semi-Detached**	**End-Terrace**	**Terrace-Bay**	**Terrace-Flat**
Treated Floor Area (pre-retrofit)	325	180	105	110	130
External wall	335	206	150	100	90
Roof	190	115	75	80	60
Floor	150	103	68	70	55
Windows	58	30	18	21	20

Table 4.4 *Average areas in m^2 of the case studies measured and recorded.*

4.5.10 Dataset and software used introduction

The modelling structure that correlates both energy and cost is fairly recent in UK retrofit but crucial to making valid decisions on retrofit approaches. In previous attempts such as the Green Deal programme, it was proven that significant gaps between the projected and actual energy performance occurred due to the disconnected inadequate strategies approach. This had an apparent impact on its failure to provide a sustainable retrofit market with unrealistic energy savings and high mortgage rates.

On the other hand, the Passive House methodology due to the utilisation of a comprehensive building physics approach addresses the challenges of retrofitting existing buildings in the whole and offers transparency on energy demand results. Therefore in this research to model the energy demand and the required retrofit applications the Passive House Planning Package (PHPP) was used; this is the official software from the Passive House Institute. The cost related determinants were not part of the software but were calculated separately. A newly introduced plug-in called RealCosting offered the opportunity to encompass cost related factors; it focuses specifically to retrofit works and is compatible only to PHPP.

In this research the related costs not only have a great impact in testing the hypothesis (onsite/offsite applications) but also bring to the forefront the necessity to have the same “transparency” not merely in terms of energy but also in terms of cost determinants.

The next two sections describe the “logistics” and strategy behind the energy modelling (dataset and software) and by extention the cost determinants of both upfront and payback. The first section describes the pilot dataset collection and modelling before the RealCosting was introduced and the second how the research incorporated the software and provided a novel contribution to the data approach and analysis.

4.5.11 Pilot dataset construction

The schematic diagram in *Figure 4.10*, describes how the PHPP operates and what type of data need to be entered to model the building's energy demand and achieve certification (Lewis, 2014). On this research the main features that were analysed are related directly to the heat demand namely: Climate data, U-values, Areas, Windows and Ventilation.

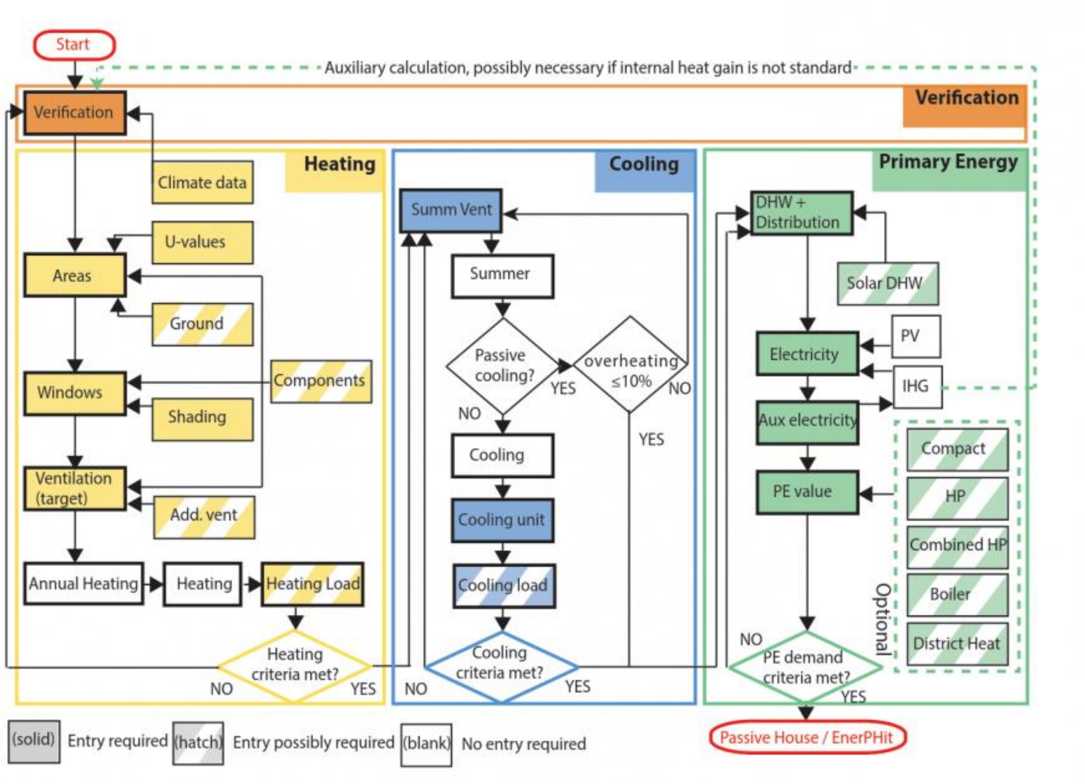


Figure 4.10 *Schematic of the required steps and data needed to be entered to model and evaluate a Passive House building.*
(Lewis, 2014),PHPP Illustrated, A Designer's Companion to the Passive HouseStandard, RIBA, page 60.

To construct the energy and cost modelling three main dataset factors were needed. Firstly, the case studies areas (dwellings) secondly the construction build-ups of pre and post retrofit applications (i.e. original wall construction-amount and type of insulation required) and thirdly the related cost of material and application/labour (onsite-offsite). In the pilot, the data relating to the building areas were taken from the case studies' drawings and initially three separate PHPP documents where constructed to model each case study (Base, Building Regulations and EnerPHit). The results were then entered into a separate document (Excel spread-sheet) for further cost analysis. This was broken down to material cost (per area or component) and labour with the EnerPHit cost scenario being analysed with both onsite and offsite elements where feasible. A representative schematic of the notion can be seen in (*Figure 4.11*).

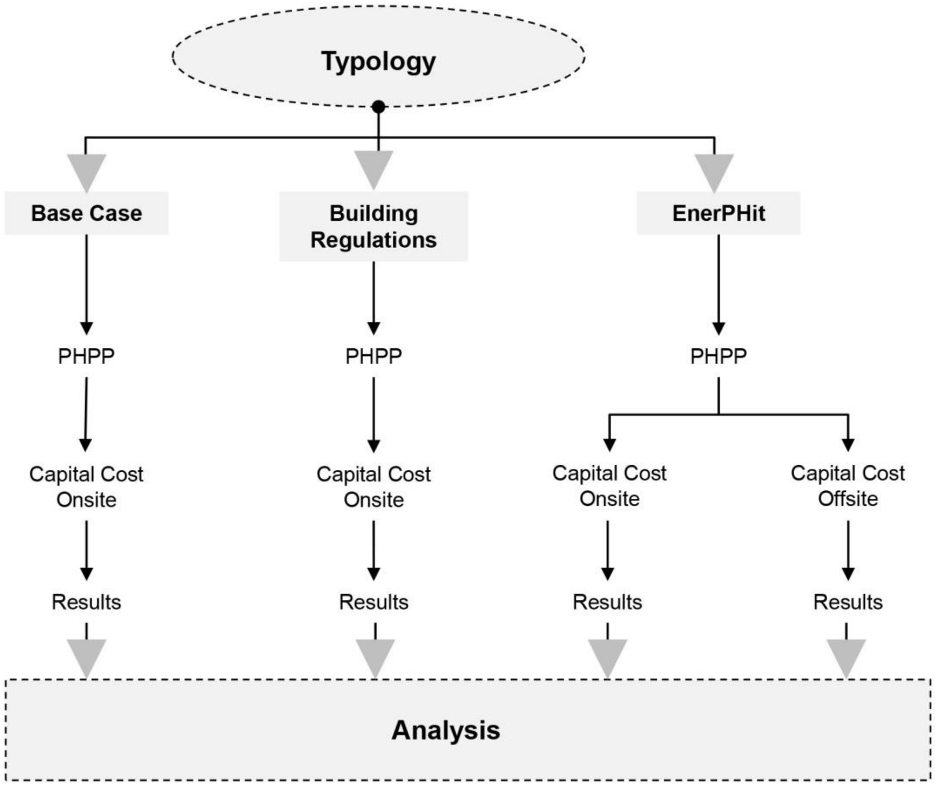


Figure 4.11 *Schematic of pilot energy and cost modelling method*

The cost dataset input were initially constructed by: using information from previous and current residential projects, referring to price books (such as SPONS) and direct engagement with personal contacts from quantity surveyors.

During the construction of this database the plug-in software was launched via the AECB (Association for Environment Conscious Building) called RealCosting. After a trial period to understand whether the software would be compatible with the research aim and methodology, it was adopted to assess the typologies’ energy and cost variations.

4.5.12 RealCosting[37]

The software works like an extension of, and in relation to PHPP. Its core function is to analyse the cost related impact of retrofit. Its cost database includes related materials and installation but also savings from energy and co-benefits such as increase of the property value and value of comfort. Most importantly to this research it generates up to 6 scenarios (i.e. Base case, Building Regulations, EnePHit etc.). The schematic below (*Figure 4.12*) demonstrates how the research modelling incorporates the software and how its compact method when compared to the pilot (*Figure 4.11*) became a key tool for the research.

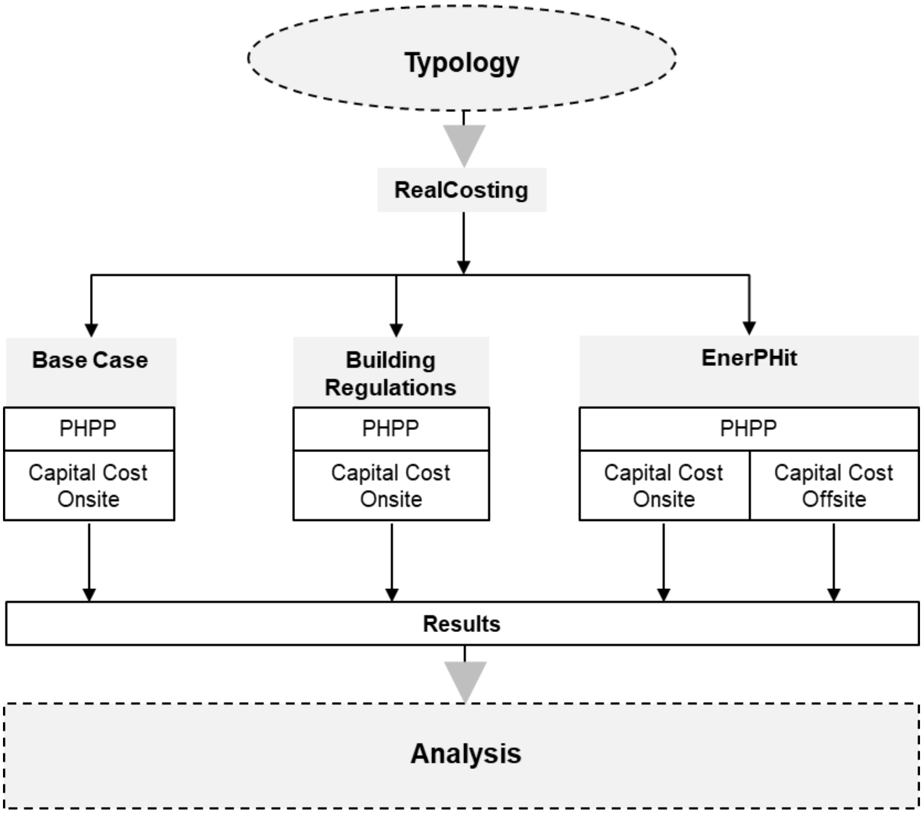


Figure 4.12 *Schematic of the RealCosting use in relation to the research*

The rationality is very similar to the pilot as the same data of the building structure are placed and the software has its own library of common material and applications. The energy cost analysis though of more than one scenario is done simultaneously.

---

[37] The software can be reviewed and purchased from : http://optimalretrofit.co.uk/software/ and the AECB website: www.aecb.net

Using RealCosting has proven particularly beneficial for the following reasons:

a. The software might be relatively new but it has been created by people with years of experience in retrofit recognising elements in the retrofit process relating either in energy assessment or cost related implications that validate the analysis.
b. It is an Excel based spreadsheet similar to PHPP thus allowing the same transparency and flexibility for the user to "track" the calculations and add data such as alternative materials or costs.
c. Taking into account co-benefits associated with the retrofit have already been added in the software. These include House Value increase (due to retrofit works), Residual Value of the materials and added comfort. The added comfort data derived from research done by the author of RealCosting, Tim Martel and conducted on the AECB (Martel, 2017). It is defined by the monetary value residents would place on the comfort internal temperatures rising due to retrofit.
d. The results of all scenarios are presented with the equivalent Net Present Value in clear graphs that allow the user to assess the results and amend if required accordingly.

4.5.13 Strengths and challenges of the modelling approach

There is an underlying coincidence that the software was launched during this project's research into equivalent objectives, the energy/cost analysis of Whole-House retrofit. One can assume that the requirement or even aspiration of such investigations is another step in the evolution of the housing retrofit in UK.

The strengths of the modelling approach in both the research pilot structure and RealCosting stands on the objective of unravelling the cost and energy determinants in retrofit. The same transparency and to some extend guaranty the Passive House's PHPP offers is also needed in terms of costing. The RealCosting software, even though it will certainly continue to be updated it has offered a novel gateway in both having all the data required in the one place while correlating to existing established software (PHPP).

The pilot’s novel contribution and challenge was identifying and testing offsite inputs, something that RealCosting has not yet included in its cost database along with some particular costings related to services relocations. Nonetheless the software offers the flexibility for the user to add and adjust the costings. By using the initial pilot data these adjustments were amended accordingly presenting a novel application of the software. This reflected the potentials and possibly further explorations from different retrofit actors. On one hand the user (designer, energy consultant etc.) can identify and amend inputs to explore possibilities on their projects that promote more efficient applications and costs. While, on the other hand offsite suppliers could recognise additional mechanisms to incorporate in their supply.

4.6. Financial approach

This section discusses the research method used to analyse the financial outcomes of the modelling and gives an overview of the determining factors of upfront construction costs and payback.

4.6.1 Cost comparison

The cost comparison was implemented within the scenarios as described in section 4.4 (Base case, Building Regulations and EnerPHit). Particular focus was given to the evaluation of achieving the EnerPHit standard with two construction approaches, onsite and offsite.

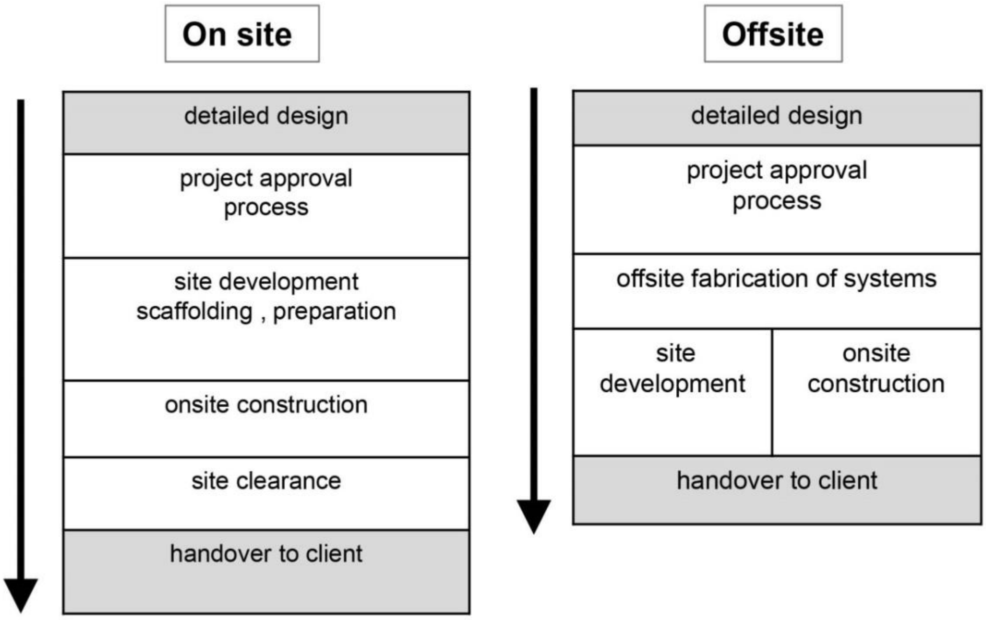


Figure 4.13. *Principal difference comparison between onsite and offsite construction*

The principal structure differences between onsite and offsite construction are summarised in *Figure 4.13*. The cost related differences usually stem from efficiencies within the supply chain found in the labour, transportation, materials and waste expenses (Hairstans, 2014; WRAP, 2009).There are different levels of offsite construction and definitions as discussed in section 3.2.4. Pan *et al.,* (2004a) categorised them in 4 levels; **Level 1** Component sub-assembly, small sub-assemblies that are usually assembled prior to installation. **Level 2** Non-volumetric pre-assembly units made up from several individual components and that are sometimes still assembled on-site in ‘traditional’ construction. **Level 3** Volumetric pre-assembly, pre-assembled units that enclose usable space or fitted onto other structures and finally, **Level 4** Modular building, pre-manufactured buildings. The thesis focuses on **Levels 1 to 3** given that it examines existing dwellings without “new extension” added per say but it will look at the feasible offsite element replacement with a better equivalent, specifically the roof. This is something that has previously be done to a pre-1919 dwelling in one of the Retrofit for the Future projects *Figure 4.9* (d) with respect to planning guidelines as the end result has no negative visual impact.

The aim of the offsite cost comparison is to provide data on the limitations and opportunities of different types of applications tested within the different types of element and eventually within the different typologies. The cost savings levels do not only focus of the material/element used i.e. the required capital cost of retrofit but also explores the payback time from energy savings (NPV) and related co-benefits (increased House Value, Residual Value and value for comfort). Ultimately, this is an assessment of the limitations but equally important the opportunities for integrating the use of offsite technology in the retrofit housing industry's most challenging properties.

4.6.2 Cost determinants used in model.

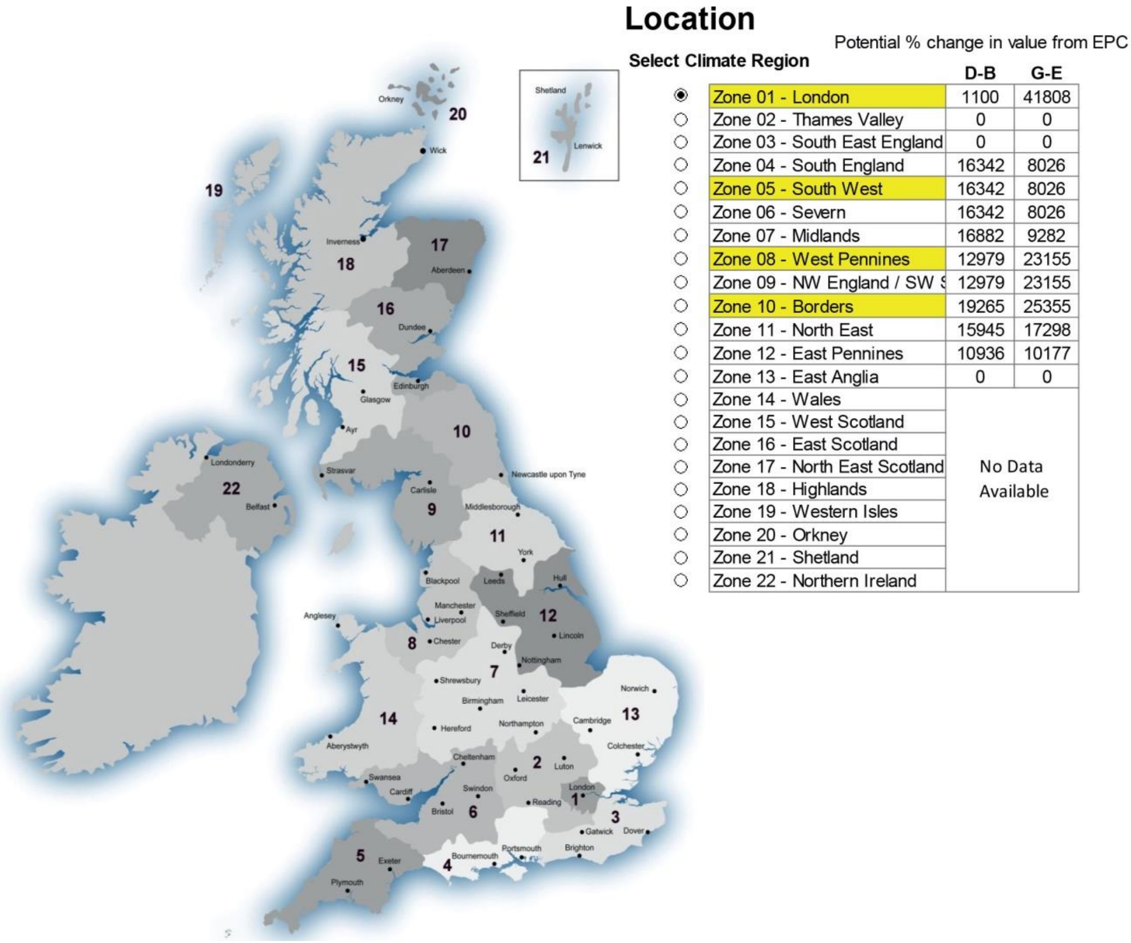
The factors influencing the heat demand and therefore, a. the cost of a building retrofit and b. the savings from the energy reduction are; *location* of the dwelling (local climate), *shape* (form factor), the build-up *materials* of the external envelop (U-values), and *airtightness* (infiltration). As the thesis is examining existing buildings the form factor cannot be altered but its influence to the energy demand will assessed within each typology. The next section details these parameters and their influence in the modelling and thesis.

4.6.2.1 Location

The local climate has a big impact on the performance of a building and a project for example in southern England is unlikely to meet the same criteria if located in Scotland where solar radiation and mean temperatures are much lower. EnerPHit as previously described takes into account this impact on the heating demand limiting values (Section 4.4.3, *Table 4.3*). Additionally the House Value due to retrofit upgrades varies significantly within different UK regions. For example in London where the house demand is considerably high, retrofit upgrades reducing the energy demand do not have a substantial impact on the increase of the House Value. To understand further this effect of location as "real estate" and location as "climatic impact " 4 regions where taken into account (*Table 4.5* and *Figure 4.14*) where climate data differ significantly along with the property value increase post retrofit[38] . Therefore all the scenarios and typologies were modelled for each of those regions. This analysis variation shows the cost impact of both energy reduction and asset according to location.

Location	Heat demand kWh/m^2.a
London	20
South West	20
West Pennines	25
Borders	25

***Table 4.5** Limiting values of specific heat demand to achieve the EnerPHit standard in different UK locations.*



Location

Potential % change in value from EPC

Select Climate Region		D-B	G-E
●	Zone 01 - London	1100	41808
○	Zone 02 - Thames Valley	0	0
○	Zone 03 - South East England	0	0
○	Zone 04 - South England	16342	8026
○	Zone 05 - South West	16342	8026
○	Zone 06 - Severn	16342	8026
○	Zone 07 - Midlands	16882	9282
○	Zone 08 - West Pennines	12979	23155
○	Zone 09 - NW England / SW	12979	23155
○	Zone 10 - Borders	19265	25355
○	Zone 11 - North East	15945	17298
○	Zone 12 - East Pennines	10936	10177
○	Zone 13 - East Anglia	0	0
○	Zone 14 - Wales	No Data Available	
○	Zone 15 - West Scotland		
○	Zone 16 - East Scotland		
○	Zone 17 - North East Scotland		
○	Zone 18 - Highlands		
○	Zone 19 - Western Isles		
○	Zone 20 - Orkney		
○	Zone 21 - Shetland		
○	Zone 22 - Northern Ireland		

***Figure 4.14**[39] Climate region selection taken from RealCosting software along with house price increase due to retrofit (right).*

The regions highlighed in yellow are those taken into account in the cost and energy modelling (Table 4.5). The map on the left shows the correspoding climatic zones.

---

[38] House Price Report, 2013
www.gov.uk/government/news/energy-saving-measures-boost-house-prices

[39] Image retrieved from www.howtopassivhaus.org.uk/ and RealCosting software

4.6.2.2 Materials

The cost of materials and rates database in regards to the onsite construction is already entered in the RealCosting software. For the offsite database as the equivalent retrofit market is still fairly undeveloped acquiring cost data from existing industries was challenging pointing out yet another barrier in the industry relating to accessing data. The cost data that were used in regards to the offsite application available were collected from previous build projects, adjusted to current construction price indexes and companies.

- Roof: the cost of offsite was a combination of cost collected from offsite manufacturers and from previously demonstrated offsite construction roof in a Retrofit for the Future project (Baeli, 2013).
- Walls: The internal wall insulation analysis adapted costs from WHISCERS which includes in its cost the entire installation and survey and for the external wall insulation the Beattie Passive “TCosy” system was reviewed where the entire building is retrofitted using their offsite construction (where applicable) and deliver a certified EnerPHit building.
- The elements that are upgraded with traditional onsite construction methods are the floors, windows/doors (excluding TCosy method), airtightness and heating and ventilation systems.

4.6.2.3 Airtightness

The airtightness of a building is not possible to be known in advanced or calculated like a U-Value but requires testing and measuring on site. Depending on the property the airtightness could have a wide range as demonstrated in the Retrofit for the Future projects varying from below <10 to >15 $m^3/m^2h@50Pa$ (The Technology Strategy Board, 2013) but this data includes properties that were build post-1919. The $10m^3/m^2h@50Pa$ figure was taken into account as a rational average. This was determined by an average of pre-1919 retrofit properties airtightness data collected from the Low Energy Database (www.lowenergybuildings.org.uk) of post and pre retrofitted dwellings. The pre-retrofit numbers ranged around 7 to >15 $m^3/m^2h@50Pa$ and the post-retrofit of around 3 $m^3/m^2h@50Pa$. but again with wide figure range between properties, the pre-retrofit (Base Case) value of 10 $m3/m^2h@50Pa$ was considered the most realistic for the modelling process and is also what the RealCosting has presumed. Accordingly, the Building Regulations assumed an improvement to 5 $m^3/m^2h@50Pa$ and EnerPHit at $1h^{-1}$ @ 50Pa as shown in *Table 4.1*. The airtightness related costs are taking into account labour and materials in terms of sealing add and repairing the existing conditions. These have been calculated according to the areas and element of each typology. Even though the additional insulation will upgrade at some level the existing airtightness, to achieve better levels understandably a series of works are done predominantly onsite.

4.7. Energy and cost modelling steps

This section demonstrates the steps of the energy and cost modelling used in the research along with the required data input as presented on *Table 4.6* along with example references in Appendix B – RealCosting modelling process. These are similar to the PHPP modelling with the exception of costs.

Steps	Actions and data input	References in Appendix
Step 1. Location & Climate data	The location and altitude of the building is selected along with respective climate data and house value after retrofit (EPC). The building's orientation is also placed and the level/number of exposed sides.	*Figure B.1*
Step 2. U-values	The U-values for each element of the building are constructed (Wall, Roof, and Floor). For each scenario different amounts of insulation are placed to calculate the required U-value.	*Figure B.2*
	Table continues on next page	

	Table continues from previous page	
Step 3. Areas	The building's areas are measured (Wall, Roof, Floor, TFA & volume) and placed along with their corresponding U-values. On this step selection on whether mechanical is used is made for each scenario (MVHR).	*Figure B.3*
Step 4. Windows	Similarly to step 2 (U-values) the thermal properties of the windows are place according to each scenario. Then the window dimensions are measured from the drawings and are listed to their corresponding wall.	*Figure B.4*
Step 5. TBs	The thermal bridges are placed and their dimensions for each element and scenario.	*Figure B.5*
Step 6. Costs	This is the breakdown for each retrofit measure cost. For each building element the material quantity, units and labour rates per measure and per scenario are placed. The cost per unit allows having different inputs (i.e. onsite/offsite prices). At this stage also the services selection is made (ventilation/heating) along with the airtightness value per scenario.	*Figure B.6* & *Figure B.7*
Step 7. Time	The costs per scenario are summarized here and selections can be made on: 1. Replacement/maintenance time per measure, 2. Retrofit evaluation period, 3. Co-benefits addition and 4. Whether the Residual or the House value will be calculated. Detailed NVP per year can also be viewed.	*Figure B.8*
Step 8. Results	When steps 1 to 7 are completed, ReaCosting generates the results for each scenario: Heat loss per element, specific heat demand, annual heat demand, tCO^2 for heating / year, capital cost, NPV for the selected evaluation period.	*Figure B.9*

Table 4.6 *Energy and cost modelling steps using RealCosting and data collected*

4.7.1 Model analysis methods

Straightforward statistical techniques were used to analyse and present the results of the modelling. For each element influence the energy demand in relation to the cost applied and consequential savings represented with tables, diagrams, pie charts and percentage component bar charts. This allowed a clear comparative analysis within the different typologies, energy standards, location, construction methods, capital cost and finally payback differentials. With this method allowed a clear evaluation of the complexities and potentials of higher energy standards and offsite mechanisms applied in retrofit.

4.8. Social approach

In this section the survey methodology on exploring the non-technical variables and dependencies is outlined. Specifically, the objective behind the survey design, the approach data collection and ultimately analysis methodology.

4.8.1. Survey justification

The questionnaire's aim is twofold; firstly to understand the industry's perception on energy standards in general; from current building regulations to Passive House along with different approaches to retrofit, Whole-House, and finally traditional construction vs offsite. Secondly, linking back to the first phase of the research the results from the energy and cost modelling are reviewed in relation to the questionnaire.

This method provides empirical data on the practicality of such practices (offsite/EnerPHit) that are put in some extend to the "test"; demonstrating how ready or willing the UK industry is, in reality, to adapt to higher standards and innovative solutions in construction that could feasibly lead to large scale applications and stronger market dynamics.

4.8.2. Survey design

Due to the broad nature of the subject matter an online questionnaire was created using the Bristol Online Survey tool (BOS). This is web based tool allowing for high flexibility on the variety of question types along with distribution and most importantly wide export possibilities into subsequent analysis software. The survey was structured in a manner of ensuring that essential data were collected to form the required analysis (Appendix C – Survey). These are detailed below:

Responders' background:

The survey begins with some exploratory questions seeking the professions and the level of experience from the respondents. The objective was to reach a wide spectrum of industry stakeholders raging from academia to the supply chain. Nineteen related professions were listed along with the optional selection. The survey was distributed using LinkedIn, the professional networking site, along with other construction professionals and colleagues known to the researcher.

The research focuses on what previous studies have named as "Middle-out" actors (Janda and Parag, 2013; Parag and Janda, 2014; Janda *et al.*,2014). Those refer to the construction industry's professionals and businesses that have the ability to influence change and the promotion of low-energy buildings, while the "Top-down" refers to governmental bodies and "Bottom-up" to the tenants, owners and users. Parag and Janda, (2014) demonstrate that the influence of the Middle-out actors as shown on *Figure 4.15* has an impact to policy makers (upstream), to clients/users (downstream) and even across the building industry (sideways).

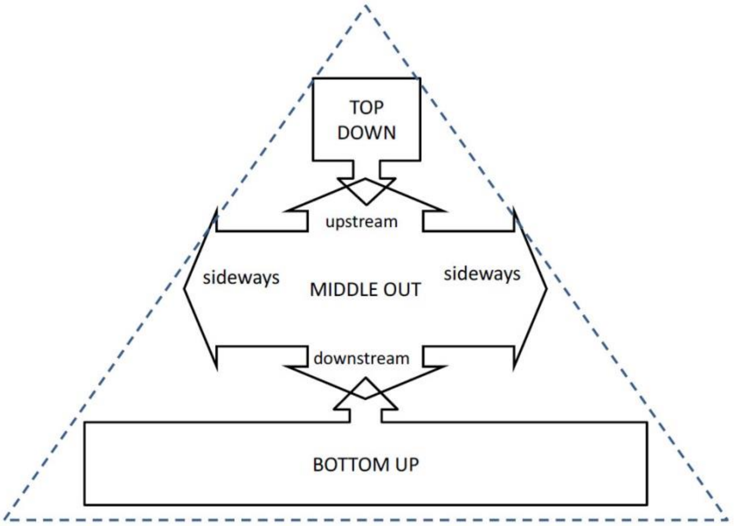


Figure 4.15 *Middle-out change: directions of influence.*
(Parag and Janda, 2014), Page 106

This influence has been recognized in: supply chains (Guy & Shove, 2000), builders (Killip, 2011a), surveyors (Hill & Lorenz, 2011), property agents (Schiellerup & Gwilliam, 2009), architects (Fischer & Guy, 2009) and engineers (K. Janda, 1999).

Janda *et al.*,(2014) argued that these actors are considered as intermediaries to deliver the innovation in construction that is mandated by regulation (top down) and when requested by the client/user (bottom up) but as stated (Janda *et al.*, 2014,page 913): *"these groups have their own habits, practices, ways of thinking about problems, and ways of working that affect their ability to provide (and interest in promoting) low carbon refurbishment."* With same principle this thesis aim is to investigate how those "Middle-out" actors perceive innovations such as offsite applications on retrofit along with high standards (EnerPHit). The main aim of this part of the study is the exploration of perceptions from stakeholders that have insights in the construction delivery and the influence as previous research suggests on both regulation and end users. Exploring those perspectives provides a validation in this research as they are the actors that can evaluate the offsite-retrofit applicability in terms of practicality as they have "hands-on" experience on: existing or live projects, clients/users, current legislation/regulation and consequently valid views on influencing barriers and incentives.

Knowledge and perceptions on energy standards:

Using a combination of Likert scale the aim was initially to apprehend their level of understanding of current energy standards beginning from the mandatory Building Regulations and then proceeding to Passive House and EnerPHit. The objective was to draw links and explore the relationship between background-experience-knowledge-perception. It continued with exploring the possible experience of being involved with a Passive House or EnerPHit project where the responders also expanded on their experience in what they found most challenging. This proved a great source of information data in relation to the model findings serving to assess whether the offsite mechanisms could address those issues and these responses are used to qualitatively inform the final analysis. The combination of experience and knowledge with higher energy standards provided a distinct categorisation within the responders in terms of "energy related background" or not which delivered another element on the analysis drawing similarities on Fishbein's and Ajzen's Theory of Planned Behaviour (TPB). Notably, looking on the assumption whether the responders that have experience or any involvement with sustainable orientated projects have predeterminations on the quality of delivery EnerPHit delivers or not according to their opinion and vice versa.

Knowledge and perceptions on offsite mechanisms:

A similar investigatory strategy was used with the focus on assessing knowledge and perceptions of offsite mechanisms followed by exploratory insights on a. feasible cost of Whole-House deep retrofit on the selected pre-1919 typologies and b. feasible cost reductions if the offsite mechanisms are used. This was utilised to understand the industry representatives' awareness on costing variations of onsite to offsite construction methods. This section was cross-tabulated with the modelling analysis made on the first phase of the research. Finally the barriers and incentives of using offsite mechanisms were examined in the survey to draw robust assumptions on feasible future approaches the industry needs to uptake. The data collection of this section is vital to the research in conjunction to the future of the retrofit industry and its offsite uptake. Similar research has been carried out with the focus not only on quantifying the benefits of offsite construction but on the industry's insights (incentives and barriers) (Goodier and Gibb, 2005; Pan *et al.,* 2004a). The focus though has mainly been to the new build sector with the retrofit only touched upon; this is understandable due to the current high demand of new housing but also provides a great opportunity for a. investigating this research gap and b. correlating the findings of previous research on new build to the findings of this research and understand the differentials in viewpoints on offsite construction when applied on new build to retrofit.

4.8.3. Survey analysis methods

Similarly to the model analysis descriptive statistics were used for the survey response analysis. Using the SPSS Statistics software the quantitative data from the survey were categorized and evaluated along with relevant cross-tabulations. The software analysis results were then inserted to an Excel base spreadsheet where graphs are generated to present the results in a comprehensive format.

Qualitative data from the open text survey questions were analysed using thematic analysis which is the method amongst the most common of qualitative data analysis (Bryman, 2012). The open text option in specific questions within the survey intended to identify key themes and ideas in the areas of the empirical data, related to the industry's challenges both perceived (attitudes) and actual (experience). As Braun and Clarke, (2006) stated: *A theme captures something important about the data in relation to the research question, and represents some level of patterned response or meaning within the data set*. Within this study, the term 'theme' is used to represent a category or theme related to the interrelated and sometimes rather intangible barriers or incentives found in the applicability of both high energy efficient standards and offsite mechanisms in UK retrofit.

4.9. Ethical considerations

The research was judged to be exempted from the requirement to secure approval via University of Northampton's institutional research ethics on the basis that it consisted of: a. technical modelling where no classified or security-sensitive materials or data where used and b. an online survey procedure which did not touch on sensitive topics or comprise of vulnerable individuals. Even so, any research which involves human participants inevitably requires consideration of the ethical implications of that work. In this respect the participants took part in a voluntary way and strict confidentiality and anonymity was upheld.

4.10. Summary

This chapter presented and discussed the analysis, design and data collection of an interdisciplinary mixed-method approach exploring the adoption of offsite mechanisms to Whole-House retrofit in UK. The overarching aim was to answer the research questions, and address the knowledge gap on the application of those mechanisms in pre-1919 dwellings along with the construction industry's perception on their pragmatic macro-scale implementation in the UK market. To this effect, a socio-technical approach was adopted that considered both technical and social factors affecting the adoption of retrofit technologies. Depending on the type of data different techniques were integrated into the analysis design to explore quantitative and qualitative data simultaneously. Specifically, the technical aspects focused on unravelling the physical boundaries of the UK typologies through energy and related cost modelling while the social aspect was explored through the survey uptake. These factors are further presented in the following chapter through the description and discussion of the findings of the PhD research.

5 Results of PhD research- Regulatory, Technical and Financial related outcomes

5.1. Introduction

The UK’s housing retrofit “evolution” as described in detail in Chapter 2 along with its subsequent drives and barriers has been the reason for the analysis model, both in terms of the energy, costing scenarios and survey. The rationale as summarised below demonstrates the progression of thought along with its contribution to the existing research.

The Retrofit for the Future programme, explored various innovations that could be adopted on the UK’s housing stock including the “Whole-House” retrofit approach but this intervention did not achieve the intended response, to be widely adopted and “kick-start” the retrofit market (Jones *et al.,* 2013). The anticipated expectations were not met but subsequent studies and research showed that there are invaluable lessons to be learnt. Initially, the “unattainable” target setting of 80% carbon reduction, which was only achieved by 50% of the cases, led to questioning whether CO_2 reduction should be considered as the main driver (Gupta et al., 2015). This argument is also supported from research done on residents’ motives for retrofit with energy bill reduction and comfort as the main drivers. Finally, a range of post-occupancy studies have showed that residents have typically not been provided with sufficient feedback and advice on how to use the systems installed showing the importance of uncomplicated control systems along with knowledge sharing (Swan, Ruddock and Smith, 2013; Tweed, 2013). Thus, three main themes are emerging from these previous findings on what are to be considered as the main incentives on retrofit uptake and those are; comfort, bill reduction and system simplicity. The same issues are examined in this thesis against the review and results of the offsite mechanisms and at what level they can be a response to these existing needs.

The following programme, Green Deal, was intended to finance housing retrofit measures through loans that would be repaid through the house utility bill savings designed around a 'Pay as You Save' model with an ‘elemental’ approach to domestic retrofit focusing on upgrading or replacing the worst performing element of the structure. Its failure apparently reflected on the fact that the cost payback from the retrofit upgrades did not reflect the equivalent loan and high rates attached along with the elemental retrofit applications being inadequately installed and failing to foresee their consequential damage(DECC and NAO, 2016; Pettifor, Wilson and Chryssochoidis, 2015; Washan and Cole, 2012). Cost and payback of offsite along with the application of the EnerPHit standard is reviewed extensively in this thesis to enhance the understanding of the complexity of each typology. This provides the opportunity to understand how far deep retrofit with offsite mechanisms could be considered “cost efficient” but equally importantly what other benefits could be achieved stretching beyond monetary gain.

The most recent step to answering the retrofit market challenge in UK is the adoption of offsite mechanisms aiming to deliver where the previous programmes were unsuccessful at; “hassle-free” and fast installation of Whole-House retrofit with the guarantee of successfully installed measures and assured energy reductions. Examples of these approaches are Energiesprong and Beattie Passive, two current organisations /companies that offer whole-retrofit as a “package” while utilising offsite construction on their project delivery. Energiesprong delivers “zero bills” retrofits through the combination of improving the building’s thermal envelope and additional renewable energy fixtures i.e. PVs[40]. The entire envelope is constructed offsite and assembled onsite and their “zero bills” guarantee extends up to 30 years. Their aim is to achieve a cost of £40,000 per dwelling but the initial UK trials have showed that they span around £70,000[41]. Beattie

---

[40] Official website: www.energiesprong.uk

[41] Jocelyn Timperley. 2016. A green leap forward? Is UK's embattled energy efficiency sector ready to Energiesprong?. [ONLINE] Available at: https://www.businessgreen.com/bg/feature/2459003/a-green-leap-forward-is-uks-embattled-energy-efficiency-sector-ready-to-energiesprong. [Accessed 1 December 2017].

Passive offers a package of retrofitting to EnerPHit standard with the guarantee of testing and subsequent certification. Their initial R&D projects utilising offsite construction have been costed on around £750/m^2 (information obtain via email correspondence by the researcher with Beattie Passive) but their aim through opportunities for economies of scale from volume are that it will also be able to achieve £40,000 per retrofit on >100 units and £36,000 on >1,000[42].

In both of the examples the aim and market prospective is to deliver retrofit taking into account barriers and lessons learned; quick delivery, performance, quality, moving away from just minimum standards and finally cost. This is achieved by obtaining control of their supply chain with the use of offsite construction and supply chain mechanism. The benefits of offsite construction have been widely researched in terms of new build (Gaze, Ross and Nolan, 2007; Monahan and Powell, 2011; Zimmermann, 2012; Krug and Miles, 2013) and even government will favour offsite manufacturing on all publicly funded construction projects from 2019 (HM Treasury, 2017). Applying offsite measures to the existing housing is more complicated as for instance the most inefficient housing stock in UK falls within the pre-1919 built (DECC and National Statistics, 2015) and this age typology is usually the most difficult to retrofit. Both of the retrofit company examples mentioned have been applied (until the time this research was made) on post 1950's properties which are reasonably easier to retrofit in practical terms (shape/construction type/planning implications) and more efficient in comparison to begin with, similarly observed in the Retrofit for the Future programme where the 80% reduction was not feasible in earlier build properties.

Extensive research on the combination of offsite measures in post-1919 housing has not yet been done apart from selective pilot projects. If the offsite approach is the next step to retrofit evolution its barriers and opportunities need to be explore in the dwellings that are most in need of energy reduction with evidence based modelling along with valid

---

[42] Ron Beattie presents at CoRE's Retrofit Live 2015 event video: https://youtu.be/OxT5OYQJ4TY?list=PL9FpedaxImwuY3oqeY9mgN-tJV6jlKCbc

perceptions and expectations from the building industry’s professionals. This research addressed this gap in existing literature by looking into this age stock’s most common typologies and explored the energy/cost reduction feasibilities and subsequent market barriers and opportunities. This is done through the construction of energy and cost modelling along with survey uptake from construction industry representatives. In this respect the original contribution of the present thesis lays in providing a novel insight of the multifactorial complex interactions involved in combining housing retrofit and offsite construction in these “challenging” typologies. While the model contributes in understanding the technical aspects, the survey becomes instrumental on bridging technical and social approaches in a holistic comprehension of the issues. This synergy looks beyond applying simply one theory or method to investigate the complex interrelated socio-technical issues.

The methodology and subsequent results are divided in to four thematic analyses and utilises three methods. The methods are energy and cost analysis in the assigned case studies of pre-1919 build dwellings and survey conduct on industry shareholders. The results are presented within the thematic analysis as follows; Section 5.2 presents modelling outputs relating to the regulatory environment, giving an overview of the energy differentials of the typologies in comparison to the energy standards and location demonstrating their physical and climatic variances. Section 5.3 deals with technical factors, showing in detail each typology’s elemental advantages/disadvantages along with software use limitations and opportunities. Section 5.4 presents modelling findings relating to financial factors, demonstrating the capital cost and payback comparison between the typologies and onsite/offsite construction.

5.2. Regulatory related outcomes

This section investigates the findings from the energy model through the lens of their significance to the regulatory spectrum. The presentation of the data explores the differences in heating demand within each standard, typology and location. Even though the technical aspects that determine each scenario's results are explored later in the thesis it is vital to overview their comparative impact. This allows an understanding of the differences between a non-retrofitted dwelling to the Building Regulations standard and Whole-House EnerPHit. By extension this provides a critical review on the present and possible future of regulations relating to housing retrofit. In case studies pre/post retrofit is a usual comparison to understand the retrofit impact but in this thesis the comparison is made in collective typologies providing a holistic review. Additionally, when the offsite element is later applied there is a clearer correlation on the benefits these elements feasibly provide according to each typology and climate.

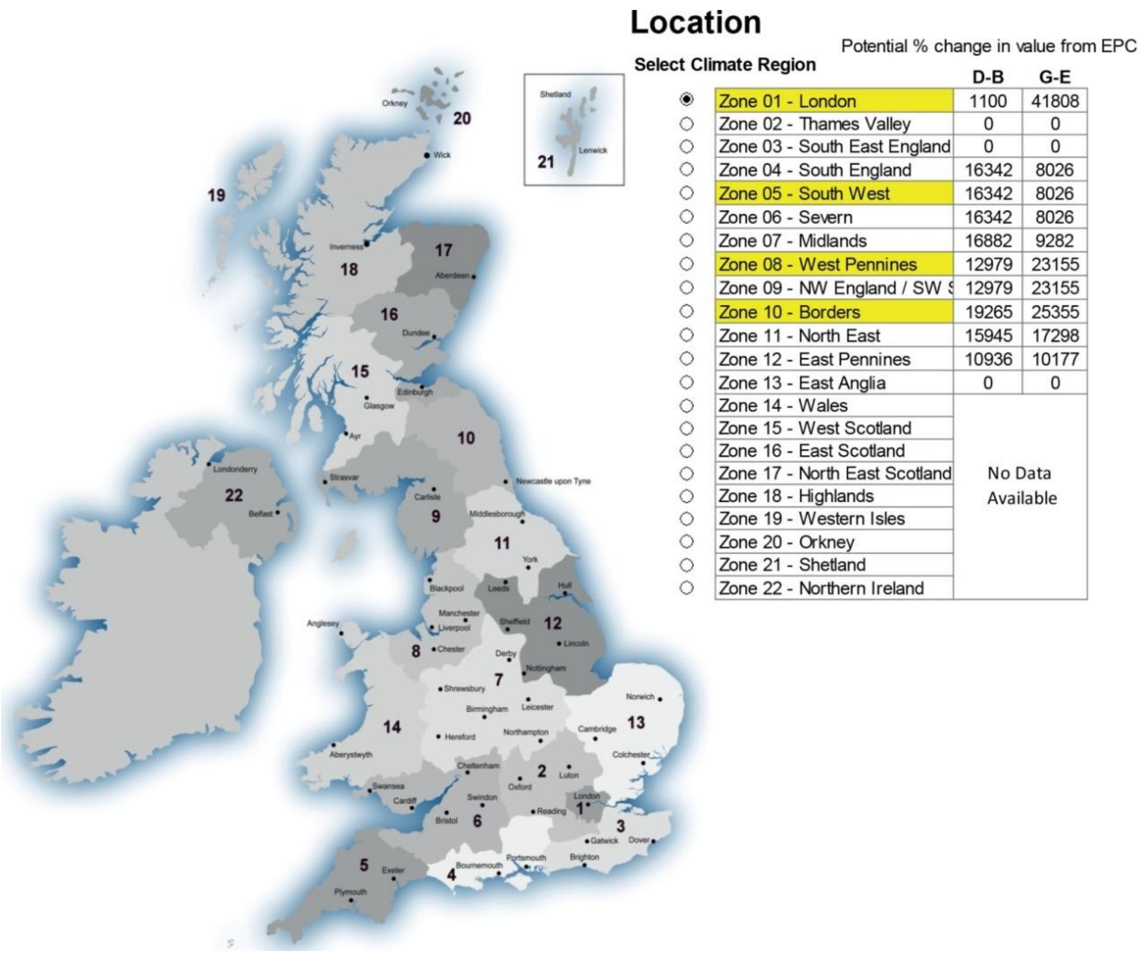
5.2.1 Energy standards review

Three types of energy modelling and four cost modelling scenarios were tested. The energy modelling scenarios are, the *Base Case* where no retrofit is taken place, *Building Regulations* minimum standards and *EnerPHit*. The cost modelling applied all the above standards along with comparing the *EnerPHit* standard applied with onsite and offsite construction mechanisms.

As explained in the methodology chapter (Section 4.4.3) the EnerPHit standard can be achieved through with the criteria of the *component method* or alternatively through compliance with the criteria of the *energy demand method*. The modelling in this thesis has taken into account the energy demand method which is met by achieving the limiting values 20-25 kWh/m^2.a. The limiting value of 20kWh/m^2.a corresponds to buildings location on a "warm temperature climate" and the 25 kWh/m^2.a to "cool temperature climate". The modelling tested the scenarios in four different regions in UK two located in the warmer and two in the cooler temperatures.

*Table (for reference only; identical to **Table 4.5**).*
Limiting values of specific heat demand to achieve the EnerPHit standard in different UK locations.

Location	Heat demand kWh/m^2.a
London	20
South West	20
West Pennines	25
Borders	25



Location

Select Climate Region

Potential % change in value from EPC

		D-B	G-E
●	Zone 01 - London	1100	41808
○	Zone 02 - Thames Valley	0	0
○	Zone 03 - South East England	0	0
○	Zone 04 - South England	16342	8026
○	Zone 05 - South West	16342	8026
○	Zone 06 - Severn	16342	8026
○	Zone 07 - Midlands	16882	9282
○	Zone 08 - West Pennines	12979	23155
○	Zone 09 - NW England / SW	12979	23155
○	Zone 10 - Borders	19265	25355
○	Zone 11 - North East	15945	17298
○	Zone 12 - East Pennines	10936	10177
○	Zone 13 - East Anglia	0	0
○	Zone 14 - Wales	No Data Available	
○	Zone 15 - West Scotland		
○	Zone 16 - East Scotland		
○	Zone 17 - North East Scotland		
○	Zone 18 - Highlands		
○	Zone 19 - Western Isles		
○	Zone 20 - Orkney		
○	Zone 21 - Shetland		
○	Zone 22 - Northern Ireland		

*Figure for reference only; identical to **Figure 4.14**.*

*Climate region selection: taken from RealCosting software along with house price increase due to retrofit (right). The regions highlighed in yellow are those taken into accont in the cost and energy modelling (**Table 4.5**). The map on the left shows the correspoding climatic zones.*

5.2.2 Regional differentials

The main variance between the regions is due to the greater heat loss that occurs in lower temperature locations thus allowing the limiting value to match the local climate in which the building exists as seen in *Table 4.5*.

In this thesis the analysis of these variances reviews how a similar building with similar standards performs in different locations. This has an “impact” on the results of the modelling analysis in regards to the amount of materials used to retrofit the property to a better performance but equally important the amount of energy saved as it effects the monetary value in terms of, energy bills, Net Present value and Return On Investment. This is demonstrated in *Figure 5.1* and *Figure 5.2* as the difference in the heat demand according to the standards varies. The *Base Case* scenario modelling showed the highest heat demand in comparison reaching up to 270kWh/m^2.a, End-Terraced house in Borders. The lowest figure was in South West, Terrace Flat with 130kWh/m^2.a and an average throughout the typologies of 200kWh/m^2.a.

To demonstrate the significance, these amounts of kWh would result in an average annual bill of £1,400- £2,000[43] for a 100m2 end-terrace property, just for heating (gas), and it is only possible to achieve average thermal comfort of temperatures typical of 17°C[44]. This temperature includes the average over the whole heating season including when the dwelling is not occupied and when unheated i.e. night time, while the EnerPHit modelling takes into account the limiting temperature of 20ºC.

---

[43] Calculated for “low” and “high” gas prices from BEIS link: www.gov.uk/government/collections/fossil-fuel-price-assumptions

[44] DECC: DUKES 2013, Table 1.1.8 [1970-2011] Link:www.decc.gov.uk/en/content/cms/statistics/source/temperatures/temperatures.aspx

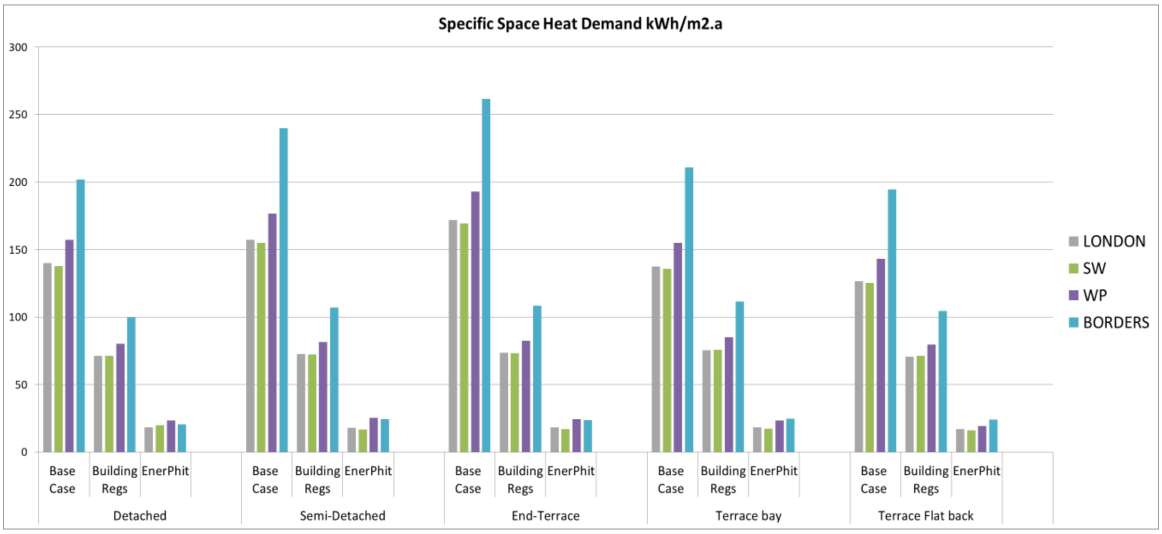


Figure 5.1 *Specific heat demand modelled results per scenario, typology and location demonstrating the corresponding differences.*

The *Building Regulations* modelling demonstrated a range between 170 to 100kWh/m^2.a which is an average of 40% reduction from the *Base Case* with only using the limiting U-values in the analysis. The *EnerPHit* scenario demonstrated an average of around 90% reduction from the *Base Case* and around 40% from the *Building Regulations* in both cool and warm climates.

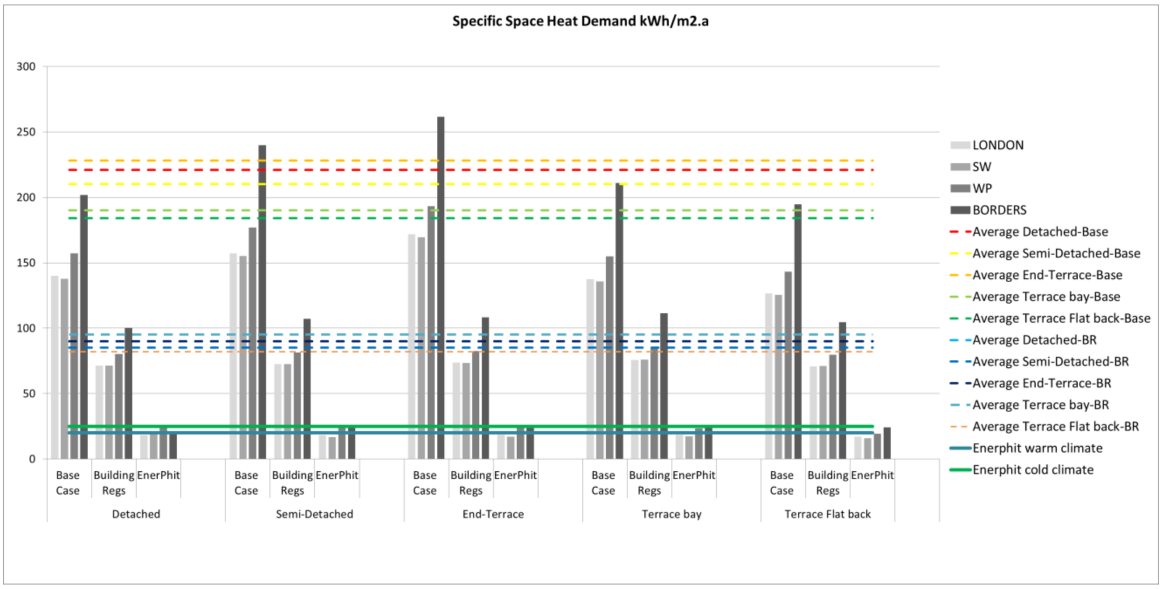


Figure 5.2 *Specific heat demand modelled results averages demonstrating wide variances when no retrofit or Building Standards is applied versus the "invariable" EnerPHit.*

The results show a reduction in heat demand up to 90% when achieving EnerPHit but the impact this has should be regarded beyond just energy saving. The heating cost for example of the worst case Base scenario (End-Terrace in a Cold Climate) of £1,800 would be reduced to an average £150 annually if EnerPHit standard is achieved; if the dwelling exists in a Warm Climate this changes to £1,500 annual heating cost for the Base case reduced to £140 for the EnerPHit equivalent. This means that there is a regional difference of around 30% in bill cost reduction and by extension to the regional impact on fuel poverty.

5.2.3 Energy standards impact

In the literature review and methodology chapter the justification for choosing the EnerPHit standard as the comparative to energy, and consequent cost effects (capital and savings) has been underlined in terms of: a. Its equivalent for new build (Passive House) is becoming more popular and is considered the fastest-growing energy performance standard (Hopfe and Mcleod, 2015), b. The current Building Regulations in retrofit and any “Top-Down” attempts so far have proven insufficient (RftF/Green Deal) and finally, c. EnerPHit’s “tested” effectiveness from monitored UK dwellings have showed that they perform as “designed” in terms of heating demand reduction, signifying a strong response to the energy gap problem.

In this respect, the modelling results as shown in Figure 5.2 have demonstrated the effect that the EnerPHit’s “invariable” specific heat demand, in comparison to the other standards, throughout the typology spectrum that was analysed. The gradual reduction of wide variances can even be observed when the Building Regulations standard is applied and significantly reduced with EnerPHit. The significance of this observation underlines the practical contribution of EnerPHit within different typologies and locations. It should be noted though that in reality when dealing with existing buildings to reach the EnerPHit’s limiting values of specific heat demand (≤20-25kWh/m^2/a) could be more challenging. Using the “EnerPHit—Quality-Approved Modernisation with Passive House Components” i.e. achieving certification through the use of upgrading components to limiting values (Passive House Institute, 2016) is also an option. Even so, the same ethos has to be addressed, with focus on the same design principles based on the use of Passive House elements and the designer has to address the same principles including, limiting existing thermal bridges, securing air tightness and implementing balanced ventilation (Passive House Institute, 2016; Torgal *et al.*, 2013). Even though the component method could have showed a higher specific heat demand than the limiting values it has to be acknowledged that the EnerPHit standard extends beyond the sole upgrade of elemental approach components. In this respect even if the EnerPHit energy demand results in higher than the limiting values (20-25kWh/m^2) the same "invariable" specific heat demand would be similar though typology/location.

The Passive House and EnerPHit is still a voluntary standard in the UK and the Zero Carbon policy that was to push the low energy agenda in new build and by extension future legislation in retrofit has been scrapped leaving only the current Building Regulations to stand. The national calculation method for the UK in assessing energy consumption in existing buildings is RdSAP (Reduced Data Standard Assessment Procedure) and now contains regional climate data (in essence the same climate regions as in PHPP) which are used for some calculations only (EPC) (DECC and BRE, 2011) and for an equivalent specific space heating demand comparable to PHPP, a separate calculation would need to be carried out on the presented space heating energy demand kWh data. Similarly, within the typologies is observed a significant heat demand differential which is partially contributed to their geometry (Form Factor) and is explored in detail in the Section 5.3. The calculated models used to predict the energy consumption of dwellings in SAP properly reflect the Form Factor and show lower energy consumption for homes with better Form Factors. Still, a study analysing the energy consumption in existing dwellings using SAP (Stone *et al* , 2014) showed that geometry (Form Factor) has much bigger influence on the calculated carbon emissions (accounting for 80% of the variance) than it does on the SAP energy rating (accounting for 30%), meaning that significant improvements in energy rating might not be accompanied by significant reductions in carbon emissions and energy cost. In contrast, in Passive House achieving a form factor of ≤ 3 is important to achieve certification while with a greater form factor better U-values are needed in order to reach the energy efficiency targets. This means that using Passive House’s PHPP will result in more accurate energy predictions, thus ensuring more accurate retrofit applications analysis in the thesis.

As detailed in the literature review chapters the regulation and legislation relating to energy use in buildings in the UK has changed, partly as a result of changes in government policy, and partly as a result of uncertainties with respect to European led directives given the vote of the UK to withdraw from the EU. Recent research suggests there has been a move towards the adoption of voluntary high level standards (Pitts, 2017) due to the limited mandatory regulation potential along with the apparent benefits of better design quality. This is also evident from this research (Section 6.2.2: Figure 6.17 and Figure 6.18) as the high majority (80%) of the participants claimed that they believe that Passive House/EnerPHit guarantees quality of construction.

This section was dedicated to reviewing the overall differences of energy standards and their consequent impact on energy demand. This analysis provides the initial critical observation on the effect these differentials have while next chapter looks in detail the technical elements influencing these results and remarks on the feasible approaches but also limitations of offsite mechanisms.

5.3. Technical related outcomes

This section describes the technical aspects of the energy and cost modelling that was taken into account and presents the consequential results of the study. The modelling method offers a novel contribution in the retrofit research as it reviews collectively the factors influencing the heat loss/heat demand on specific typologies moving beyond just single case study review. Additionally, with the use of novel software as a tool, RealCosting, the research was able to explore in detail these factors and apply the offsite element in the design.

5.3.1 Data structure overview

The typologies/case studies reviewed in the thesis and their construction build-ups with resulting U-values are the most common found in UK and similarly categorised in RdSAP (DECC and BRE, 2011) for existing dwelling assessment procedures.

- Roof: traditional timber structure with some insulation between the joist and U-value of 0.35W/m^{2}K,
- Walls: solid brick, uninsulated with a U-value of 1.7W/m^{2}K.
- Floor: ventilated suspended timber ground floor, no insulation with a U-value of around 2 W/m^{2}K adjusted to the PA (perimeter area ratio = exposed perimeter (m) / floor area (m²)
- Windows: timber single glazed.
- The airtightness of 10 m^3/(hr.m^2) @50Pa and gas boiler central heating.

These values are used in the Base Case scenario and are upgraded accordingly to Building Regulations and EnerPHit scenarios.

The software used to analyse the typologies is called RealCosting and it works like an extension of PHPP (Passive House Planning Package). Apart from analysing the energy demand and heat loss for each scenario it also evaluates the cost required for each to be upgraded. The data that need to be entered, similarly to PHPP, relates to:

- Climate data
- TFA (treated floor area)
- Area and orientation of external fabric (Walls, Floor, Roof and Windows)
- U-value of each element of the fabric
- Airtightness
- Ventilation system
- Heating system

The RealCosting software is relatively new (as is EnerPHit) but was tested for 3 years by the AECB (Association for Environment Conscious Building) prior to its release in 2017.

The developer behind the software is Tim Martel (http://optimalretrofit.co.uk), Architectural Technologist, Passive House Designer and Retrofit Coordinator. Its copyrights are owned both to AECB that is a seller of PHPP as well and Tim Martel.
The software proved valuable for the research as it enables cross reference of the PHPP to cost breakdown of the retrofit along with simultaneously being able to compare up to 6 possible retrofit scenarios. Additionally, there is a library for common thermal bridging variations and most significantly to the retrofit benefits the software includes capital cost breakdown of costs by time and building element, Net Present Value, including the cost of the build, heating, maintenance, cost of running the MVHR or MEV. The feasible benefits according to the type of retrofit scenario also include co-benefits and increase in house price post retrofit that are looked at in detail in the next chapter. Its limitations include the fact that the cost library does not yet include offsite elements that are explored in this thesis and additional costs related to design fees and service relocation but being an Excel based spreadsheet the user is allowed to enter their own values and most importantly its transparency regarding how results are determined (similarly to PHPP).

The Base Case scenario that is used as the main comparison reflects the realistic construction of a pre-1919 house which is the most energy ineffective in the UK but taking into account the basic contemporary upgrades such as some insulation in the roof and boiler. The better equivalent retrofit upgrades have been added accordingly to achieve the required standard. The results not only showed a significant difference between the typologies but also the within the region they would exist. Below the results are presented for each typology in regards to the space heat demand and look in detail at the related heat loss through each element. It should be noted that ‘losses’ from thermal bridges (TB’s on the graphs) can be negative, in other words they are gains. This is because some thermal bridges reduce the losses that would be expected from simple geometry, which effectively makes them ‘gains’. Even though the breakdown of heat loss is not a complete breakdown of the Space Heat Demand; because there are other parts to the calculation, internal heat gains, from windows etc. they reflect which element of the fabric performs the worst and needs the most “attention” in upgrading.

5.3.2 Modelling elements and “limitations”

As the study is aiming to compare onsite/offsite measures, the costs of current offsite market measures were fundamental. Unfortunately cost breakdowns from a range of suppliers were challenging to obtain, largely because the offsite market focusing on housing retrofit is relatively small, raising the question of the information accessibility barrier. This is also reflected in the survey results as the majority of responders stated that ”*Insufficient access to information on feasible cost or energy benefits*” would have the strongest impact on choosing offsite construction (Section 6.2.7: *Figure 6.53* and *Figure 6.55*). The offsite products and elements data that were obtained that could offer both thermal efficiency (thermal conductivities) and cost information that could be compared to onsite construction are in regards to Internal Wall Insulation from WHISCERS, roof from an average cost per m^2 from offsite manufacturers including adjusted data from the Envirohomes’ “loft pod” for a Retrofit For the Future project (Baeli, 2013) and overall cost per m^2 for Beattie Passive’s TCosy. Thus, the onsite/offsite U-values remain the same and the cost breakdown is analysed in the next section (5.4).

5.3.3 Typologies heat loss and heat demand

This section looks at the heat demand of each individual typology in the separate climates tested along with the individual building’s fabric element heat loss. This demonstrates the advantages and disadvantages of each typology that has a consequential impact on the amount of material required for the dwelling to be retrofitted and the subsequent cost.

5.3.4 Detached typology energy heat demand

The Detached house has an extensive heat loss through its fabric since it consists entirely of external walls. The form factor though, in terms of its geometry i.e. the relation of the useful area to external fabric makes the space heat demand reasonable in relation to its size. Thus, in terms of achieving a “demanding” standard such as EnerPHit could be relatively easier in regards to the amount of interventions required. As seen from *Figure 5.3* the difference of space heat demand within the regions is significant with a difference of approximate 12-35% between warm and cool climates.

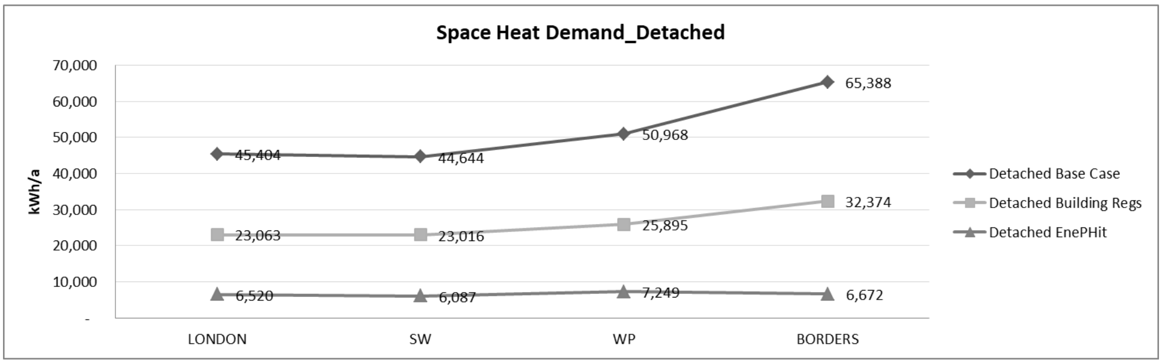


Figure 5.3 *Presenting the average space heat demand (kWh/a) in the Detached typology per scenario modelled and location.*

Figure 5.3 demonstrates a clear comparison on the amount of the annual heating energy demand that is influenced by the applied standard and location. The Detached typology being the largest dwelling in comparison has the highest numerical differences. This provides a significant grasp on understanding the annual amount of energy that is saved when a property is retrofitted and what it signifies in terms of comfort, cost and CO_2 impact.

A difference of approximate 40,000kWh annual heat demand is observed within London, South West and West Pennines regions from an un-retrofitted detached dwelling upgraded to EnerPHit standard and up to 60,000kWh in Borders. In terms of savings cost this is translated for the Borders region to £3,000 (gas) or £9,000 (electric) annual bills and £2,000 (gas) or £6,000 (electric) for the rest of the regions respectively. The tonnes of CO_2/ year[45] equivalent would be 8 to12 if gas is used for heating and 23 to 35 in the case of electricity. These figures are halved when the Build Regulations scenario is applied. The modelling also looked at the average heat loss through each element as

---

[45] LEBD (Low energy Building Database) Fuel usage coefficients: www.retrofitforthefuture.org/leb/technical-information/fuel-usage-coefficients/

presented on (*Figure 5.4* and *Figure 5.5*). This provides an opportunity to understand in depth each typology's "advantages" and "disadvantages" in terms of their morphology and significantly to the research understanding the complications related on applying feasible offsite mechanisms on the required elements of the proposed retrofit.

Warm Climate

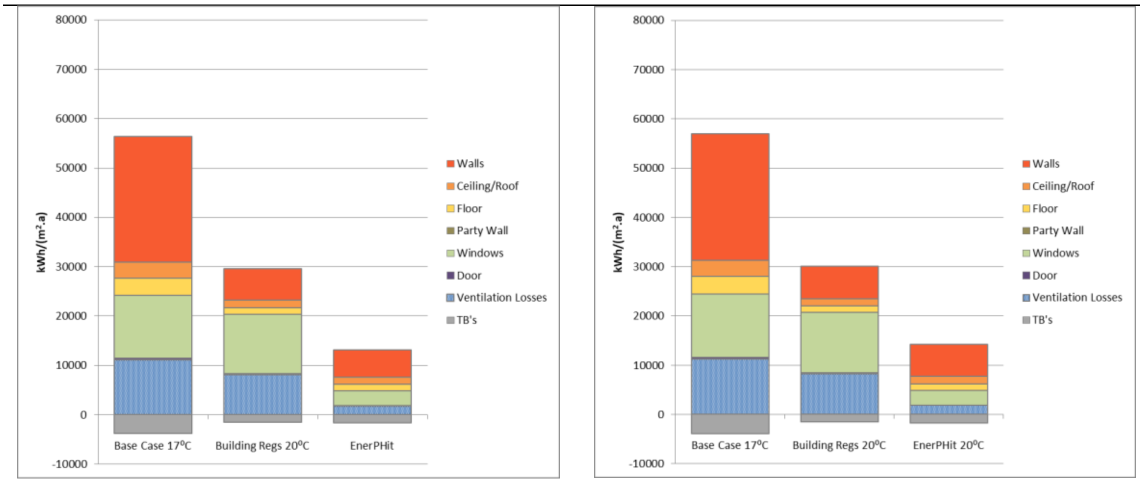

London
South West

Figure 5.4. *Detached typology modelled average heat loss per building element in UK warm climate*

Cool Climate

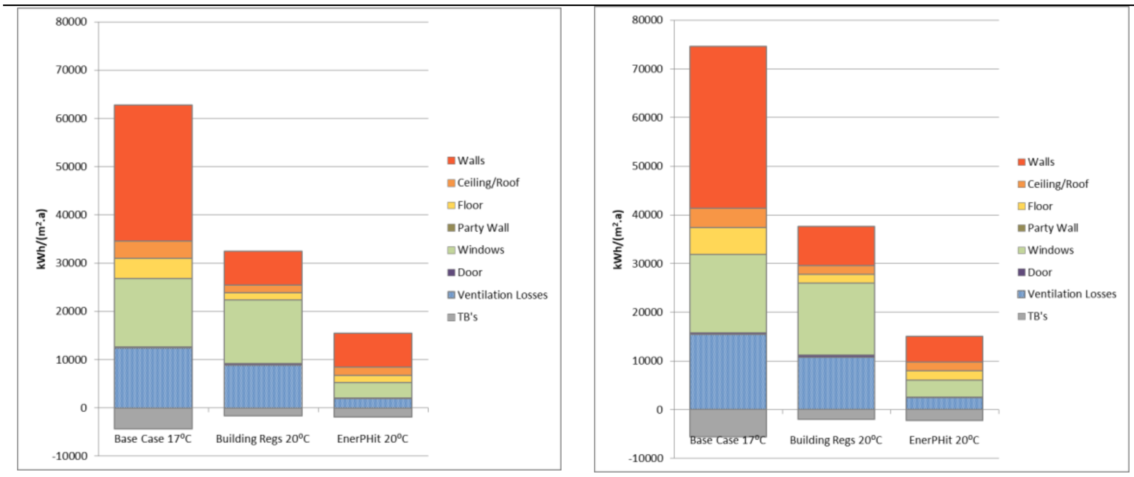

West Pennines
Borders

Figure 5.5. *Detached typology modelled average heat loss per building element in UK cool climate*

The most heat loss is observed through the external wall followed by windows and ventilation losses which is the result of the high air volume (high ceilings) that is usually met within this typology. The main remarks to be made from *Figure 5.4* and *Figure 5.5* are that a. the regional per element heat loss differences are logically proportional but numerically different demonstrating that a “common” retrofit price will possibly be not feasible in every UK location as more or less material / labour will be required to achieve the required standard and b. the challenges of incorporating offsite measures to the two other most inefficient elements, windows and airtightness, might be challenging (in the case of windows) and not feasible in the case of airtightness as the upgraded works need to be made on site. Finally, c. similarly to the previous remark the heat loss through the wall when both Building Regulation and EnerPHit are applied is dramatically reduced, with the EnerPHit 12-20% lower but the highest difference that contributes to the EnerPHit’s standard are the thermally improved windows and the high reduction in ventilation losses.

The overall observations demonstrate that when compared to the Base Case, achieving the EnerPHit standard the heat loss through the walls is reduced to 80-85% (Warm/cool regions) from the Base Case and even 75% when upgraded to Building Regulations standard. The second element with the highest heat loss is through the windows with an average 77 % reduction (EnerPHit) and 10% on Building Regulations. The highest reduction in percentage not overall numerical value is observed in the ventilation losses with an average of 80-85% on EnerPHit and 30% on Building Regulations.

5.3.5 Semi-Detached typology energy heat demand

The Semi-detached house has a smaller amount of external fabric in relation to the Detached as it shares a party wall with a neighbour. In principle, this should demonstrate a less specific heat demand (kWh/m^2.a) than the Detached but the average form factor from the case studies showed it to be less advantageous while, the difference between regions is proportionally similar ranging between 15-35% (*Figure 5.6*).

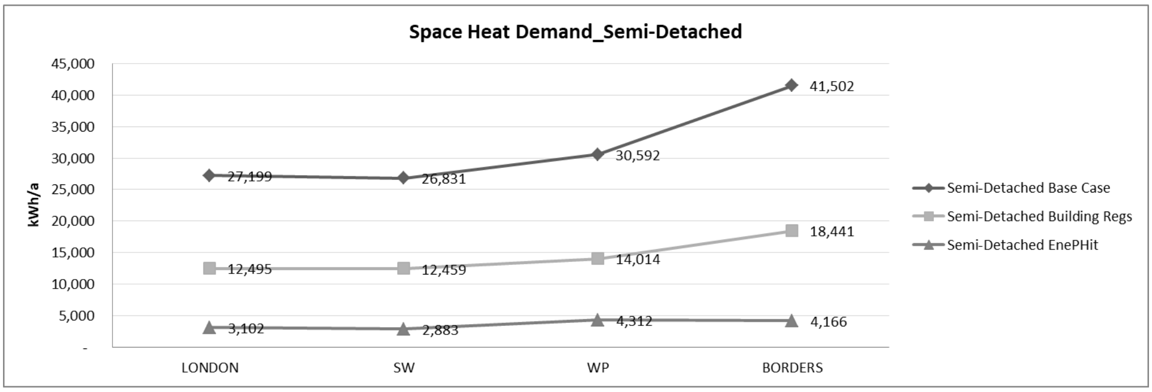


Figure 5.6 *Presenting the average space heat demand (kWh/a) in the Semi-Detached typology per scenario modelled and location.*

In the Semi-Detached typology as observed in *Figure 5.6* the difference is approximate 25,000kWh annual heat demand within London, South West and West Pennines regions from the Base case scenario to the EnerPHit standard and up to 36,000kWh in Borders. The annual bill savings in the Borders region would be £1,800(gas) or £5,400 (electric) and £1,250 (gas) or £3,750 (electric) for the rest of the regions respectively. The tonnes of CO_2/ year equivalent would be 5 to 7 if gas is used for heating and 15 to 21 in the case of electricity. In comparison to the Detached typology when the Build Regulations scenario is applied the reductions are approximately 55% lower as the Semi-detached is less efficient thus interventions have a greater impact. When the annual heat demand (kWh/year) is compared to the specific heat demand (kWh/m^2.a) the "efficiency" of a property can be reviewed and the comparison of the relatively similar typologies Detached and Semi-detached provides a good example. The Detached due to its size has a significantly higher average annual heat demand of approximately 30% (*Figure 5.3* and *Figure 5.6*) but the Semi-detached has higher specific heat demand (*Figure 5.1*) of about 5%. This shows that there is a clear difference on high upfront capital cost for retrofit works (i.e. bigger property) but greater payback (i.e. inefficient property), meaning that the morphology of the dwelling is relevant to its efficiency thus the cost of retrofit and its payback through bill reduction is as well.

Even though this relationship will be explored in detail later in the thesis, it is this initial comparison of moderately similar typologies that presents these differences. This has an obvious implication when it is translated into industry and policy “logistics”. As explained in section 5.2.3 the current assessment procedure for energy efficiency in existing buildings (EPC) is RdSAP which underestimates the form factor in its calculation in comparison to PHPP (Stone *et al* , 2014). This underestimation has an impact on the amount of both the materials used to achieve the required energy upgrade (capital cost) and consequent energy savings (payback).

Warm Climate

London | South West

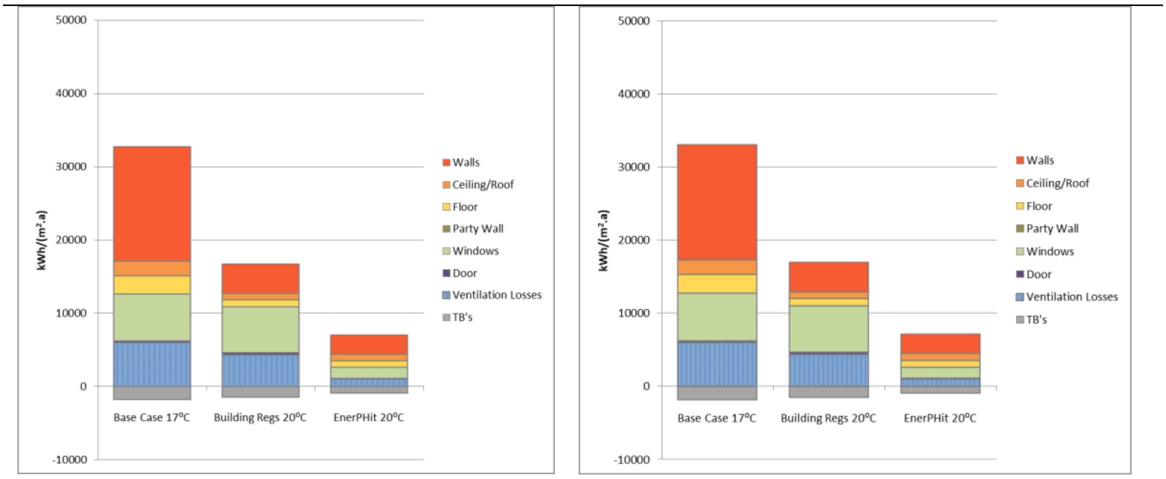


Figure 5.7 *Semi-Detached typology modelled average heat loss per building element in UK warm climate*

Cool Climate

West Pennines | Borders

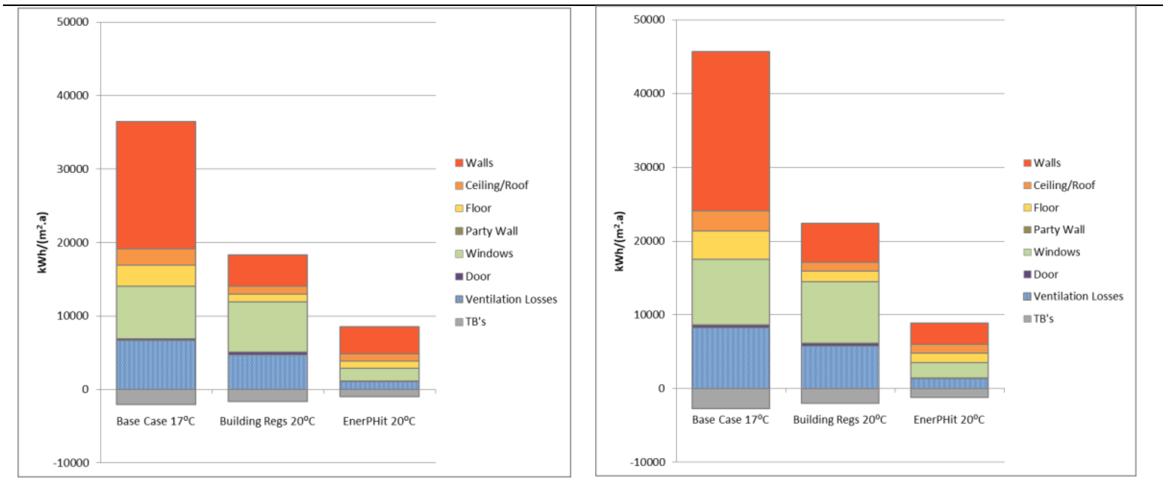


Figure 5.8 *Semi- Detached typology modelled average heat loss per building element in UK cool climate*

When each element is reviewed separately (*Figure 5.7* and *Figure 5.8*), it is observed that the most heat loss is through the external wall. Secondarily, through the windows closely to ventilation losses where the ceilings are lower and resulting to less air volume.

By achieving a recommended EnerPHit the heat loss in the extremal wall is reduced by 80-85% and from the Base Case and even 75% when is upgraded to Building Regulations standards showing that “easier” offsite mechanisms related to wall insulation could have a significant benefit. The window losses are reduced by 75% and the ventilation losses are reduced 85% on EnerPHit and 30% on Building Regulations.

5.3.6 End-Terrace typology energy heat demand

This typology is similar to the Semi-detached as it also shares one of its walls with a neighbour. The great difference within this typology is the great amount of external wall area in relation to the treated floor area resulting to the worst form factor within all the typologies. Due to its geometry, this type is usually the most challenging to retrofit and to achieve a higher standard such as EnerPHit and has the worst specific heat demand in relation to all other properties (*Figure 5.1*).

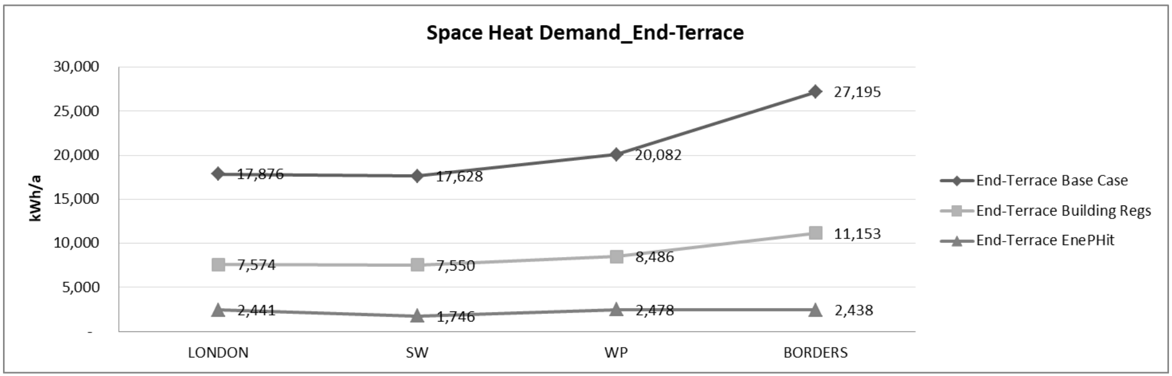


***Figure 5.9** Presenting the average space heat demand (kWh/a) in the End Terrace typology per scenario modelled and location.*

As seen from *Figure 5.9* the difference in space heat demand within the regions is significant, approximately 14-36% between warm and cool climate. Additionally, the reduction in annual heat demand between the Base Case scenario and EnerPHit was approximately 16,000kWh within London, South West and West Pennines regions and up to 25,000kWh in the Borders. The annual cost saving from heating bill for the Borders region would range from £1,250 (gas) or £3,750 (electric) and £800 (gas) or £2,400 (electric) for the rest of the regions respectively. The tonnes of CO_2/ year equivalent would be 3.2 to 5 if gas is used for heating and 5 to 15 in the case of electricity. Similarly to the Semi-detached when the Build Regulations scenario is applied there is a significant reduction of approximately 60% on the energy and related heating bills along with equivalent CO_2 emissions. This typology is the least efficient in comparison to the others reviewed as it has a combination of both a high external envelope area and worst form factor.

Warm Climate

London | South West

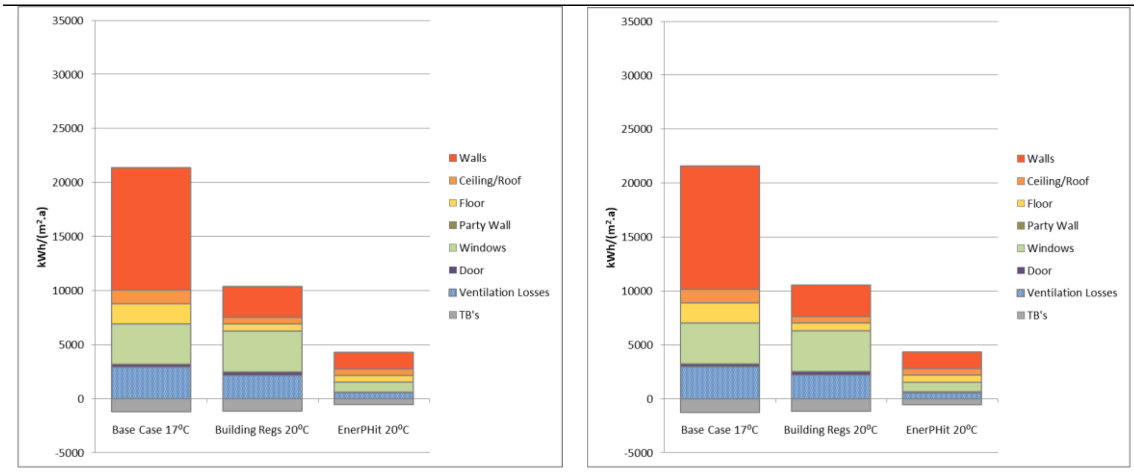


***Figure 5.10** End Terrace typology modelled average heat loss per building element in UK warm climate*

Cool Climate

West Pennines | Borders

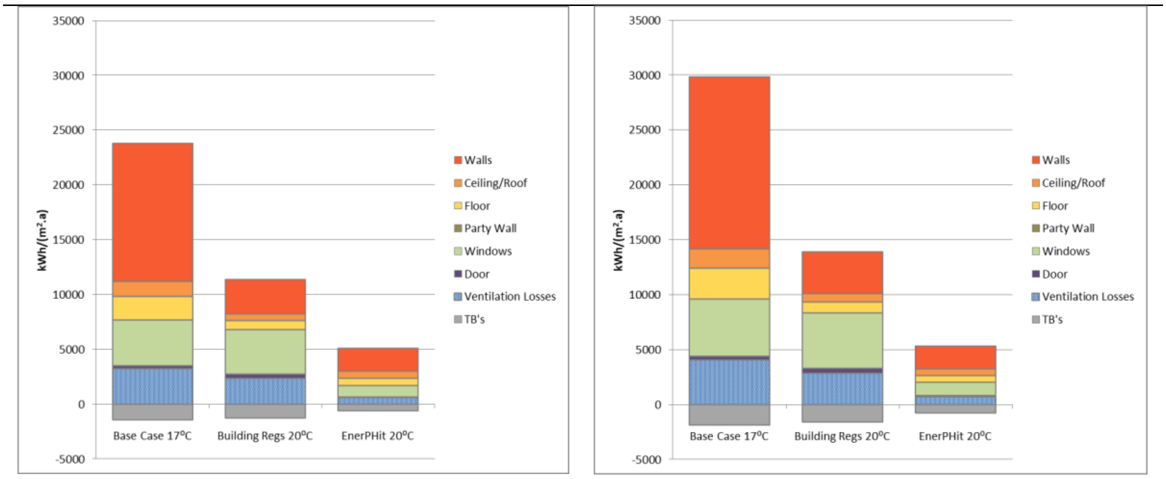


***Figure 5.11** End Terrace typology modelled average heat loss per building element in UK cool climate*

In *Figure 5.10* and *Figure 5.11* it is demonstrated that most heat loss is through the external walls which accounts for almost 50% of the entire elements heat loss in the Base Case scenario. By upgrading the wall with insulation considerably to achieve the EnePHit standard, the heat loss is reduced by 90% from the Base Case scenario and even up to 70% when is upgraded to Building Regulations standard. The external wall is the main element with the highest heat loss in most of the typologies due to the amount of external area but in the End-Terrace there is predominance if compared with the other building elements and the other typologies. This is also reflected when the element heat loss graphs (*Figure 5.10* and *Figure 5.11*) are reviewed in relation to the annual space heat demand (*Figure 5.9*); the Building regulations in the element breakdown presents a reduction of 5% within the windows and around 25% in the ventilation losses but by reducing the wall heat loss to 70% it offers an overall reduction of 60% in the total annual demand. This fact could present a good opportunity to apply offsite mechanisms to wall insulation that could be beneficial in theory. The EnerPHit scenario reduces the ventilation losses by 80% and the window losses by 70% that are predominantly onsite construction works.

5.3.7 Terrace Bay typology energy heat demand

The Terrace Bay typology has the same geometry as the End Terrace but shares two walls with neighbours resulting in less heat loss by comparison. This is reflected in the overall heat demand comparison between these two typologies (*Figure 5.9* and *Figure 5.12*) with an approximate 10% difference. The regional heat demand differences are ranging from 15 to 35%.

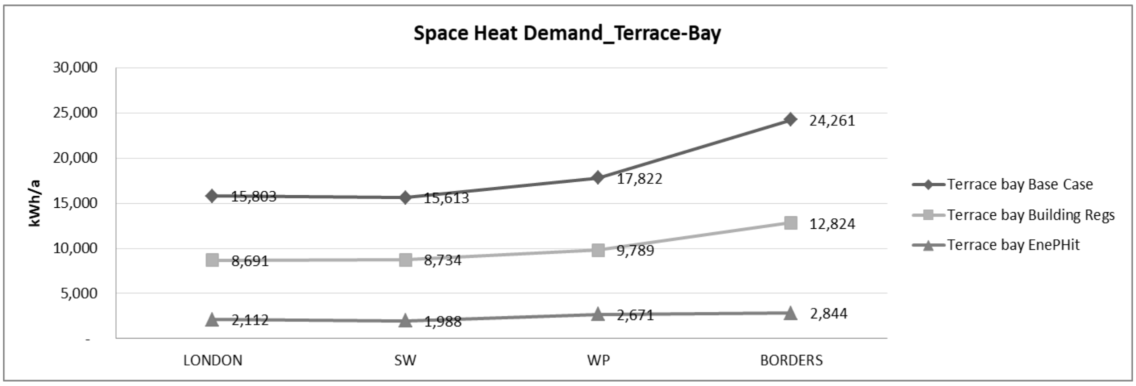
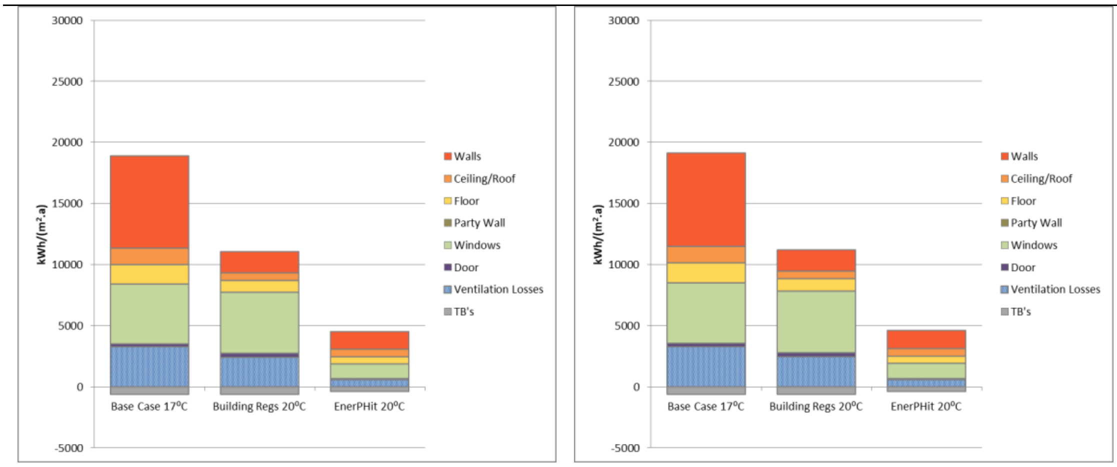


Figure 5.12 *Presenting the average space heat demand (kWh/a) in the Terrace Bay typology per scenario modelled and location.*

As observed in *Figure 5.12* the annual space heat demand is reduced when retrofitted from the Base Case to EnerPHit, approximately 13,000 kWh in London and South West, 15,000kWh in West Pennines and 21,000 kWh in Borders. For the Borders region the cost reduction from heating bills would be £1,000(gas) or £3,150 (electric) annual bills and £650-750(gas) or £1,950-2,250 (electric) for the rest of the regions respectively. The tonnes of CO_2/ year equivalent would be 3 to 4.2 if gas is used for heating and 8 to 12 in the case of electricity. These figures are reduced by 50% when the Build Regulations scenario is applied similarly to the Detached typology.

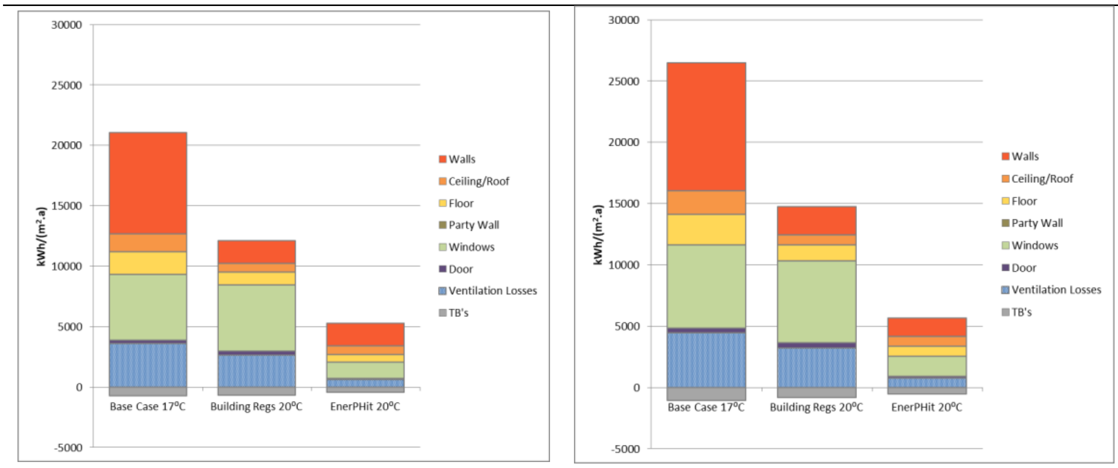
Warm Climate


London

South West

Figure 5.13 *Terrace Bay typology modelled average heat loss per building element in UK warm climate*

Cool Climate


West Pennines

Borders

Figure 5.14 *Terrace Bay typology modelled average heat loss per building element in UK cool climate*

Figure 5.13 and *Figure 5.14* show that heat loss through the external walls is almost equal to the window heat losses, this is due to the higher ratio of window in the external envelope (Bay windows) in comparison to the other typologies. The wall and ventilation heat loss differences between the Base case and EnerPHit are within the region of 80-85% and in comparison to the Building Regulations 75% and 35% respectively. This points to the issue of the feasible benefit limitations of offsite mechanisms in a typology as such since the windows (unless part of an external prefabricated wall element) and airtightness work are mainly through onsite construction.

5.3.8 Terrace Flat typology energy heat demand

The Terrace Flat is the most efficient typology overall balancing both a very good form factor and a compact external wall area. This makes the ability to reach a higher standard easier and the absence of bay windows and extensions makes the applications of insulation easier as well. The overall heat demand is greater than the Terrace Bay (*Figure 5.12* and *Figure 5.15*) but this is due to the greater size of the dwelling and its efficiency in the specific heat demand analysis comparison is reflected in *Figure 5.1* and *Figure 5.2*.

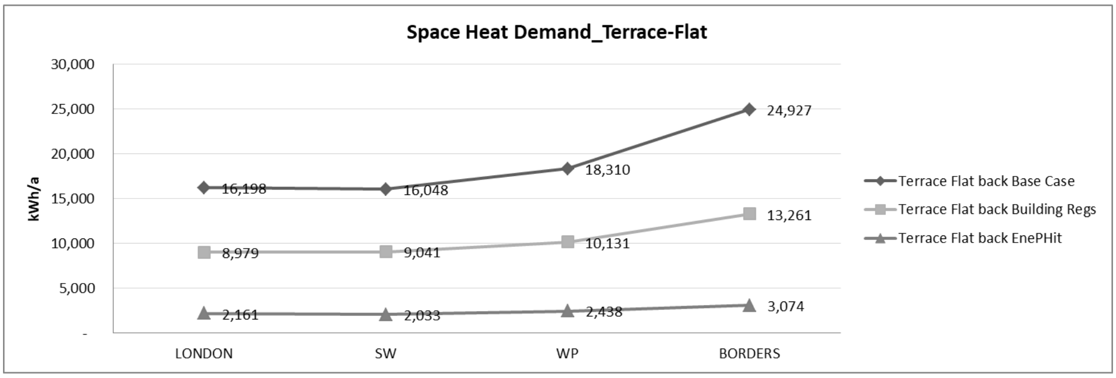


***Figure 5.15** Presenting the average space heat demand (kWh/a) in the Terrace Flat typology per scenario modelled and location.*

As shown on *Figure 5.15* the annual heat demand reduction in the Terrace-Flat typology from Base Case to EnerPHit accounts for approximately 14,000kWh in London South West regions, 16,000kWh in West Pennines and 22,000kWh in Borders. The equivalent annual bill reduction for these would amount to £1,100 (gas) or £3,300 (electric) annual bills for Borders and £700-800 (gas) or £2,100-2,400 (electric) for the rest of the regions respectively. The corresponding reductions in tonnes of CO_2/year would be around 3 to 4.5 if gas is used for heating and 9 to 13 in the case of electricity. These figures are reduced by 40% when the Build Regulations scenario is applied, lower than any of the other typologies.

Warm Climate

London | South West

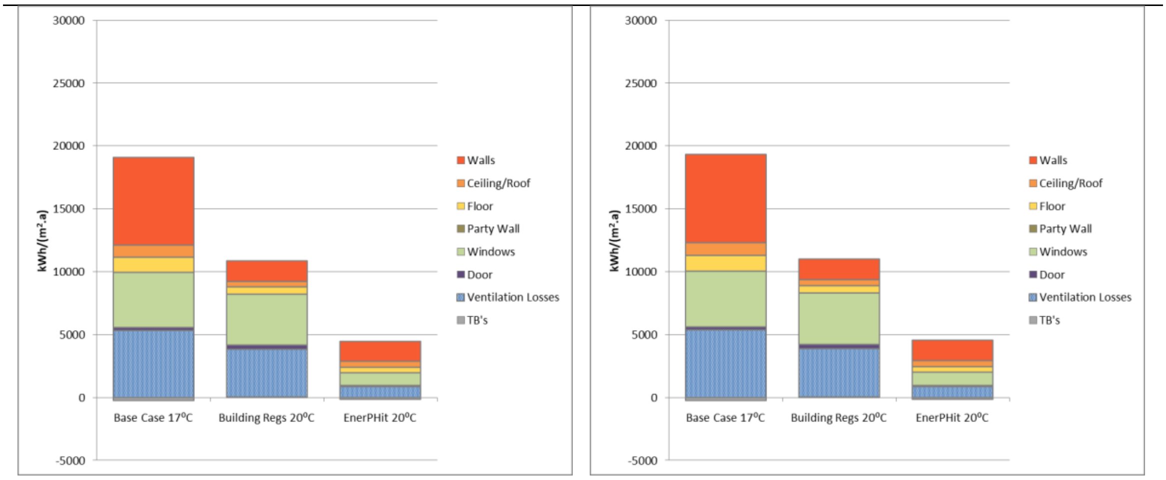


Figure 5.16 *Terrace Flat typology modelled average heat loss per building element in UK warm climate*

Cool Climate

West Pennines | Borders

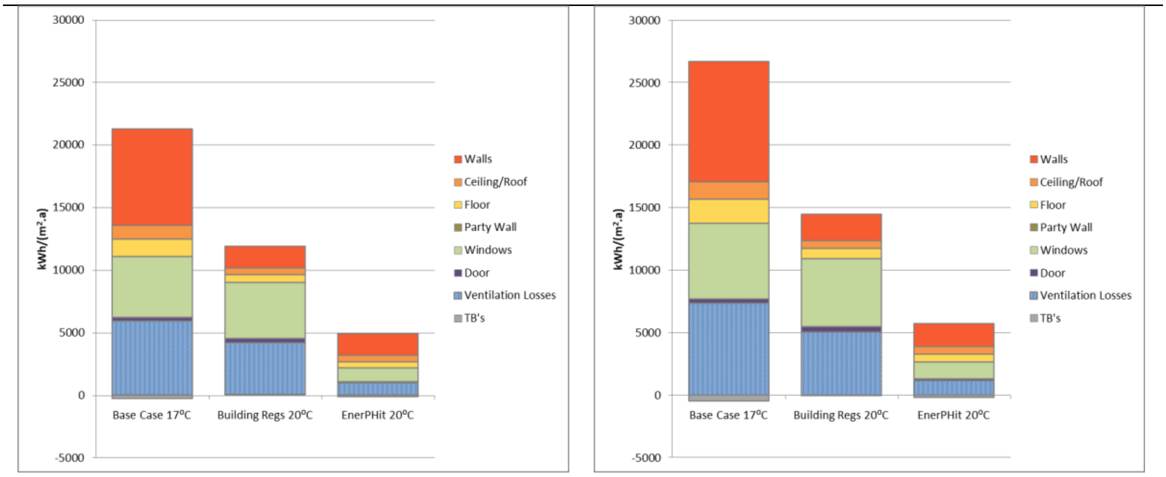


Figure 5.17 *Terrace Flat typology modelled average heat loss per building element in UK cool climate*

Figure 5.16 and *Figure 5.17* show that the Terrace Flat has the lowest heat loss, in comparison to the other typologies, through the walls due to the lower amount of its external surface area, this is almost equal to the ventilation and window losses. By achieving a recommended EnerPHit airtightness of 1 /hr (ach) the ventilation heat loss is reduced to 80% from the Base Case and to 25% when is upgraded to Building Regulations standard while the windows upgraded to the EnerPHit present a 75% reduction. The external wall heat loss is reduced by 75% and 85% respectively. This typology is usually the easiest to retrofit in terms of complexity due to its flat wall elevations but similarly to the Terrace-bay the implications of offsite applicability stand on the fact that the greatest impact would be made with onsite techniques that include airtightness and window upgrade.

5.3.9 Technical significances and findings

The differential between typologies specific heat demand (kWh/m^2.a) as seen in *Figure 5.1* in the previous section is an average 40-60% within the Base case and Building Regulation scenarios and up to 90% when EnerPHit is applied. The worst to best heat demand typology ranged from End-terrace, Semi-detached, Detached, Terrace-Bay and Terrace-Flat. The overall annual heat demand (kWh/year) climate differences throughout the typologies ranged between 12-35% demonstrating a significant impact in regards to the subsequent cost of retrofit and payback that are analysed in detail in the next chapter. Similarly in all typologies apart for the *Flat Terrace* it is observed that between the two cool climate regions (West Pennines and Borders) there is a slight "inconsistency" when it comes to the average space heat demand on the modelled EnerPHit. When the typology is located in West Pennines even with a warmer climatic condition than Borders it has slightly higher space heat demand. This is due to the pre-determined insulation thicknesses that exist on the offsite methodology tested and can be equally compared with the onsite equivalent. The insulation thickness required to achieve the limiting specific heat demand <25kWh/m^2.a (cool climate) in West Pennines was thinner in comparison than in Borders due to the milder climate. As seen from the *Figure 5.4* to *Figure 5.17* understandably the external walls are the predominant element with the highest heat loss followed by the window and ventilation losses. There is variance between the amounts of heat loss within these three elements depending on typology and climate that influences the amount of work and materials required to achieve the required standard. Those practical consequences have an impact on regulation related to housing retrofit and subsequent offsite mechanisms.

In terms of upgrading the external wall regardless whether onsite or offsite mechanisms are applied is to a certain extend straightforward; while achieving the required airtightness (EnerPHit) is much more challenging as it requires more attention to detail (Gillott *et al.,* 2016; Loveday and Vadodaria, 2013) and usually extensive site work supervision (Price and Marincioni, 2014). This brings into consideration that the offsite measures, in terms of technical application advantages, might only go so far when it comes to retrofit but conceivably suppliers that offer “offsite retrofit packages” (Beattie Passive/Energiesprong) guarantee its suitable application. Similar observations are made related to the impact of window upgrade from single to triple glaze in regards to heat loss reduction. Triple glazed windows are usually double the cost of double glazing (The Technology Strategy Board, 2014) but their cost could possibly significantly be reduced in economies of scale such as “offsite retrofit packages”. Additionally, the windows according to current offsite mechanisms can only be combined to external wall insulation techniques fitted in combination with the additional external envelope.

In summary, the technical related findings showed that there is a clear variation in both energy reduction possibilities and subsequent feasible offsite applications within the typologies and locations modelled. Thus, there is a consequent related impact in cost from both energy reduction (bills) and construction method approaches (onsite/offsite). These are presented and discussed in the next section.

5.4. Financial related outcomes

This section of the thesis reviews the cost analysis results from the modelling that examined the implications of onsite to offsite retrofit techniques on the selected typologies. As argued in section 5.1 there is currently a lack of research and available information on the implications, benefits and cost of housing retrofit with offsite mechanisms within the UK’s pre-1919 stock. Collective data in scale regarding deep retrofit costing can almost only be found from the costing analysis made from the Retrofit for the Future programme (The Technology Strategy Board, 2014) with only a handful of cases using offsite in pre-1919 dwellings. With the current market that is involved in deep/Whole-House retrofit and offsite focusing on later build typologies the research offers a novel contribution by analysing in detail the factors influencing the cost of offsite mechanisms in typologies that are of greater “need” to be benefited from.

5.4.1 Model analysis components

The cost analysis used information already in the RealCosting analysis and added/subtracted the costs related to offsite mechanisms. The main offsite mechanisms that were applied are:

- Offsite Internal Wall Insulation with the method of WHISCERS which includes in its cost the entire installation and survey.
- WHISCERS Internal Wall Insulation and Offsite Modular Roof.
- Then the result are compared to External Wall Insulation the Beattie Passive TCosy system that includes all cost related to reach the required EnerPHit standard and the cost data are in £/m^2.

The elements that are upgraded with traditional onsite construction methods are the floors, windows/doors (excluding TCosy method), airtightness, heating and ventilation systems. The depth of the insulation used and cost are based on realistic values. For example the Internal Wall Insulation that was used is the same that WHISCERS uses in their applications (K18 Kingspan) and the available thicknesses are from 32.5 to 92.5mm. Thus, the cost increases or decreases not only in relation to the amount needed for the external wall but in some cases where the limit 92.5mm was not sufficient consequently the floor or roof insulation increased accordingly. It should also be noted that the size of the Treated Floor Area is automatically adjusted by the RealCosting software accordingly to the internal insulation applied. Finally, for the Base Case a reasonable amount for upgrades was assigned in regards to general decoration/painting and boiler upgrade within the assigned timeline.

5.4.2 Modelling cost elements and adjustments

The RealCosting software has an extensive cost library that includes cost of materials per application and labour. The library though can be amended or updated accordingly to suit the user’s model. In this thesis the cost inputs placed in the model in the onsite and offsite scenarios are detailed in *Table 5.1*.

Element	**Onsite IWI**	**Offsite IWI**	**EWI (Beattie Passive)**
Wall	K18 Kingspan insulation. Cost data from various suppliers taken the average for each thickness such as: www.insulation-online.com	WHISCERS Cost data adjusted from: - Research Council UK: http://gtr.rcuk.ac.uk/projects?ref=620051 - Invest in Innovative Refurbishment – Garth House Bicester Project: DECC, 2016, Link: www.brookes.ac.uk/about-brookes/news/bicester-s-garth-house-makeover-cuts-energy-bills-for-a-historic-building/	All-inclusive ≈750/m^2 (Information obtain via email correspondence by the researcher with Beattie Passive on R&D projects)
Roof	RealCosting Library	RealCosting Library and offsite manufacturers including (Baeli, 2013) for offsite.	
Floor	Ibid.	RealCosting Library	
Windows	Ibid.	Ibid.	
Airtightness and Miscellaneous	Ibid. and data included for service relocation	Ibid. and service relocation included in WHISCERS	
Services	RealCosting Library		
Design, Survey and Certification (EnerPHit)	Average cost taken from: - Design fees AJ: http://aj100.architectsjournal.co.uk/FeesCalculator.aspx - Certification fees: AECB, Link: www.aecb.net/publications/aecb-faq-passivhaus-certification/	- Survey included in WHISCERS	

Table 5.1 *Data collection references that were used in the cost modelling of the scenarios*

5.4.3 Cost model results

The cost of upgrading from the Base Case to Building Regulations and EnerPHit depends on the typology's efficiency and location as the results showed on the energy analysis. The cost analysis of each offsite method compared to onsite was reviewed in two ways: a. the average total capital cost in pounds and b. the average capital cost per m^2 of floor area. When the average total capital cost is reviewed (*Figure 5.18*, *Figure 5.20* and *Figure 5.22*) it initially appears that the cost is relative to the size of the building apart from the comparison between Terrace Bay and End Terrace as those are the typologies with the worst and best energy efficiencies .

This relates back to the heat demand variations observed in the energy modelling. As *Figure 5.19* and *Figure 5.21* demonstrate the required capital per m^2 for retrofit in each scenario and location and it is an almost exact reflection to the *Figure 5.1* of the specific space heat demand. The cost therefore has a direct connection to the heat loss which by extension has a direct connection to the typology and location of the dwelling (climate).

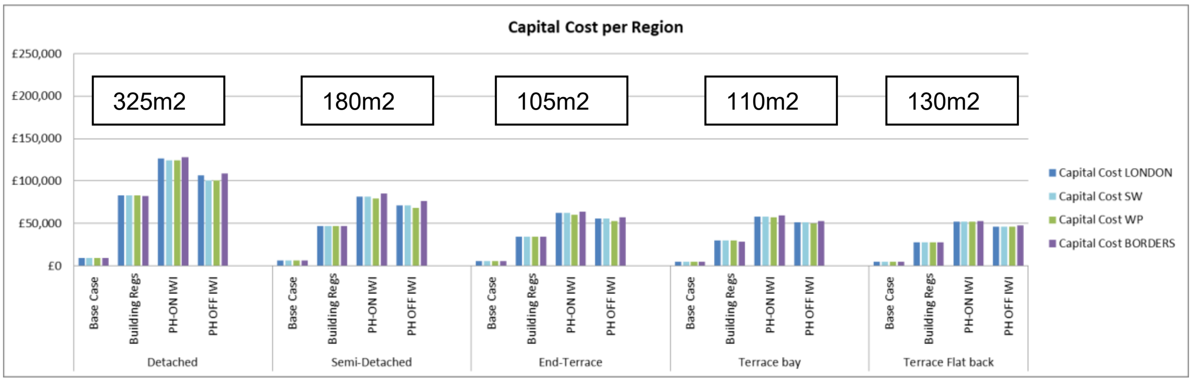


Figure 5.18 *Capital cost comparison of onsite construction with offsite element of* ***Internal Wall Insulation****.*

As seen from *Figure 5.18* the EnerPHit scenario has the highest upfront capital cost in relation to the Building Regulations due to the amount of additional materials used and labour needed to achieve the standard. The additional cost ranges between 30-50% which translates to additional £20,000 to £50,000 to achieve EnerPHit. The cost is reflects the size of the property in the first four (Detached, Semi-detached, End-Terrace and Terrace-Bay) while the Terrace Flat has the lowest in comparison due to the “lower” amount of retrofit interventions needed to achieve the required standard. The regional differences range from £1,000 to £6,000. In terms of applying the Internal wall insulation using offsite techniques the cost reduction ranges approximately from £5,000 to £20,000 presenting a clear cost benefit and evidently greater in properties with a larger area of external wall.

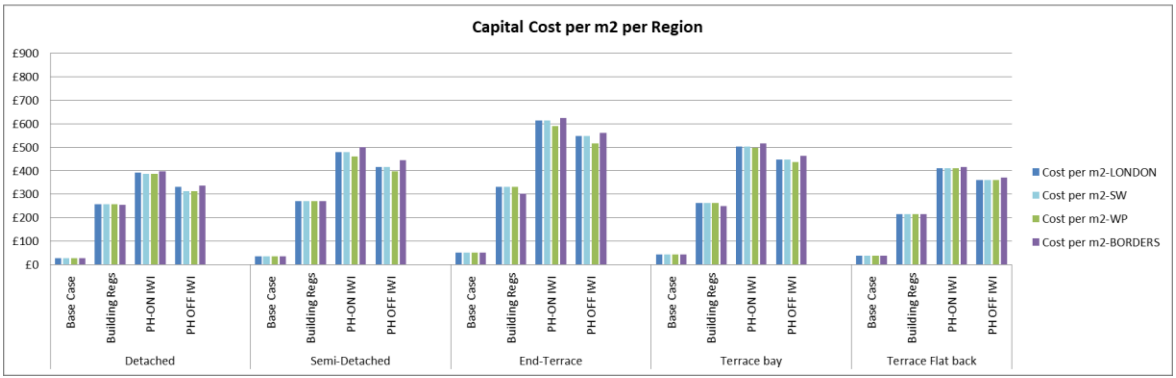


Figure 5.19 *Capital cost (**per m^2**) comparison of onsite construction with offsite element of **Internal Wall Insulation***

When the same cost is reviewed in terms of the property size, i.e. £/floor area as shown in *Figure 5.19* then the relation of cost of works to the efficiency of the dwelling is clear. The least efficient typology, the End-Terrace requires more capital in relation to its size to achieve the required energy efficiency standard while the largest typology, the Detached and Terrace-Flat require the lowest.

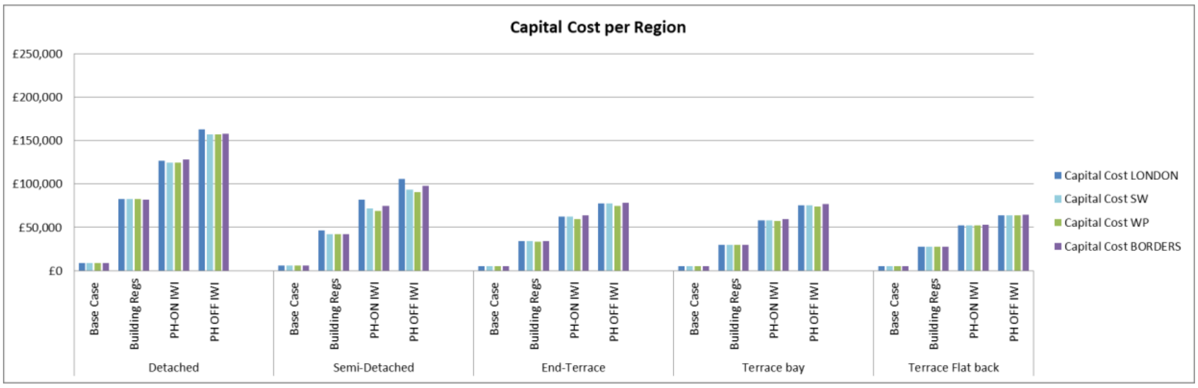


Figure 5.20 *Capital cost comparison of onsite construction with offsite element of **Internal Wall Insulation and Roof***

Replacing the roof with an offsite structure improved equivalent along with the combination of offsite Internal Wall Insulation to achieve the EnerPHit standard increases the cost against onsite. The additional cost ranges from £10,000 to £30,000 and is proportional to the property's roof size. Even though the offsite Internal Wall Insulation reduces the cost in comparison to onsite, the higher offsite roof cost is not "compensated" by that reduction.

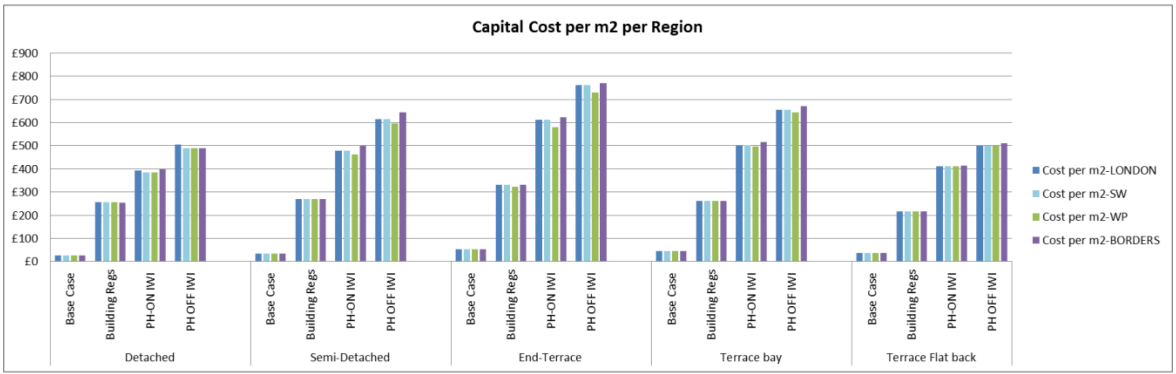


Figure 5.21 *Capital cost (**per m^2**) comparison of onsite construction with offsite element of **Internal Wall Insulation and Roof***

Similarly to *Figure 5.19*, *Figure 5.21* shows that the cost of the retrofit works when reviewed in terms of £/floor area then the efficiency of the typology is reflected.

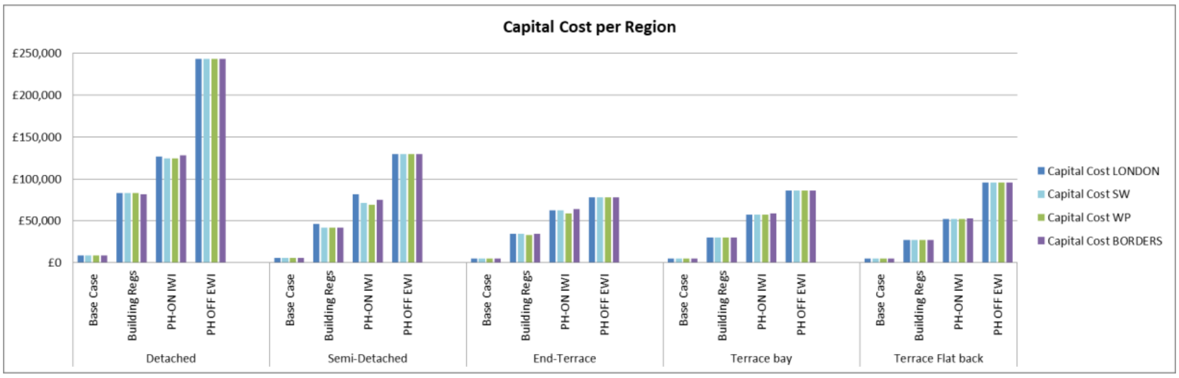


Figure 5.22 *Capital cost comparison of onsite construction with offsite element of External Wall Insulation **(offsite "retrofit package")***

As observed from *Figure 5.22*, the "retrofit package" has the highest upfront capital cost in comparison to the other offsite measures. As the cost of this "service" comes from £/m^2 of the internal area property the additional cost is relative to floor size and the cost difference of offsite versus onsite construction to achieve the EnerPHit standard ranges from £15,000 to £115,000. Nonetheless, the different energy efficiency of the typologies still has an impact. As seen from the least efficient typology; End Terrace has the lowest cost difference between the two offsite applications as it already relatively the most challenging/costly to retrofit.

The initial cost analysis has shown the following clarifications: a. adding the offsite construction element becomes beneficial in terms of upfront capital cost overall when the Internal Wall Insulation (WHISCERS) is applied and the cost reduction is greater relative to the amount of external wall of the typology. b. When the roof element is added along with the offsite Internal Wall Insulation the capital cost is greater than the onsite construction equivalent. In this case the area of the typology's roof dictates the rise in the cost. Finally, c. the offsite retrofit "package" has the highest upfront capital cost and is relative to the typology's internal floor area.

5.4.4 Onsite and Offsite differences

In this section the onsite and offsite differences are reviewed in more detail. *Figure 5.23* presents a clear comparison of all the scenarios of onsite and offsite construction capital cost per m^2 to achieve the EnerPHit standard. The most "cost effective" is when WHISCERS offsite Internal Wall insulation is applied with an average reduction ranging from 10-19% (*Figure 5.24*). When offsite roof was added to the calculation then the construction cost actually increased on an average between 18-23% (*Figure 5.25*) and finally if compared to the "retrofit package" the cost is increased on average between17 to 49% (*Figure 5.26*).

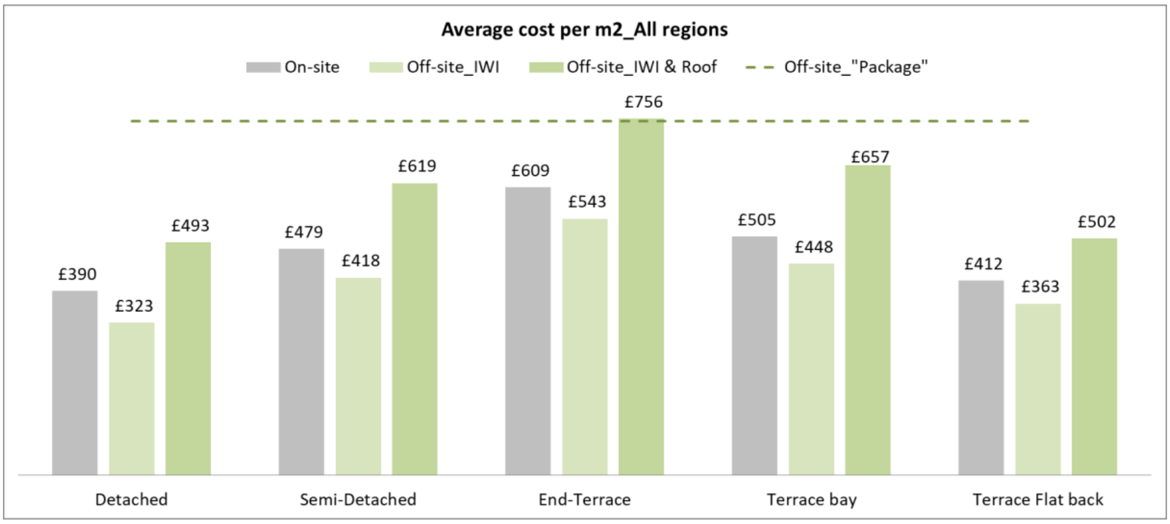


Figure 5.23 *Average cost per m^2 comparison between typologies and onsite to offsite applications to achieve EnerPHit.*
(The offsite "Package" is assumed £750/m^2 in all typologies)

The first thing that is observed is the variance in cost within the typologies, demonstrating the technical and subsequent cost complexity of Whole-House retrofitting. So in terms of market uptake and upscaling by using offsite mechanisms even in technical terms (cost/energy) and not taking into account further external factors (regulation/consumer) could be more than challenging especially for these typologies.

5.4.4.1. Offsite Internal wall Insulation (WHISCERS)

The cost of using this system is reduced by including in its price manual labour that is the most costly element in the application. Apart from the pre-cut offsite of the insulation and fitting that fundamentally saves labour time and material, it also includes survey and service relocation when it is compared with traditional breakdown of works, WHISCERS can offer up to 19% cost reduction.

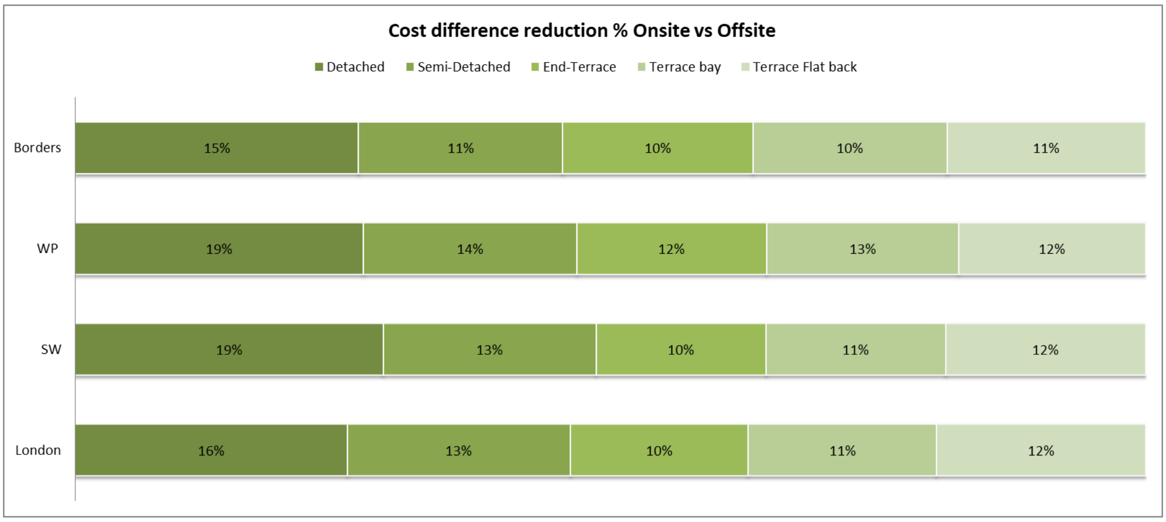


Figure 5.24 *Cost difference* ***reduction*** *percentage using Offsite Internal wall Insulation versus onsite*

As calculated in the energy analysis the primary heat loss in most cases is through the external wall and consequently the reduction of heat loss through this element has an impact in the heat demand. The cost reduction through offsite mechanisms therefore has a higher capital cost reduction in typologies with more m^2 of external wall (*Figure 5.24*). In terms of regional differences it observed that that South West and West Pennines regions have greater cost reductions than counterparts and this is due to the lower thickness of insulation needed to reach the required standard. For example in Borders the limiting value of heat demand to achieve EnerPHit is 25kWh/m^2 but due to climatic conditions ("cool climate") to achieve this thicker insulation is needed in comparison to its counterpart West Pennines which has a milder climate. The same effect is observed when London and South West are compared.

5.4.4.2. Offsite Internal wall Insulation (WHISCERS and Offsite Roof)

When in the scenario additional offsite fabric element is introduced, that of the roof, the cost increases significantly (*Figure 5.25*). The cost rise is mainly due to the amount of materials and feasible labour to construct an additional structure to be fitted either on top of the existing one or replacing it (the cost in the model has taken an average for both cases).

In clear comparison with the onsite element upgrade the insulation needs to be applied on and under the rafters and ensuring a continuous airtightness layer but the offsite equivalent will need additional timber structure (to match existing), slate, insulation and in the case of replacement the demolition cost of the existing. If the roof is replaced though, extra room space could be added to the property that will increase the House Value and reviewed further in the next section.

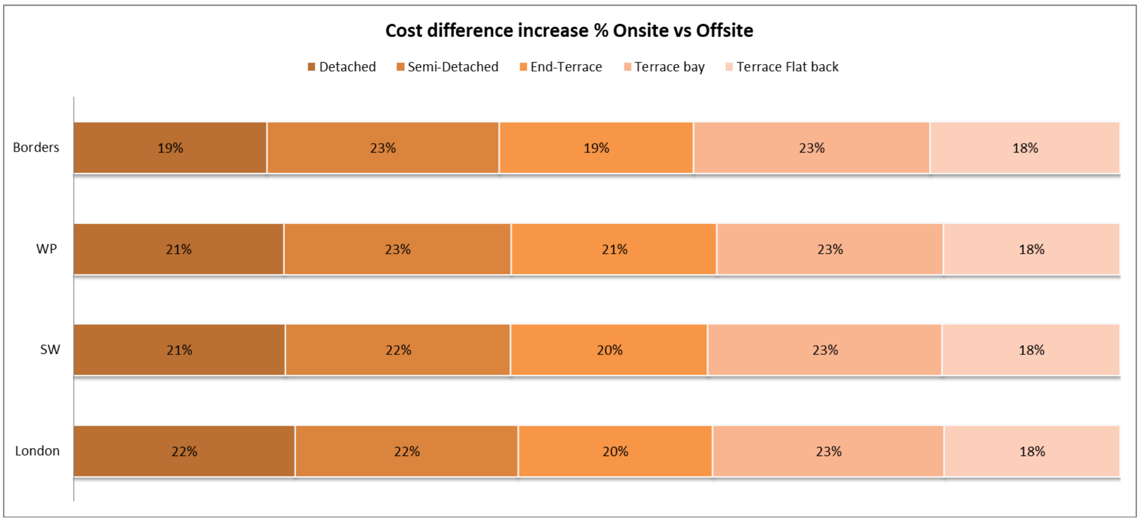


Figure 5.25 *Cost difference* ***increase*** *percentage using Offsite Internal wall Insulation and Roof versus onsite*

As seen on *Figure 5.25* the increase in cost is relative to the amount on roof area per typology. In terms of regional differences there is a correlation between the initial amounts of insulation needed similarly to the Internal Wall Insulation analysis i.e. Borders region has the lowest increase in cost in comparison as it has the highest capital cost to begin with (onsite works to reach EnerPHit).

5.4.4.3. Offsite External Wall Insulation (“Retrofit Package”)

The External Wall Insulation retrofit package proved to be the most expensive in capital cost when compared with the other offsite scenarios and only “matched” the cost in one typology (End-Terrace) with offsite Internal Wall Insulation and roof (*Figure 5.23*). It should be noted that the cost given is from R&D projects that have not be replicated at scale and up taking the retrofit as a “Design and Build” contract they also guarantee the dwelling is tested and certified to ensure it is built as designed. Additionally the cost that is aimed to be reached (£40,000 per property) is similarly seen in the cost modelling in the cases of Terrace-Flat that is relatively similar to post 1950's terrace houses i.e. flat elevations.

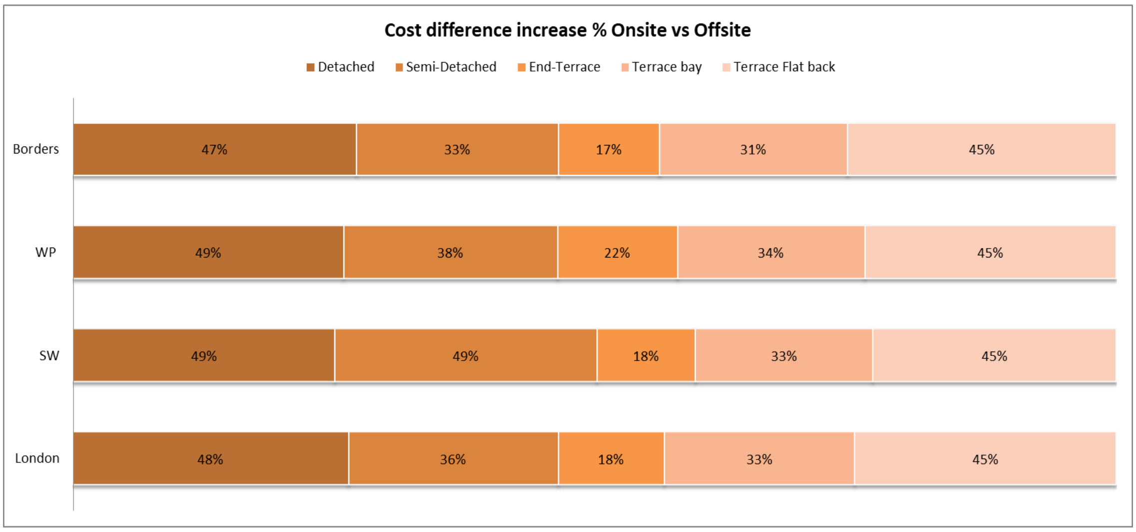


Figure 5.26 *Cost difference* ***increase*** *using Offsite External Wall Insulation ("retrofit package")*

Figure 5.26 shows that the percentages of cost increase in this method of delivering EnerPHit with offsite mechanisms correlates on the amount of the typology's internal floor space but also on its efficiency. This is reflected on the fact that the least efficient typology (End-Terrace) has the lowest increase.

In comparison the Offsite Internal wall Insulation (WHISCERS) was the most economical in regards to capital cost of retrofit and the guarantee of application for the specific element (wall) could be assumed but there is still "risk" as the other works need to be done with independent sub-contractor/builder coordination and "risk" has been identified by other research as one of the barriers for "Whole-House" / low energy retrofit (Janda *et al.*, 2014; NEF and EEPB, 2014b). The addition of offsite roof element increases the cost but there are feasible benefits if additional living space is added. Also the retrofit "package" with offsite elements is the most expensive in comparison but has the advantage of the guaranteed performance and can be considered as a "one-stop-shop" that could have a great market potential. This also has a reflection to survey results, as "Better quality of build" was the highest incentive in percentage for choosing offsite mechanisms in retrofit over monetary value “if cost was lower” (*Figure 6.47* and *Figure 6.49*) and even in the thematic analysis (*Table 6.1* and *Table 6.2*) “finding a competent contractor” to deliver Passive House/EnerPHit was a reoccurring concern.

5.4.5 Payback analysis per offsite scenario and typology

To calculate the monetary payback of the retrofit the calculation includes the capital cost against the savings in energy use through the reduction of bills, value of retrofit comfort, the increase on House Value and/or the Residual Value of the materials used. The savings through bill reduction (gas heating is assumed in the calculation) has taken into account the indicative fuel price rise from DECC, (2014b). A discount rate of 1.5% has been applied taking into account 3.5% (30 years) from the Green Book (HM Treasury, 2013) rate suggested by the Government and subtracting 2% inflation. The value of retrofit comfort (co-benefits to the occupier) figures were taken from a survey conducted by the RealCosting author (Tim Martel, AECB) on how much occupants evaluate the comfort the retrofit offers i.e. the increase in temperature from 17 ºC to 20 ºC and the survey showed a value of £50 per month. The increase in House Value figures are based on real data from 300,000 homes using the sale price and EPC rating[46] i.e. the amount of House Value increase due to energy saving measures; additionally the increase in House Value is reviewed when the living area is increased (offsite roof) with regional prices taken from the ONS[47] (*Table 5.2* and *Table 5.3*). The values differ significantly within different regions (*Table 5.2*) where for example in London due to the high house demand/price there is low value increase due to retrofit upgrades but has the highest value in comparison on additional floor area (*Table 5.3*)

---

[46] House Price Report: www.gov.uk/government/news/energy-saving-measures-boost-house-prices

[47] ONS House price per square metre and house price per room, England and Wales:: www.ons.gov.uk/economy/inflationandpriceindices/datasets/housepricepersquaremetreandhousepriceperroomenglandandwales

Climate Region	EPC rating D-B
Zone 01 - London	£ 1,100
Zone 05 - South West	£ 16,342
Zone 08 - West Pennines	£ 12,979
Zone 10 - Borders	£ 19,265

***Table 5.2** House price increase relative to EPC rating increase (energy efficiency) and according to the house's location*
These figures were used in the cost modelling to calculate the Return On Investment after the retrofit in relation to the House Value.

Climate Region	Cost per m^2
Zone 01 - London	£ 6,639
Zone 05 - South West	£ 2,478
Zone 08 - West Pennines	£ 1,543
Zone 10 - Borders	£ 1,271

***Table 5.3** House price cost per m^2*
These Figures were used in the cost modelling to calculate the Return On Investment after the retrofit in relation to the House Value only when compared to the feasibility of additional space granted with the offsite roof.

The Residual Value after retrofit takes a different approach from the House Value and is not included in the same calculation. It calculates the remaining value of the retrofit based on what was paid for it and the life remaining. For example the insulation has a 60 year lifespan and through energy saving its cost has been paid back in 25 years but if half the life remains less than half the value remains because, as with most items, the value decreases most rapidly in the first few years. A separate analysis was necessary using either the increased House Value or the residual to have a clear comparison.

5.4.5.1 Offsite Internal wall Insulation (WHISCERS)

The payback from retrofit to EnerPHit standard with traditional onsite construction is beneficial in the long run in most cases as the graphs below demonstrate. The offsite Internal Wall Insulation has proven the most cost effective offsite mechanism in comparison (*Figure 5.23* and *Figure 5.24*), thus including the payback from heating energy savings it is clearly expected to be the most beneficial with the amount highly dependable on the typology and location.

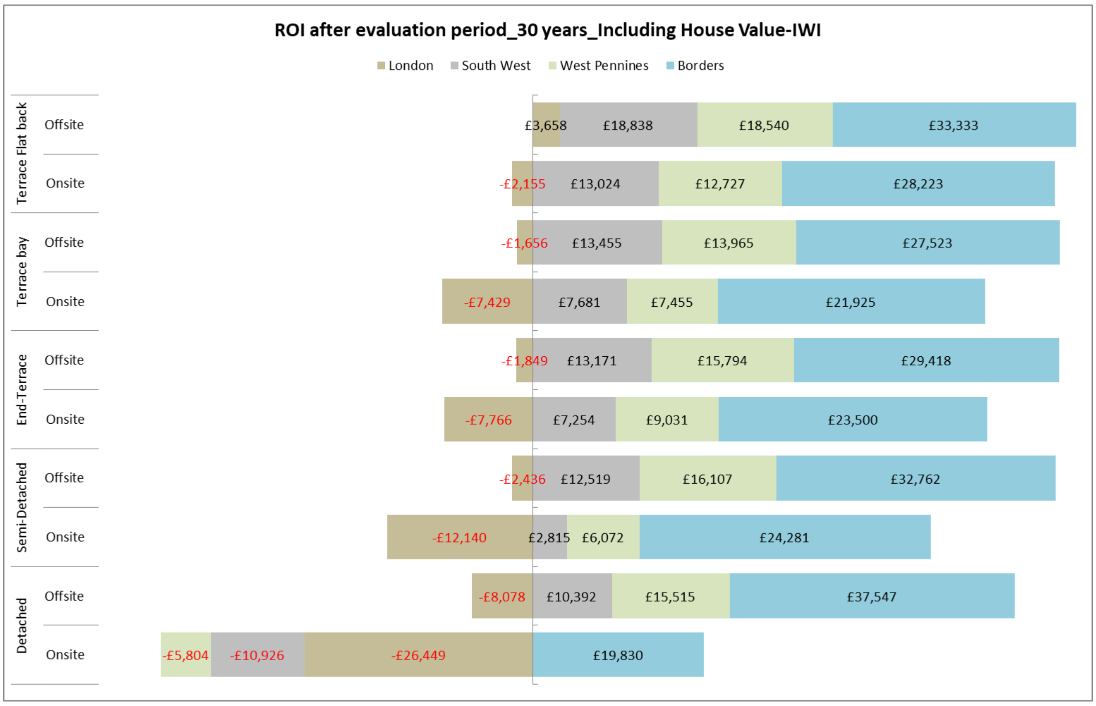


Figure 5.27 *Return On Investment that includes* ***House Value****. Using Internal Wall Insulation as the comparison element of Onsite versus Offsite measure*

The initial remark to be made from *Figure 5.27* is that the increase in House Value is profitable for all the regions apart from London with the exception of the Terrace Flat as it is the most efficient typology. The Detached typology due to its high capital cost makes the onsite construction payback profitable only in the case were the property is located in the Borders.

When the offsite application (WHISCERS) is used it provides a greater impact on the monetary payback due to the Detached typology's extensive external wall. *Figure 5.27* also offers an important representation on the complexity of feasible monetary benefits of Whole-House retrofit in general; with London and Borders locations viewed as the two opposites in the spectrum. Due to the high property value as seen from *Table 5.3* unrelated to any energy efficient improvements and the warmer climate, the London located typologies seem not to have a direct profit from retrofitting to EnerPHit standard but the offsite application reduces the “gap” significantly.

On the other hand, in Borders the “harsher” climatic conditions have a direct effect in the payback of retrofitting to a higher standard along with the property value increase due to this effect (*Table 5.2*). The South West and West Pennies regions have interestingly a more “comparable relation” as the balance of energy savings and property value has somewhat similar results. This is due to correlation of the higher payback through energy reduction in the case of West Pennies but lower House Value, while in South West region the opposite is applicable.

The percentage of cost benefit of offsite Internal wall Insulation and onsite when the increase House Value is taken into consideration and even in the case of London the “loss” is reduced. The offsite measures in this case can offer up to 20% more return in comparison to onsite demonstrating a better value in profit (Appendix D: *Figure D.1*).

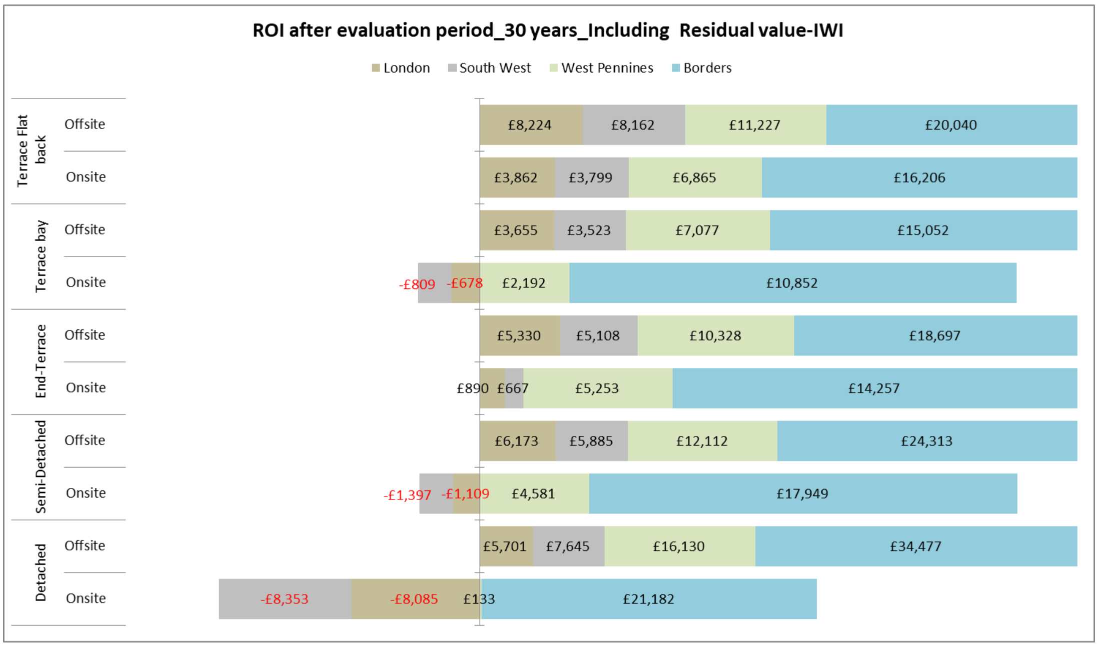


Figure 5.28 *Return On Investment that includes **Residual Value**. Using Internal Wall Insulation as the comparison element of Onsite versus offsite measure*

The London retrofit value increases if the Residual Value is taken into account as shown in *Figure 5.28* while in other regions decreases in comparison. This demonstrates once more the impact of location not only in terms of climate but also of property value. The Residual Value has a reduced return when compared to the House Value with the exception of London. The return on investment is better with offsite measures of up to 10% (Appendix D: *Figure D.2*). Even though the profit value of offsite between these two evaluations (House and Residual) is fluctuating when compared they both show the impact of the return on investment the offsite mechanisms offer.

In sections 5.4.7 to 5.4.11 it will be reviewed how the NPV changes over time (House Value increase) and how the “deep retrofit” is cost effective in the long run and in what way offsite mechanisms’ capital cost reduction could increase the NPV by reducing the “payback” time.

5.4.5.2 Offsite Internal wall Insulation (WHISCERS and Offsite Roof)

The payback when the offsite roof is applied dramatically changes as seen from *Figure 5.29* and *Figure 5.31* as in both cases of House and Residual Value the offsite construction has a lesser investment payback than the onsite due to the much higher capital cost.

In the case that the offsite roof offers additional living space the House Value increases considerably as the property value especially in London (*Figure 5.30*) has a great monetary impact. This is a demonstration of layers of possibilities and this “logic” of additional benefit apart from direct connection to the energy reduction has been previously explored i.e. a kitchen upgrade can be used as a “trigger point “(EST, 2011; Killip, 2011) to include energy efficient measures interconnected with the refurbishment works. The same rationale can be applied when the roof upgrade is considered to some extend as loft conversion.

Even though a detailed breakdown of loft conversion has not been included in this analysis to argue the onsite offsite cost, it should be noted that onsite loft conversions range from £20,000 to over £60,000 (Ransome-Croker, 2018) (assuming minimum Building Regulations equivalent). The analysis in this thesis of offsite roof in combination with the cost reduction from the offsite Internal Wall Insulation showed an additional cost of £10,000 to £30,000 against an onsite construction element upgrade to achieve EnerPHit. This means that in comparison offsite roof could still be cost beneficial along with the added “comfort” element of quick installation.

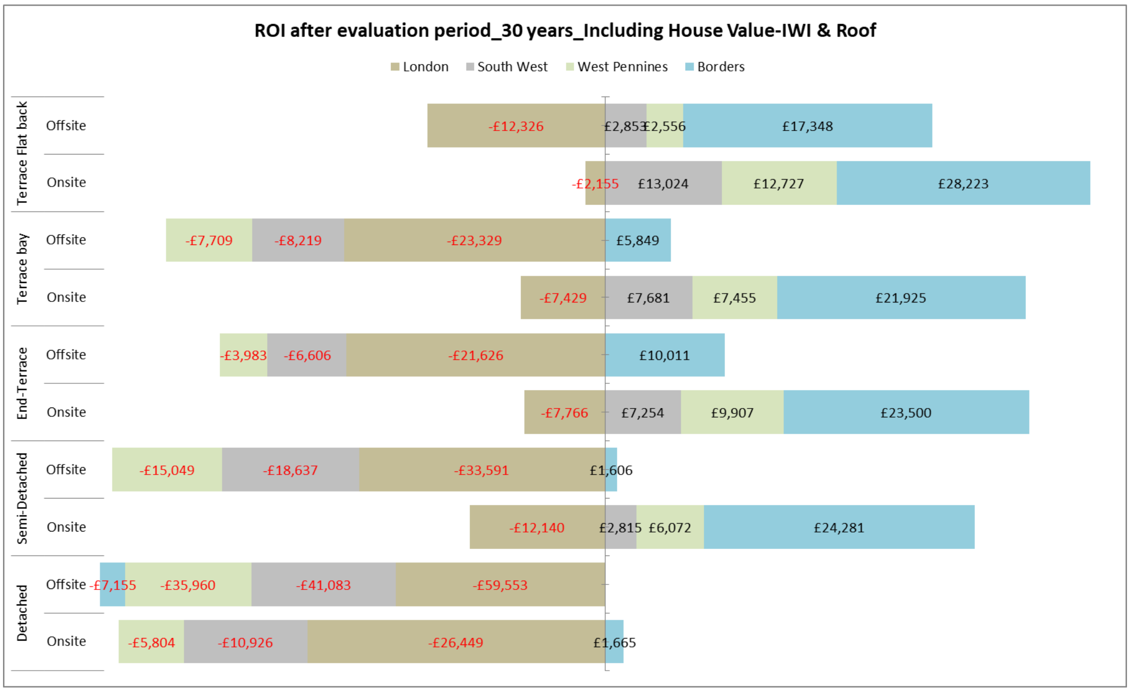


Figure 5.29 *Return On Investment that includes* ***House Value****. Using Internal Wall Insulation and Roof as the comparison element of Onsite versus Offsite measure*

Additionally, as demonstrated in *Figure 5.29* this offsite scenario can still have a clear profit payback in some cases. For example, in all typologies there is still a return made in the Borders region. This is due to the combination of the amount of energy saved due to the harshest climatic conditions resulting in higher heat loss and consequently higher energy saved in comparison and the high increase in House Value from energy upgrades as seen in *Table 5.2*.

Similarly, the Terrace Flat proves profitable in all regions with the exemption of London. This is due to the typologies’ efficiency to begin with and subsequent lower upfront capital cost with the addition of smaller roof area in comparison to the other typologies. When the offsite/onsite differences are reviewed in terms of percentage there is a great difference in favour of onsite works up to 30% (Appendix D: *Figure D.3*).

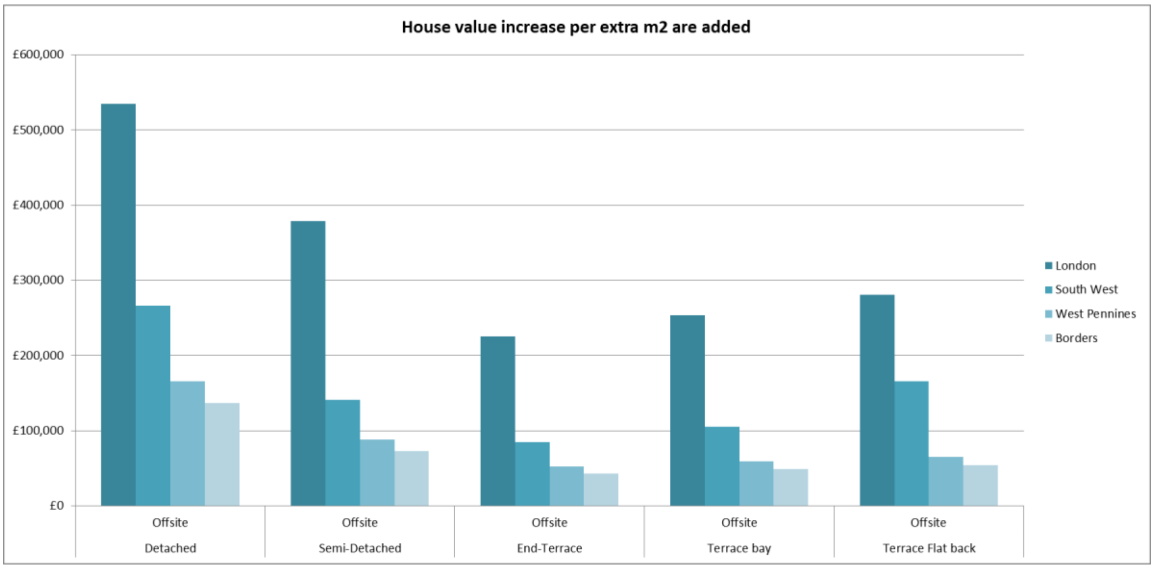


Figure 5.30 *Feasible increase in House Value if the offsite roof adds further living space in the property*

Even so, *Figure 5.30* shows the average amount of House Value increase if the offsite roof provides additional living space. The highest increase is seen in London as the cost of property per m^2 is the highest in UK. In all cases with the exception of the Borders region the additional space could "pay" for the cost of works demonstrating that there could be additional benefits in taking up offsite techniques in retrofit.

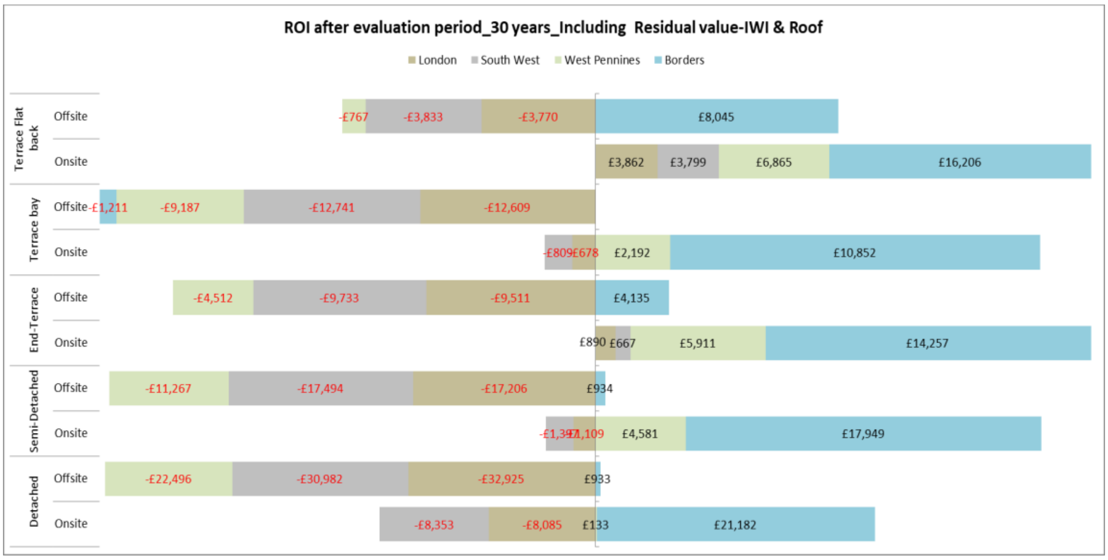


Figure 5.31 *Return On Investment that includes **Residual Value**. Using Internal Wall Insulation and Roof as the comparison element of Onsite versus Offsite measure*

The Residual Value in this case is even lower when it comes to offsite and is only beneficial in the Borders region (*Figure 5.31*) with the exception of Terrace Bay that has a small loss. Similarly to *Figure 5.28* it is observed that when House Value is taken into account the payback seems to be considered of higher payback benefit giving the property location a greater impact.

The onsite scenario when reviewed in terms of percentage proves to be up to 20% more cost efficient than offsite with the Residual Value taken into account and the percentage is lower than the House Value comparison due to the lower payback (Appendix D: *Figure D.3* & *Figure D.4*).

5.4.5.3 Offsite External Wall Insulation ("Retrofit Package")

When compared to the rest of the offside applications modelled, the retrofit package appears to have the highest capital cost and "worst" return on investment on either calculation made; House or Residual Value. Nonetheless, as described in section 3.2.2 and 5.4.4.3 this application guarantees the EnerPHit delivery and it should be taken into account that it includes unforeseen costs on site, something that it can be realistically modelled in this calculation.

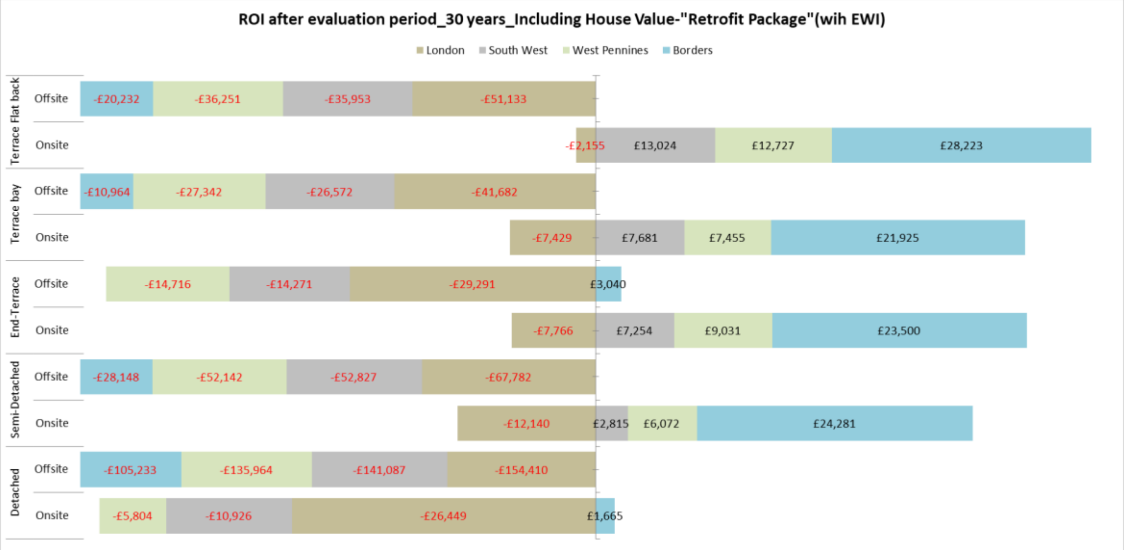


Figure 5.32 *Return On Investment that includes **House Value**. Using "Retrofit Package" as the comparison element of Onsite versus Offsite measure*

From the cost modelling it is observed that the only typology (offsite measures) and location combination that proves "profitable" within the 30 year mark is the End-Terrace in Borders climate as this is the least efficient typology in the "harshest" climate condition modelled (*Figure 5.32*) where it was also reflected on the initial upfront cost analysis in *Figure 5.23*.The loss is mainly dependable to the floor area of the typology but also to the location and efficiency. The Detached for example has the highest loss due to its size and is greater when the typology is located in warmer climate with lower House Value (EPC) such as London. The percentage difference in favour of the onsite scenario spans up to 50% (Appendix D: *Figure D.5*) which the highest difference in comparison.

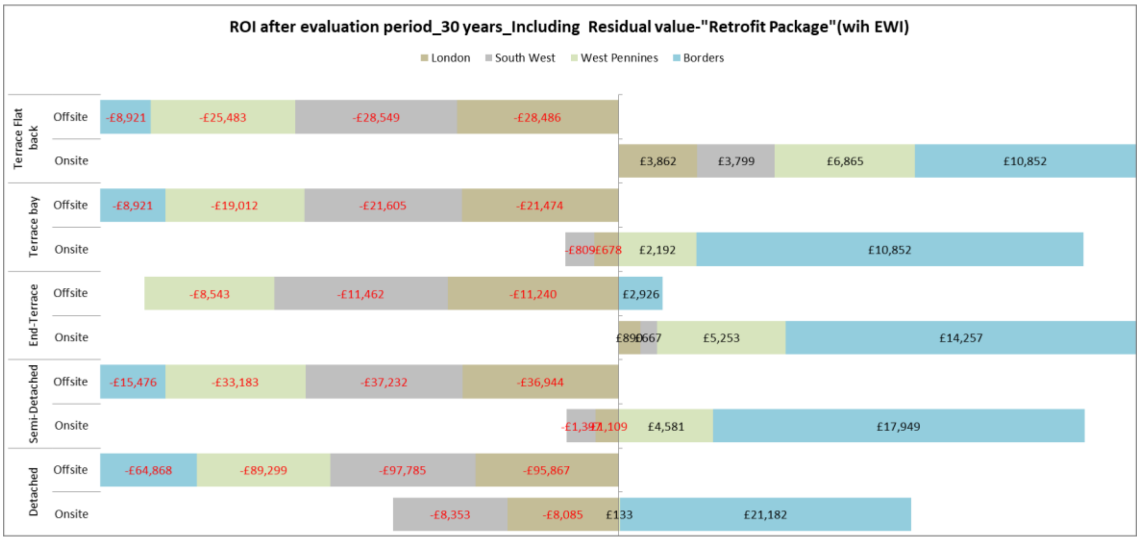


Figure 5.33 *Return On Investment that includes* ***Residual Value****. Using "Retrofit Package" as the comparison element of Onsite versus Offsite measure*

The Residual Value is equally better on the onsite scenario but the offsite "package" is presented with lower loss in comparison to House Value. Similarly only the End-Terrace in Borders has a cost benefit (*Figure 5.33*). This reduction in loss in comparison to the House Value is due to the fact that the cost of the applications are taken in m^2 of floor area rather than per material used. Therefore even though this measure is still more expensive to make a profit, the Residual Value is perceived "higher" than the House Value. This will also be more evident in the next section (5.4.10) where the NVP timeline is reviewed.

The percentage differences are reduced in comparison to the House Value stretching up to an average of 30% in favour of onsite (Appendix D: *Figure D.6*). This offsite retrofit measure has shown to be the most costly on the upfront cost and on the long run but is also the only one that guarantees the delivery of the EnerPHit standard that includes all applications thus questioning whether the additional cost reflects the quality value of the retrofit delivery.

5.4.6 Payback findings summary

The Return On Investment modelling was made to understand the profitability of the deep retrofit measures (EnerPHit) in the long run against an equivalent un-retrofitted dwelling and compare onsite to offsite measures. By applying this to the calculation methods an in-depth overview of the offsite mechanisms to the responded typologies was able to emerge.

By calculating two different methods of increased House and Residual Value the results showed the diversity of offsite applications, typologies and locations. When the Internal Wall Insulation is applied with offsite methods it proves initially the most beneficial upfront cost as it focuses on the element (external wall) with both the highest amount of area and highest heat loss. This reflected also in the long run with the House Value having a greater monetary benefit against the Residual and also providing an initial reflection on the impact of the dwelling's location that stretches beyond its climatic relation to the energy demand. When the offsite roof is also added as an element the upfront cost increases significantly but the feasible additional space could provide an increase in the House Value to offset the entire cost of works thus showing that there is another layer of possibilities in the exploration of offsite mechanisms in retrofit. Finally, the "Retrofit Package" being the most cost intensive in comparison to the other offsite scenarios showed no Return On Investment within the 30 year threshold. Then again the consideration that the retrofit applications are overseen by the same company that specialises in Passive House/EnerPHit construction raises the question of benefits in that span beyond monetary gain but focus more in the quality of retrofit delivery.

5.4.7 NPV per typology introduction

The Net Present Value refers to the value of “cash flows” over the timespan of an investment, both positive and negative. In this modelling the investment refers to the cost required for each retrofit scenario, the “cash flows” are translated into bills, savings and increased property value, while the timespan is the assigned 30 years. When the capital cost is paid back before the 30 years it is considered a “profitable investment” and cash flows of the remaining years are considered the payback/ Return On Investment. To understand the chronological Net Present Value differences amongst the scenarios modelled a series of graphs were generated. This visual representation extends over the typical 30 year financial period mark allowing for an understanding that (and when) the Whole-House retrofit with offsite mechanisms could still be beneficial over the longer term. It also provides a depiction of the payback time in the most efficient scenarios offering an understanding on the impact of heating energy reduction. Additionally, the Building Regulations scenario is also included allowing a clear comparison on the retrofit payback within minimum standards retrofit to EnerPHit (Onsite and Offsite). An example of the NPV is presented in *Figure 5.34* and explanatory illustrations on how they are read in *Figure 5.35*. The complete graph series are listed in Appendix B and the year each scenario is paid back are summarised in *Table 5.4*, *Table 5.5* and *Table 5.6*.

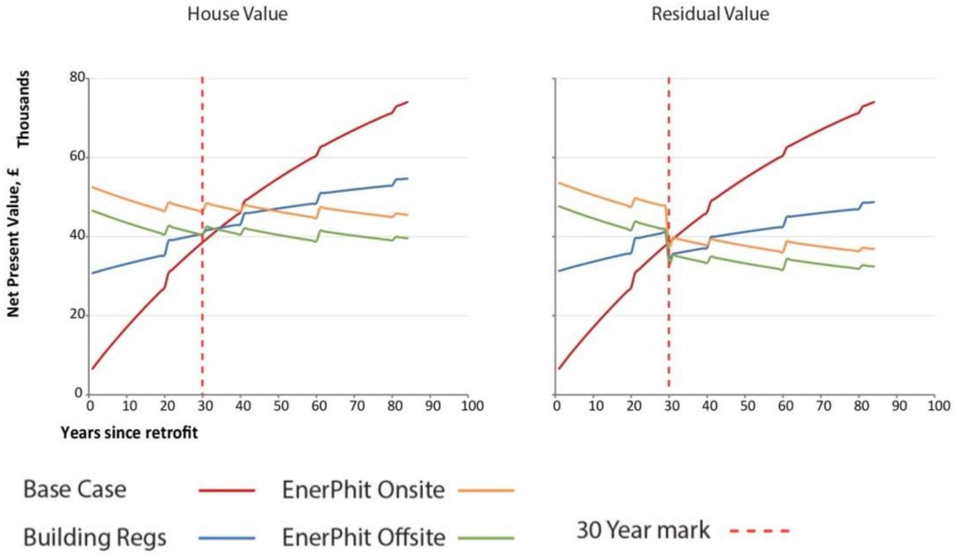
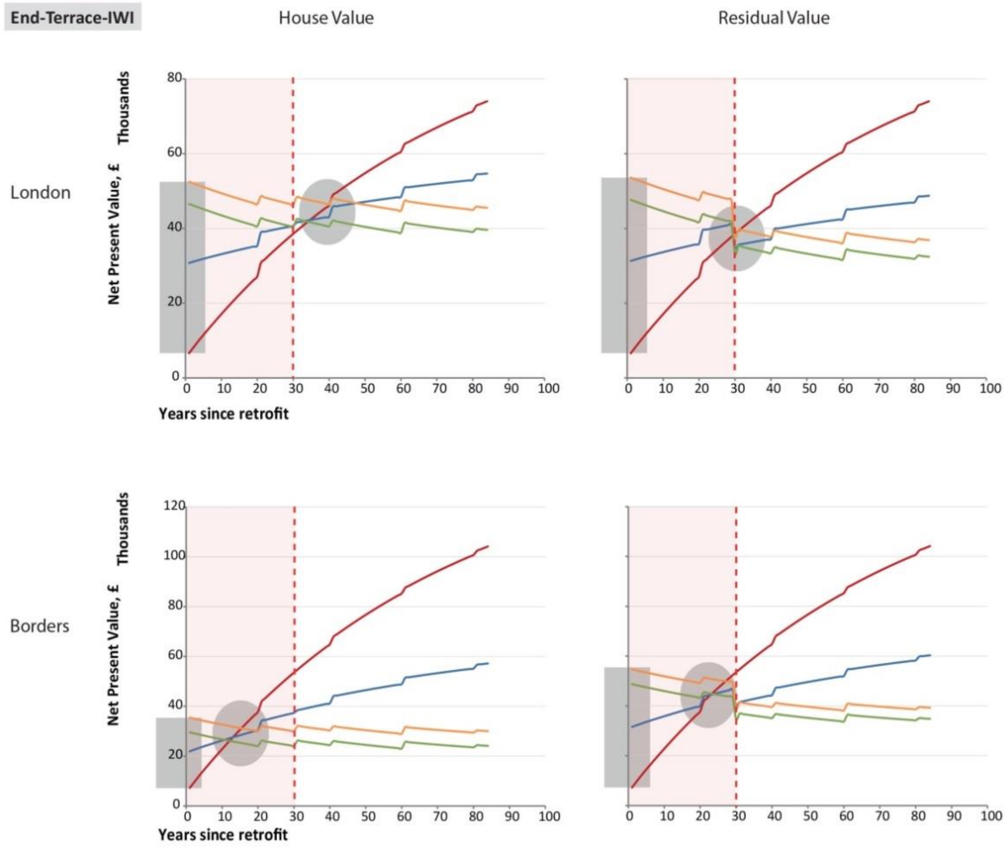


Figure 5.34 *Examples of NVP graphs*



▭ **1**. This area represents the 30 year period that evaluates the financial “payback” for each scenario.

▮ **2.** This part of the figure shows the capital cost for each scenario. As seen from above there are two main differences presented: location and value (House or Residual). Taking into account the House Value (EPC) in London for example has significantly less impact than a dwelling in Borders as demonstrated in *Table 5.2*. Also the House Value “reduction” in the capital cost is applied at year 0 versus the 30 year mark of the Residual.

● **3.** This points to the “intersection” between the scenarios. As seen from point 2 the Base Case (red line) has the lowest capital cost but as time passes the cost of energy bills makes it more cost-intensive (line ascending in the graph). On the other hand the EnerPHit scenario has the exact opposite effect. Therefore as the Base Case is the un-retrofitted dwelling when a scenario of a retrofitted equivalent passes the point of intersection it begins to be more cost-beneficial. When this occurs before the 30 year threshold then the savings from bill reduction for each year becomes a positive return on investment. If it occurs after then it becomes a “loss” as presented in section 5.4.5.

***Figure 5.35** Explanatory illustrations for NPV*
The illustrations used the two locations with the most differences (London-Borders) as examples for a clearer demonstration.

5.4.8 NPV per typology with Internal Wall Insulation

As analysed in the previous sections the Internal Wall Insulation as an offsite element is the most profitable in monetary value in comparison. When the House Value is included the payback period with the exception of the London scenario is always prior to the 30 year mark (*Table 5.4*). Nonetheless, even in London the payback time does not extend significantly and this offsite approach provides an earlier payback of up to 13 years against onsite and over 20 years against Building Regulations. The Borders location has the fastest payback in both house and residual <30years with the best scenario of Terrace Flat that the payback period is only just 8 years (*Table 5.4* & Appendix E: *Figure E.5*).

HOUSE VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat		
	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.
London	47	37	58	42	32	40	42	32	33	42	32	38	33	28	32
South West	39	26	50	28	22	28	22	18	20	22	16	23	18	12	18
West Pennines	35	22	45	27	20	27	22	17	19	23	19	24	17	13	16
Borders	29	18	28	18	15	16	16	12	13	15	11	11	11	8	10
RESIDUAL VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat		
	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.	Onsite	Offsite IWI	Building Regs.
London	40	30	38	32	30	30	30	30	30	32	30	30	30	29	30
South West	39	30	40	32	30	30	30	30	30	32	30	30	30	29	30
West Pennines	33	29	34	30	28	30	30	28	30	31	30	30	30	25	30
Borders	30	25	30	28	22	23	27	22	12	29	24	25	22	20	22

Table 5.4 *Payback time of offsite Internal Wall Insulation comparison*

5.4.9 NPV per typology with Internal Wall Insulation and Roof

When the roof is also added as an offsite element the capital cost is increased and consequently the payback period as presented on *Table 5.5* and in Appendix E*: Figure E.6* to *Figure E.10.*The ≤30 year mark is mainly achieved in Borders with the exception of the Detached typology, while the Terrace Flat achieves a payback <30 years in all locations with the exception of London. The highest and the lowest payback time difference in favour of the onsite construction approach is seen on the Detached typology; with 23 years in London (highest) and 5 years in Borders (lowest) in the House Value calculation. When the Residual Value is taken the differences are smaller but with London having the highest of 16 years in Terrace bay typology and the Borders Detached actually coming even.

.

HOUSE VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat		
	Onsite	Offsite IWI& Roof	Building Regs.	Onsite	Offsite IWI& Roof	Building Regs.	Onsite	Offsite IWI& Roof	Building Regs.	Onsite	Offsite IWI& Roof	Building Regs.	Onsite	Offsite IWI& Roof	Building Regs.
London	47	75	58	42	65	40	42	58	33	42	65	38	33	47	32
South West	39	58	50	28	48	28	22	38	20	22	41	23	18	28	18
West Pennines	35	51	45	27	43	27	22	35	19	23	40	24	17	27	16
Borders	29	34	28	18	29	16	16	23	13	15	25	11	11	18	10
RESIDUAL VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat back		
	Onsite	Offsite IWI& Roof	Building Regs	Onsite	Offsite IWI& Roof	Building Regs	Onsite	Offsite IWI& Roof	Building Regs	Onsite	Offsite IWI& Roof	Building Regs	Onsite	Offsite IWI& Roof	Building Regs
London	40	51	38	32	47	30	30	41	30	32	48	30	30	36	30
South West	39	51	40	32	47	30	30	41	30	32	48	30	30	35	30
West Pennines	33	42	34	30	40	30	30	30	30	31	42	30	30	32	30
Borders	30	30	30	28	30	23	27	30	12	29	33	25	22	29	22

***Table 5.5** Payback time of offsite Internal Wall Insulation & Roof comparison*

5.4.10 NPV per typology Offsite External Wall Insulation (“Retrofit Package”)

Having the highest capital cost amongst the other offsite measures compared, the offsite package, has understandably the longest payback periods in comparison as presented on Table 5.6 and in Appendix E: *Figure E.11* to *Figure E.15*. On the London location for example, only the End Terrace has payback of <70 years in the House Value .Similarly, the End Terrace has the only <30 year mark on both House and Residual calculation. The Residual Value in comparison has shorter payback time spans with differences in favour to onsite construction of 60 years, the highest in Detached London and 3 years the lowest in the End Terrace in Borders. While in the House Value, 65 years the highest and 13 years the lowest respectively.

HOUSE VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat		
	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs
London	47	>100	58	42	>100	40	42	60	33	42	95	38	33	>90	32
South West	39	>100	50	28	79	28	22	43	20	22	60	23	18	78	18
West Pennines	35	>100	45	27	73	27	22	42	19	23	60	24	17	72	16
Borders	29	79	28	18	45	16	16	29	13	15	39	11	11	45	10
RESIDUAL VALUE															
	Detached			Semi-Detached			End-Terrace			Terrace Bay			Terrace Flat back		
	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs	Onsite	Offsite "Retrofit Package"	Building Regs
London	40	>100	38	32	60	30	30	40	30	32	53	30	30	62	30
South West	39	>100	40	32	60	30	30	40	30	32	55	30	30	62	30
West Pennines	33	85	34	30	55	30	30	39	30	31	50	30	30	58	30
Borders	30	58	30	28	38	23	27	30	12	29	38	25	22	41	22

***Table 5.6** Payback time of offsite “Retrofit Package” comparison*

5.4.11 NPV Building Regulations

When the Building Regulations scenario is reviewed in relation to the EnerPHit standard and the equivalent onsite/offsite mechanisms it is observed that: if compared to the EnerPHit standard with onsite construction it has quite similar payback time in most cases even though the capital cost differs significantly. Due to the difference in energy reduction after the time the capital cost has been “paid pack” the EnerPHit scenario starts to generate greater long-term returns versus the Building Regulations. Similar Passive House and EnerPHit economic calculations have previously been made by the Passive House institute (https://passipedia.org), (Thu and Kaufmann, 2016) and there have been a few UK based case study publications (Neroutsou, 2016; Guermanova and Arora, 2015) demonstrating the long term economic benefits.

Nonetheless, there is a need for more UK specific evidence based research demonstrating these long term economic benefits in the retrofit market. Even though the thesis has contributed in the holistic review of specific typologies and locations there is still need of a “wider spread” access to feasible benefits similar to offsite mechanisms. When the EnerPHit standard with the selected offsite mechanisms is compare to the Building Regulations scenario the offsite Internal Wall Insulation reduces the payback time up to years 24 years(*Table 5.4* & Appendix E: *Figure E.5*) making a substantial positive difference while the additional offsite roof has almost the opposite effect (*Table 5.5* & Appendix E:*Figure E.6 to Figure E.10)*. Finally, the Retrofit Package scenario has the highest difference against Building Regulations. Only in the typologies of End Terrace and Terrace Bay (*Table 5.6* & Appendix E: *Figure E.11* to *Figure E.15*)in the Residual Value calculation the Retrofit Package payback becomes profitable over the Building Regulation and this after 60 years.

5.4.12 Financial significances and findings

The rationale behind "payback" is that it is highly interconnected with heating energy reduction in retrofit as the main outcomes are translated in bill savings. The scenarios modelled though showed that the payback differs considerably within; a. each offsite measure, b. each typology and c. climate and location. Below is the summary of how these determinants influence these outcomes and how they contribute to the existing literature.

5.4.13 Offsite measures outcomes

The offsite measures modelled presented different outcomes on their feasible benefits. The offsite Internal Wall Insulation (WHISCERS) proved the most economical application with subsequent beneficial outcomes in the long run (Return On Investment). The application benefits also comprise of faster installation of the product and its price includes the relocation and refit of the existing services. The additional offsite element of the roof increases the cost of the retrofit making it profitable in terms of the energy reduction payback only in a few typologies and locations. The major benefit this application holds stands on the fact of feasible additional space it could provide in significantly lower delivering time as it is constructed offsite and delivered completed on site. The offsite package (Beattie TCozy) proved the most costly and only has a cost return benefit in one typology. The key benefit of this application stands on the holistic services it provides under the same company thus assuring the works are delivered by the same source that guarantees delivery and consequently reduced snagging and defects. Additionally, as previous research from Tim Martel (RealCosting creator) has shown and has been included in this thesis' calculations (explained in Section 5.4.5) where people would pay for the comfort of increased internal temperatures the same could correspond for fast delivery and guarantee of performance as also observed in the survey results (*Figure 6.47*) where "shorter building times" and the "commissioning and guarantee” are recognised by the participants as incentives to choose offsite in a retrofit projects. Previous research has shown that dwelling renovation could be linked with influencing residents on adapting low-energy installation to be done simultaneously (EST, 2011; Killip, 2011; Karvonen, 2013; Pettifor, Wilson and Chryssochoidis, 2015), similarly offsite retrofit measures can offer additional benefits to energy reduction such as the increase of living space (Offsite Roof). Finally, “green mortgage” discounts depend on the delivery of energy standard certificates with the highest discounts being in regards to EnerPHit and the AECB’s “similar” standard (GOLD) process of 1.25%[48] showing that there are further benefits and possibilities when guarantee of delivery is part of the “equation”.

5.4.14 Typology significances

The technical differences between the typologies and relative heat loss/heat demand were detailed in the previous section and it was understood that there is a direct correlation to the amount of energy along with bills saved with each retrofit application. The cost of offsite retrofit measures depending on the morphology of each typology verifies that a common retrofit price “tag” cannot be feasible with the current market offsite mechanisms and techniques. For example the Internal Wall Insulation (WHISCERS) had higher cost reductions in typologies with greater amount of external wall, the Offsite Roof presented higher amount of capital cost in typologies with greater roof area and the Retrofit Package in typologies with greater floor area.

5.4.15 Location significances

The location of the property plays a major role as in the case of a dwelling retrofitted in Borders for example has a greater value in terms of being more energy efficient in terms of bills reduction and increase of property value due to the “sustainable” upgrade while in

---

[48] Ecology Building Society: www.ecology.co.uk/mortgages/c-change-discounts/

London as property is in so much high demand the retrofit “investment” becomes profitable when additional living space is added and in most cases it surpasses the capital cost of the entire retrofit. This has an “instant” monetary payback as payback through bills is sometimes not as attractive due to the amount of time period required (Britnell and Dixon, 2011; Karvonen, 2013; Hope and Booth, 2014). This shows that there can be a great market incentive for offsite retrofit as it also corresponds with faster delivery time. In conclusion, there is a wider spectrum of “profitable” possibilities when the location of the retrofit is considered, including offsite techniques and there is a correlation in selection based upon the site’s climatic conditions and property value. Considering all these factors the thesis financial model approach has contributed novel understanding about the complexities surrounding the application of offsite measures when combined in UK housing retrofit. Comprehending these complexities offers an opportunity to consider wider approaches, processes and techniques that could be valuable in the evolution of the Whole-House retrofit in the exiting UK housing spectrum.

6 Results of PhD research- Social related outcomes

6.1 Introduction

In this section the results of the survey are analysed with the aim to explore perception from construction industry representatives on offsite mechanisms in delivering house retrofit in higher energy standards. Previous research has been done on the incentives and the influence of the construction industry in low energy construction as described in section 4.8.2. Relevant to this research is what Parag and Janda, (2014) explain by way of "Middle-out actors", i.e. industry representatives that : *"effect change upstream to top actors (e.g., policy makers), downstream to bottom actors (e.g., homeowners and clients), and sideways to other middle actors (e.g., other builders and participants in the building supply chain)"* (page 913). With the same principle in focusing on ""Middle-out actors", the survey investigated what is until now unexplored perceptions, awareness, knowledge, and attitudes towards the offsite construction on low energy retrofit and how these could consequently influence its future market.

The technical and financial opportunities or limitations have been examined in this thesis through evidence base modelling but without consideration of attitudes and perceptions of the building industry, the analysis would not have been complete. Previous research in UK housing retrofit as detailed in the literature review (2.5.7) explored incentives and barriers of both industry and users in the need to upgrade the existing stock. On the other hand, the UK offsite construction has demonstrated similar research dynamics (3.2.4) but focused on the need to deliver new housing while retrofit with offsite measures perceptions is limited to few pilot cases (3.2.6).

Thus, the original contribution of the survey uptake and analysis stands on the research theme itself, the focused investigation of offsite techniques, stretching further than overall low energy retrofit. This is achieved through the model analysis but with the vital incorporation of the "human perception element" thus connecting technical and non-technical variables to achieve a holistic understanding of feasible wider applicability.

6.2 Survey results analysis

The survey as described in the methods chapter section 4.8.2 was constructed within three principal themes: *Responders' background, Knowledge and perceptions on energy standards and Knowledge and perceptions on offsite mechanisms.* The *Responders' background* focuses mainly on experience with low energy design and is correlated with each survey answer to understand whether the answers are influenced by existing skills and knowledge. The method of how these where categorized is presented in section 6.2.1. The level of *Knowledge and perceptions on energy standards* focuses on the responders' knowledge, experience and confidence on existing and voluntary energy standards. These answer results are presented and explored in sections 6.2.2 and 6.2.3. The *Knowledge and perceptions on offsite mechanisms* is represented in the rest of the survey questions aiming to provide an insight on the participants' understanding and opinions on offsite approaches in retrofit along with feasible the incentives and barriers for its applicability. This is presented and explored in sections 6.2.4 to 6.2.7.

Finally, in section 6.3 the analysis on open text responses provides a more in depth understanding on the participants' site experiences and opinions in regards to retrofit and offsite.

6.2.1 Participants analysis

Figure 6.1 below illustrates the range of professions of the 64 participants who completed the online survey. Even though the initial aim was to reach the wider construction industry it has consciously focused mainly on the "middle-actors". The construction industry representatives of this term have been identified to have a great influence in low energy design (Parag and Janda, 2014; Janda *et al.*, 2014). This is due to their hands-on problem solving as they are the intermediate actors between regulation and clients/consumers. Due to the subject of the research, the survey extended to participants with specific background in energy design or consultancy (i.e. Passive House) along with backgrounds in research and academia. The survey structure question for the professional background of the participants allowed selecting more than one profession if applied. The separation to primary, secondary and tertiary aims to show the range of skills within the participants and does not exclusively depict what they consider as their principal occupation. With a similar aim the follow up question was in regards to the level of professional experience in the industry (*Figure 6.4*).

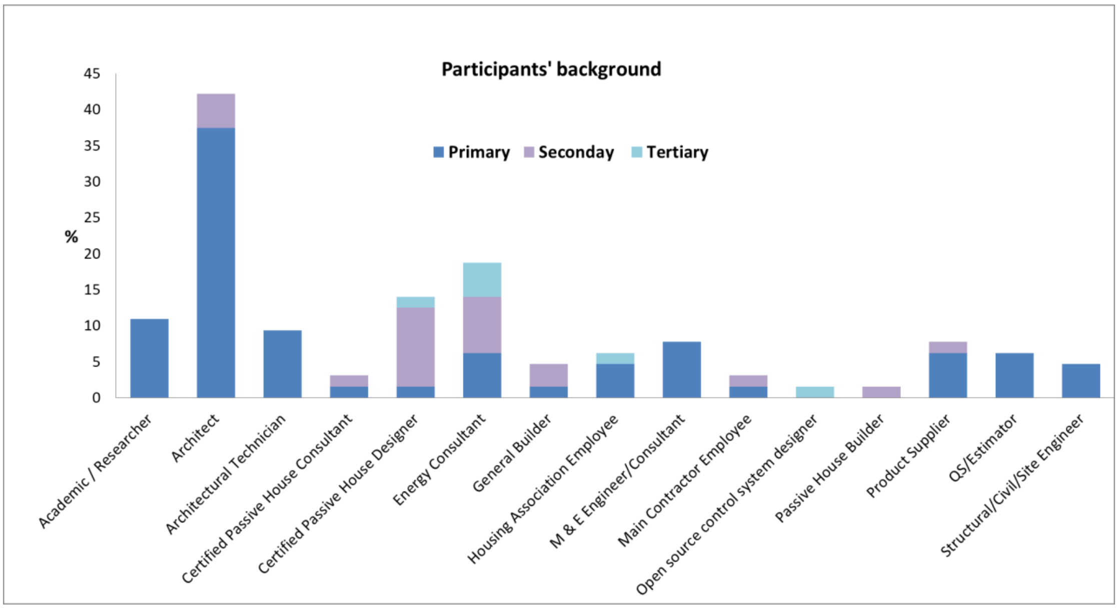


Figure 6.1 *Participants' professional background and percentage within the survey*

The highest participation was within the architectural group and even though there is a range of energy specialists, the highest number of participants did not have an "energy background" (*Figure 6.2* and *Figure 6.3*). The higher number of architects is in one hand realistically driven from the researcher's professional contacts but on the other hand could have an interesting input to this section of the research. The influence of the architects as part of the "middle-actor" group could be reviewed as a "sub-category" by itself as an intermediate within the other groups. This is also explored by research (Fischer and Guy, 2009) into the architects' influence and challenging role in low energy design as intermediaries between the other groups (engineers, energy consultants etc.). With this in mind the larger representation of architects provides a wider reflection on the industry's attitudes and pragmatic use offsite in low energy retrofit.

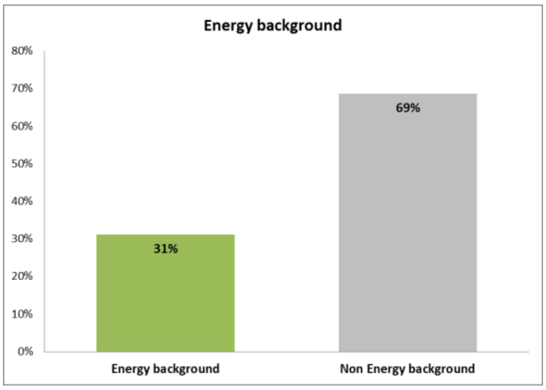


***Figure 6.2** Participants' background relative to involvement with energy focused projects or education*

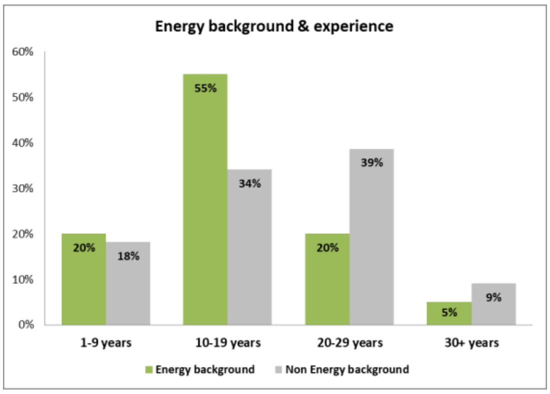


***Figure 6.3** Participants' energy background and years of experience in their field*

The second step was to group the participants within two groups, those with "energy background" and those with "non-energy" background (*Figure 6.2*) with the purpose to analyse the collected data in greater detail in terms of recognising whether their knowledge of energy reduction mechanisms has an impact on their responses.

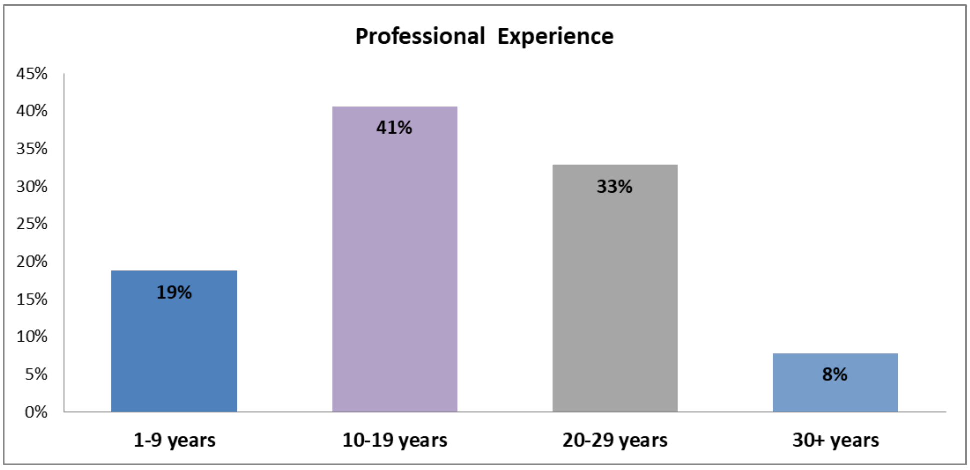


***Figure 6.4** Participants' years of experience within their field*

The experience ranges with the majority between 10-19 years and 20-29 (*Figure 6.4*). The energy background participants are within the majority of the lower years of experience as energy certification and consultancy is relatively new (*Figure 6.3*).

6.2.2 Level of understanding of standards

Examining the participants' understanding of existing standards a series of questions using a Likert scale were posed. The scale ranged from 1= "Minimal or no understanding" to 5="Significant understanding". The first two looked at the regulated standards related to energy conservation by the Building Regulations on new and existing buildings followed by voluntary deep retrofit and Passive House/EnerPHit.

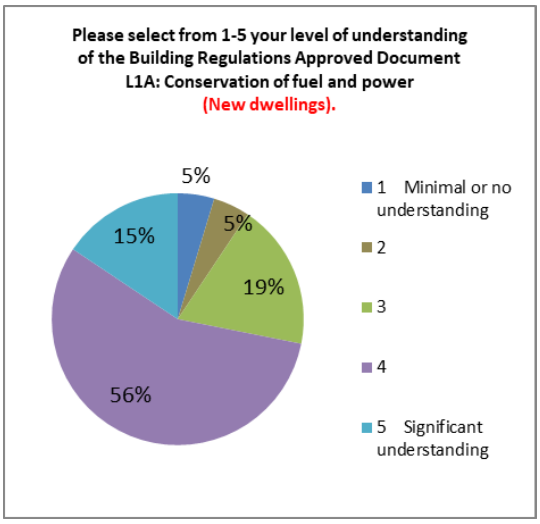


Figure 6.5** Participants' level of energy standards understanding-Building Regulations **Part L1A

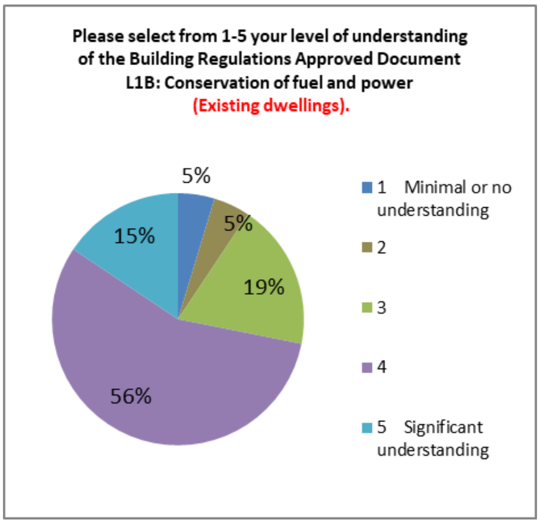


Figure 6.6** Participants' level of energy standards understanding-Building Regulations **Part L1B

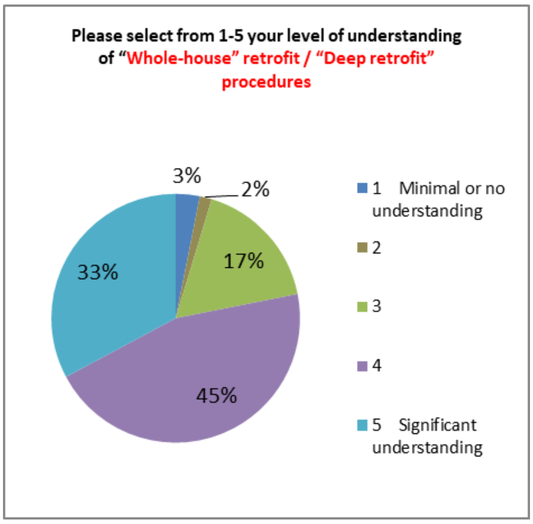


***Figure 6.7** Participants' level of energy standards understanding- "Whole-House" retrofit / "Deep retrofit"*

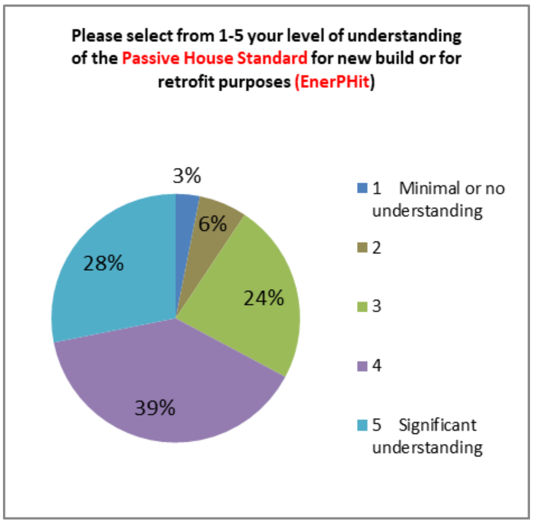


***Figure 6.8** Participants' level of energy standards understanding- Passive House and EnerPHit*

The understanding level distribution of the Building Regulations was an exact match on both new and existing Buildings with the majority selecting a ranking of 3 to 4 leaning towards significant understanding (*Figure 6.5* and *Figure 6.6*). This is understandable as all industry representatives will have to take into account the Building Regulations in a project. In non-regulated standards the leaning towards significant understanding held a greater percentage (*Figure 6.7* and *Figure 6.8*) which led to examining in more detail the selections within the categorised groups of "Energy and Non-Energy Background". The distribution once again between Building Regulations (new/existing) was identical (*Figure 6.9* and *Figure 6.10*) within the two groups and the ones with the Energy Background on all occasions have the most confidence in significantly understanding regulated and unregulated standards in energy reduction both in new and existing buildings(*Figure 6.11* and *Figure 6.12*).

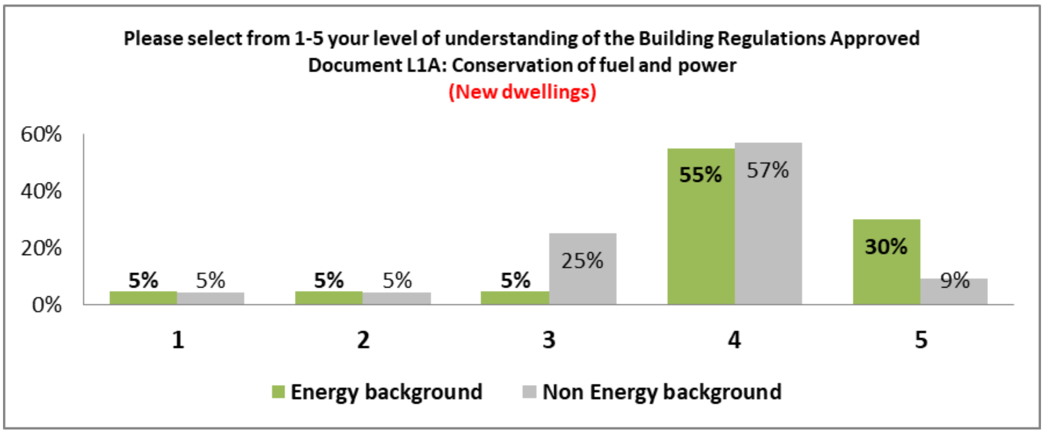


Figure 6.9 *Participants' level of energy standards understanding-Building Regulations* ***Part L1A*** *within the predetermined groups*

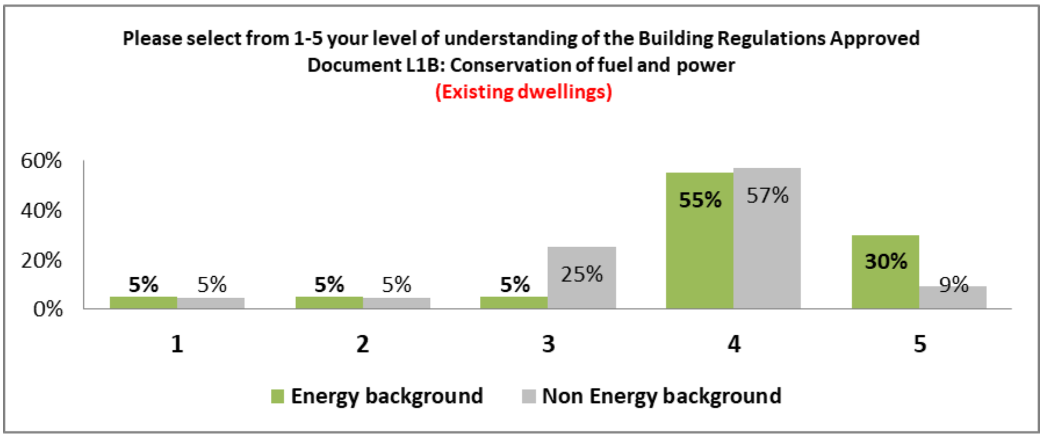


Figure 6.10 *Participants' level of energy standards understanding-Building Regulations* ***Part L1B*** *within the predetermined groups*

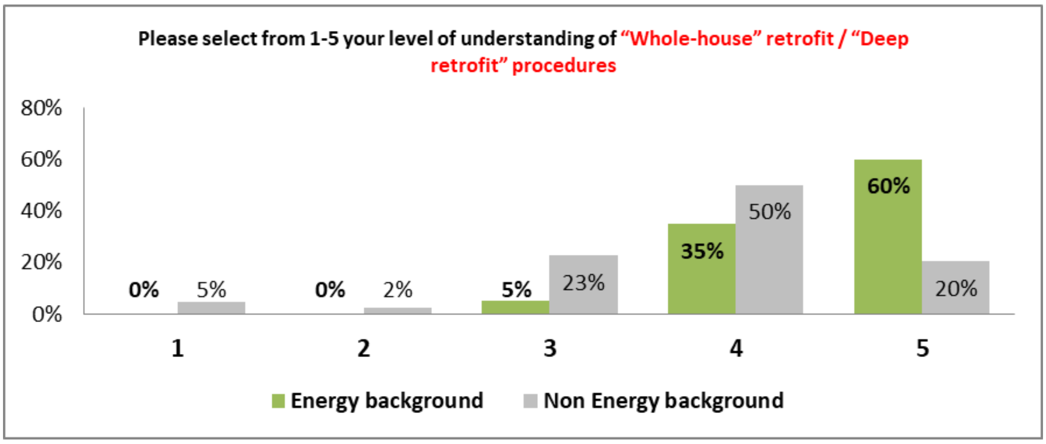


Figure 6.11 *Participants' level of energy standards understanding- "Whole-House" retrofit / "Deep retrofit" within the predetermined groups*

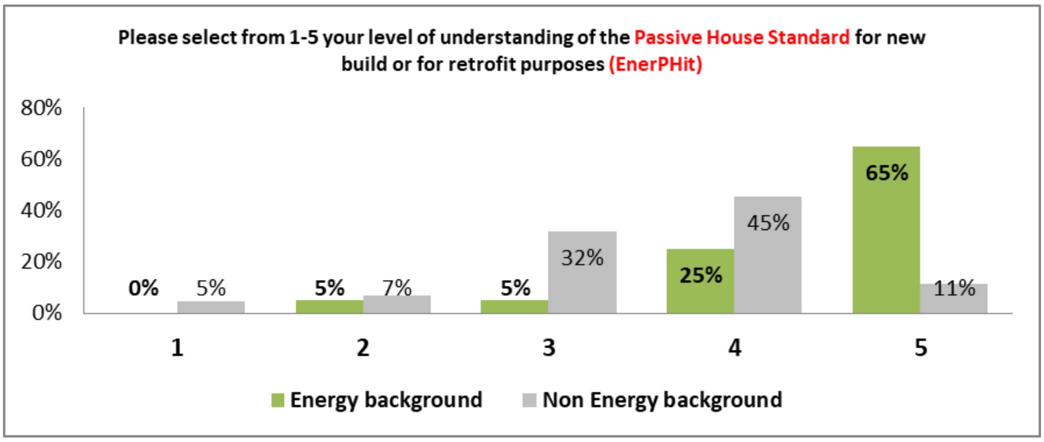


Figure 6.12 *Participants' level of energy standards understanding- Passive House and EnerPHit within the predetermined groups*

Overall the participants showed that they are aware of both mandatory and voluntary energy standards suggesting that the industry is possibly becoming more aware to more than government policies. Plus there has been progress in terms of creating training programmes to produce Retrofit Coordinators for example from the Retrofit Academy (www.retrofitacademy.org/) aimed at a wide variety of industry actors. "Understanding" the standard though does not mean that that there also is a practical knowledge which is something that was investigated in the follow up questions. Comparing the level of knowledge proclaimed by the participants in this thesis and what has been investigated in previous studies results in some interesting findings. One of the biggest barriers identified in low energy retrofit that has been remarked from previous studies is" lack of knowledge and skills" (Heffernan *et al.*, 2015; NEF and EEPB, 2014b; Stieß and Dunkelberg, 2013; Topouzi, Killip and Owen, 2017) along with demand (or lack of) originated either from the consumer or legislation (J. Fawcett, 2014). When those are reviewed in relation to this thesis' results there a few assumptions to be made in conjunction to their novel contribution. Seeing that the majority of the participants proclaimed to have a high level of understanding of legislation and non-mandatory energy standards it could be "translated" in two ways: a. that there could be disconnection on "personal liability" i.e. the participant could have the knowledge required but the surrounding actors on the projects do not and b.it could be interpreted that the "knowledge gap" is actually closing as more construction professionals become more energy conscious.

6.2.3 Past experience with Passive House

In inquiring whether the participants had any past involvement with Passive House or EnerPHit the aim was to explore further the participants' opinions on the standard and whether they had actually been involved in an actual project or not. As seen from *Figure 6.13* and *Figure 6.14* the overall results showed that almost half of the participants have been involved in Passive House or EnerPHit projects with the majority engaged on new build Passive House; this is understandable, as the standard is older than EnerPHit. When the results are reviewed within the assigned groups the highest percentage of participants with an energy background have had involvement with Passive House or EnerPHit projects but there is also a significant amount of 45-30% of participants with non-energy background of that have been associated with them (*Figure 6.15* and *Figure 6.16*). This raises the question whether Passive House /EnerPHit is becoming more of a common practice and industry-defined standard.

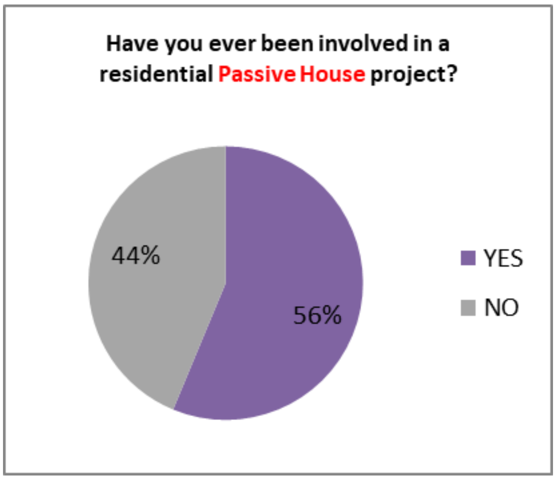


***Figure 6.13** Participants' previous involvement with a Passive House project*

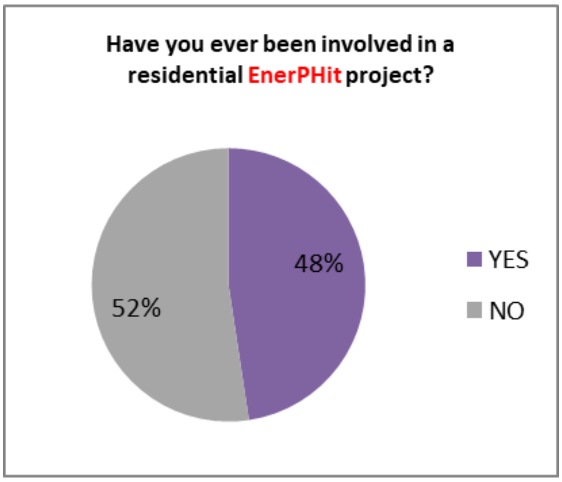


***Figure 6.14** Participants' previous involvement with an EnerPHit project*

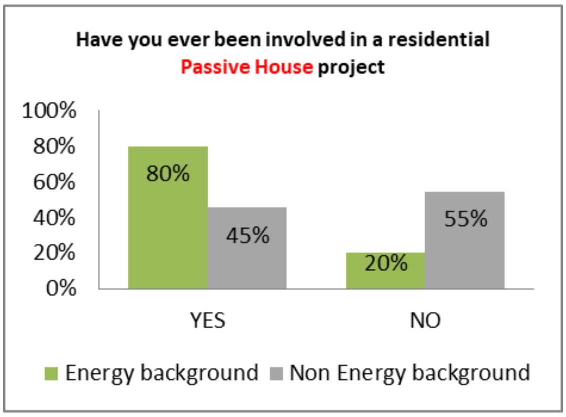


***Figure 6.15** Participants' previous involvement with a Passive House project within the predetermined groups*

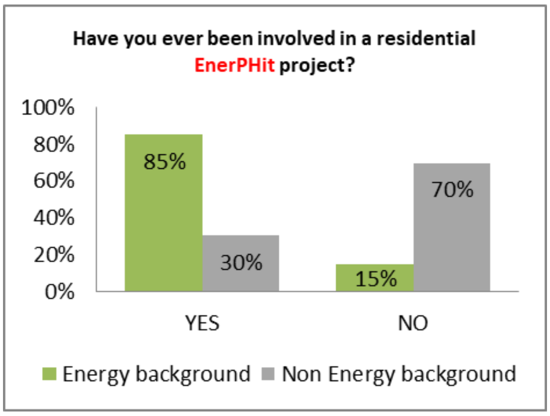


***Figure 6.16** Participants' previous involvement with an EnerPHit project within the predetermined groups*

This could coincide with the subsequent question on whether participants believed that a Passive House/EnerPHit project could guarantee the quality of construction (*Figure 6.17* and *Figure 6.18*). The majority within both groups believe that it does, showing confidence in the standard. Contrary to confidence on the standard actual application in UK might be questionable as when the participants were asked whether there is sufficient knowledge and experience across the UK's construction industry to deliver the EnerPHit standard the opinions were diverse (*Figure 6.19* and *Figure 6.20*) .Within the responders with an energy background a significant percentage >40% disagreed suggesting that, even though the standard might have assurance, the industry in UK falls short in delivery.

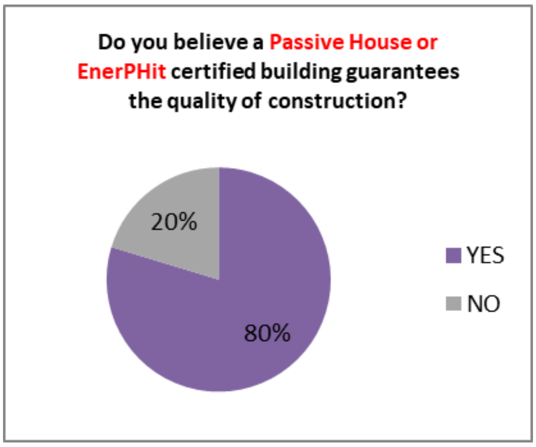


Figure 6.17 *Participants' opinion on the feasible quality guarantee of a Passive House or EnerPHit project*

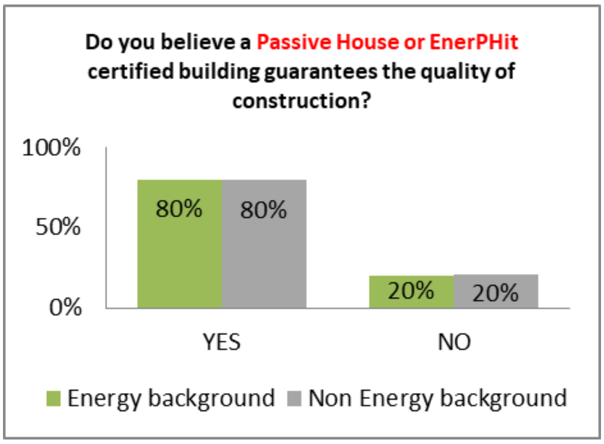


Figure 6.18 *Participants' opinion on the feasible quality guarantee of a Passive House or EnerPHit project within the predetermined groups*

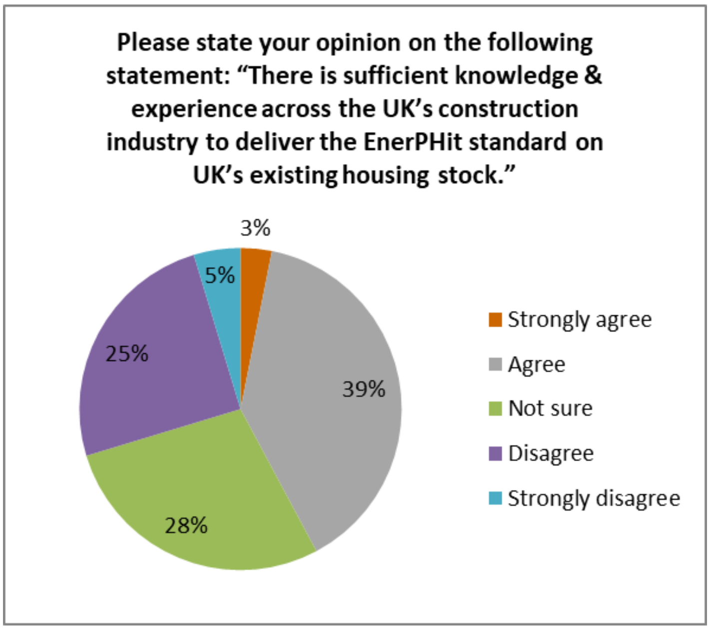


Figure 6.19 *Participants' opinion on the current UK's construction industry ability to deliver the EnerPHit standard*

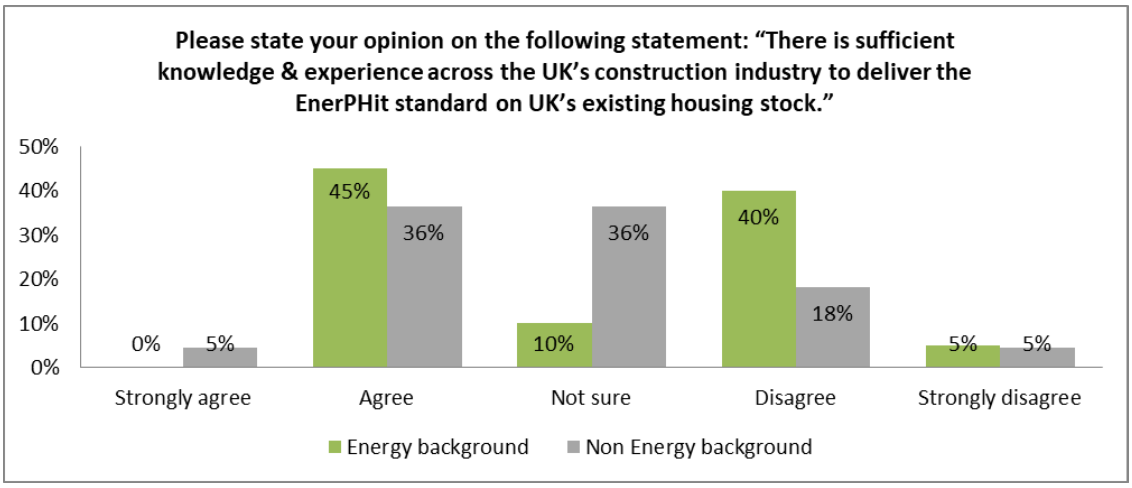


Figure 6.20 *Participants' opinion on the current UK's construction industry ability to deliver the EnerPHit standard within the predetermined groups*

There are more than 150 Passive House certified projects, >800Units in UK and more than 20 EnerPHit (www.passivhaustrust.org.uk) with growing examples of UK social housing adopting the standard (Exeter, Norwich, Manchester). Due to the end of Zero Carbon Homes, Passive House has been viewed as an alternative standard to adopt (Pitts, 2017), it is becoming more “popular” so it is understandable that more industry actors have been involved in a project and consider that certification guarantees the quality of construction (*Figure 6.17*). Lack of skills is a reoccurring barrier though in retrofit that has been acknowledged (NEF, 2014; Bonfield, 2016) and it is evident in the survey participants as a high percentage declared that they do not believe there is enough expertise in the UK construction industry to deliver EnerPHit (*Figure 6.19*). It has to be acknowledged though that the offsite retrofit suppliers have been aiming to respond to this industry shortfall by having control of their quality of retrofit delivery (Beattie Passive and Enegiesprong).

6.2.4 Level of offsite knowledge and confidence

Similarly to the energy standards questions the participants were asked to rate their knowledge of and confidence in offsite construction; initially as a general approach and then following with a question specifically to housing retrofit. The scale ranged from 1= “Minimal or no understanding/confidence” to 5=” Significant understanding/confidence”. The results showed that there was significant knowledge and confidence in offsite construction in general along with its use to deliver housing but when it came to offsite combined with housing retrofit the confidence in its application has dropped (*Figure 6.21* to *Figure 6.26*). When looked within the groups the non-energy background has a greater knowledge and confidence in offsite construction than the energy one but dramatically decreases when applied to retrofit. While the energy background group appear to have the same outlook on the offsite/retrofit approach in terms of confidence there are no observed “*extremes”* (*Figure 6.22*, *Figure 6.24* & *Figure 6.26*). The overall attitudes reflect that the industry is more accepting of the offsite construction concept but uncertain when it applies to retrofit.

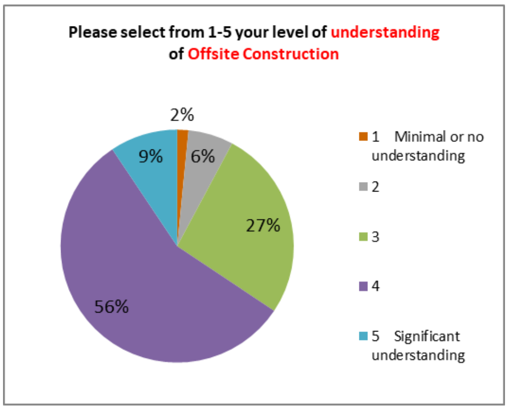


Figure 6.21 *Participants' understanding of offsite construction*

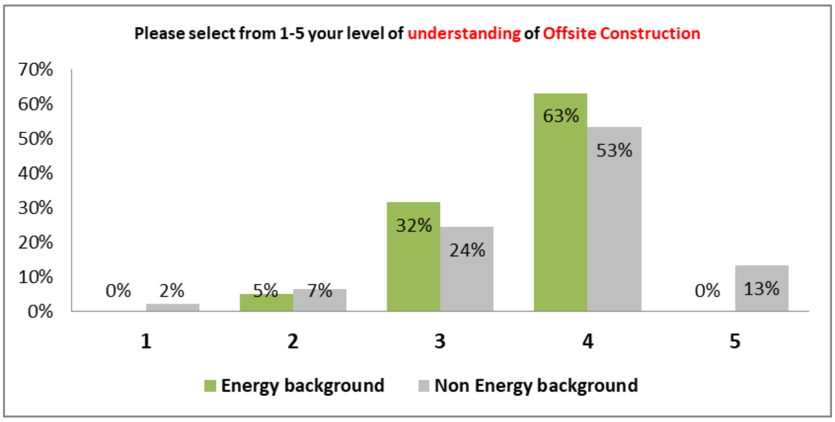


Figure 6.22 *Participants' understanding of offsite construction within the predetermined groups*

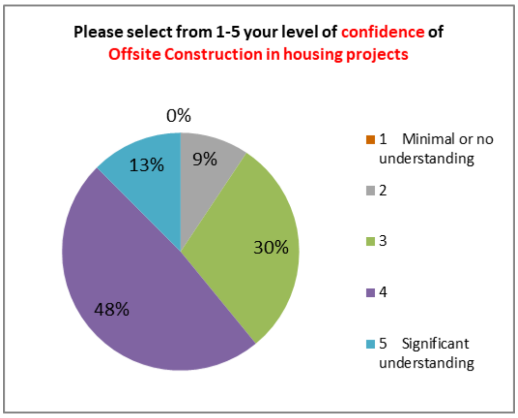


Figure 6.23 *Participants' confidence of offsite construction in housing*

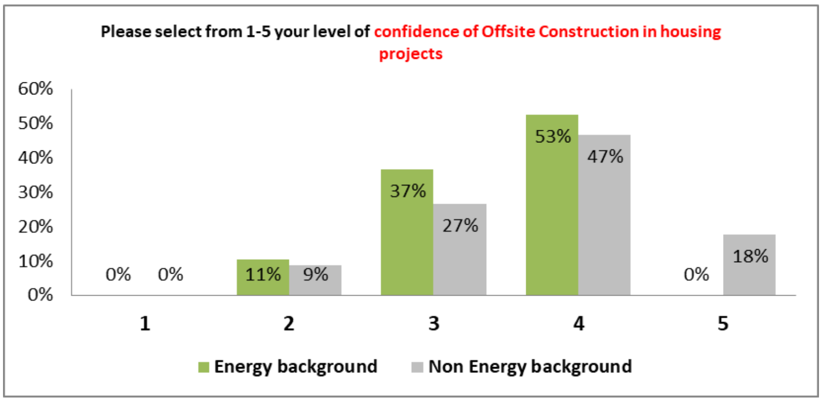


Figure 6.24 *Participants' confidence of offsite construction in housing within the predetermined groups*

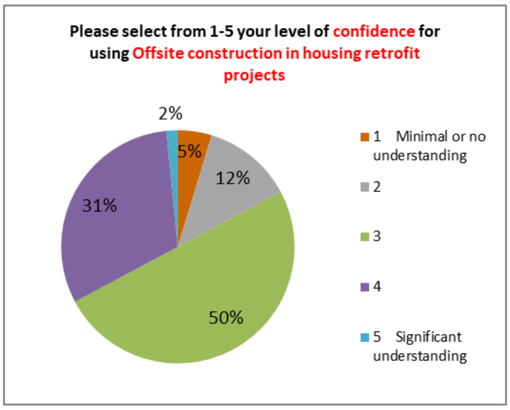


Figure 6.25 *Participants' confidence of offsite construction in housing retrofit*

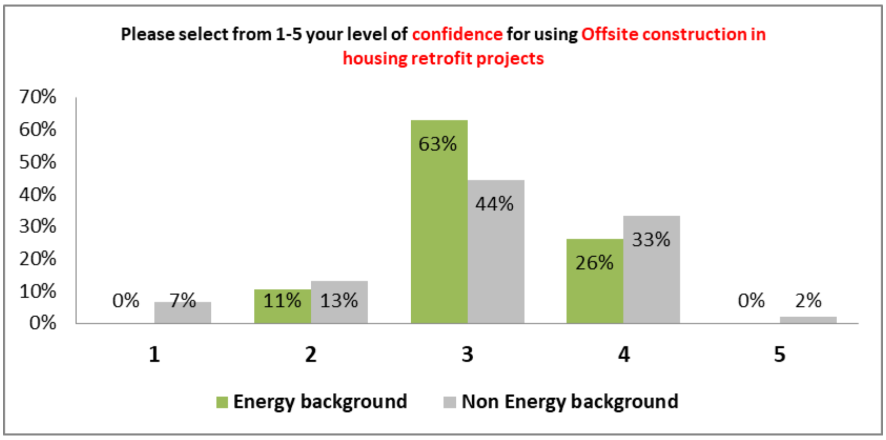


Figure 6.26 Participants' confidence of offsite construction in housing retrofit within the predetermined groups

Offsite construction in new build has a current momentum as with the need of new homes in the UK has been viewed as the eventual solution for delivery[49] (Farmer, 2016). The application to retrofit though it seems is not approached with the same confidence (*Figure 6.25* and *Figure 6.26*). This could be due to the fact that the offsite applications in

---

[49] London mayor urged to adopt offsite housing to meet city's housing needs. (2017, September). TTJ - The Timber Industry Magazine, 453(6809), 8. Retrieved from: http://link.galegroup.com/apps/doc/A513760623/ITOF?u=nene_ukandsid=ITOFandxid=0ccd9d40

retrofit measures are relatively new and it relates to a follow up question in assumption that there is not enough “accessible” data on the advantages of these applications (*Figure 6.53*). The Bonfield review (Bonfield, 2016) has recognised this obstacle to retrofit in general and there has been progress as a BSI Retrofit Standards Task Group has been formed to address this with amongst others a focus on accessibility to materials, standards, feedback and competence (www.bsigroup.com). This could prove a practical opportunity for retrofit suppliers with offsite measures to have greater market exposure and be evaluated.

6.2.5 Cost estimations

In a series of questions the participants were asked to estimate the cost of “Whole-House/Deep” retrofit within the pre assigned typologies and then to estimate the feasible reduction through offsite mechanisms. The initial cost estimation was presented with cost per m^2 (£/m^2) and the feasible reduction was presented in percentages (%). The options for the initial costs ranged from “I have no opinion/view on this matter “, <£200, £200 - £400, £400 -£600, £600- £800, > £800 and the feasible cost reductions as “I have no opinion/view on this matter”, “No reduction”, <5%, 5-10%, 10-20%, >20%. By transposing the data from the cost modelling the answers were categorized on whether the participant overestimated, were within the modelled values or underestimated along with allowing the review of the answers in more detail within the assigned groups. The onsite retrofit construction modelling provided a “definite” cost mark within the assigned variables (typology/location) but when different offsite techniques and measures are applied the models showed that it is highly diverse. The overall estimated cost for onsite deep retrofit was predominantly overestimated within the “more” energy efficient typologies; Detached, Semi-Detached and Flat-Terrace (*Figure 6.27*, *Figure 6.31*, *Figure 6.43*). Surprisingly, the group with the energy background had the highest percentage of overestimating these typologies but also the ones with the highest percentage that where within the modelled values in the “less” energy efficient typologies; End-Terrace and

Terrace-Bay (*Figure 6.37* and *Figure 6.41*). This could be a reflection on the unpredictable cost that is met on live projects that the model cannot account for but the “energy group” responders have met in their experience.

The results on overall cost reduction estimations, through offsite mechanisms, offer a more intricate observation when paralleled with the modeled results. The percentage options were transposed to the graphs as <5%= low, 5-10%=moderate, 10-20% high and >20%=very high. The initial observation is that the predominant attitude leans towards a “moderate” reduction of around 40 to 45% apart from Terrace Bay (*Figure 6.40*) where the majority of responders considered a “low” cost reduction.

A high percentage was also observed in participants with “no opinion” in regards to the feasible cost reduction offsite mechanisms of around 25% raising the question on a. whether there is a lack of wide available information on offsite practices throughout the industry in relation to retrofit and b. lack of offsite practices’ “acceptance”.

When the survey results are cross-tabulated with the cost modellings, the findings have to evidently be analyzed within the two aspects of onsite and offsite construction. The onsite EnerPHit cost as seen from the thesis section 5.4.3, varied within different typologies and regions but the averages ranged around £400 to £600 per m^2 (*Figure 5.23*). The majority of the responders overestimated three out of five typologies with almost equal percentages between “energy” and “non-energy group”. This observation could be interpreted in two “conflicting” ways, firstly as previously mentioned the cost model could have not accounted for possible unforeseen cost within these typologies and secondly the possible lack of understanding of the typology differentials within the industry.

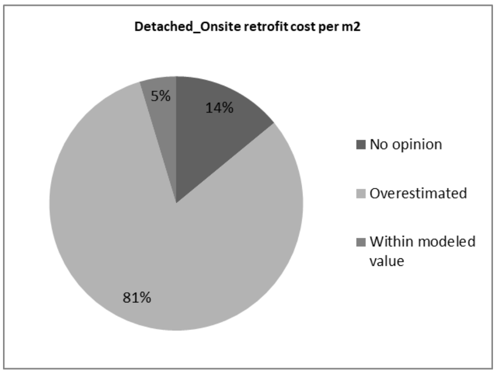


Figure 6.27 *Participants' cost estimation of Whole-House Retrofit/EnerPHit-Detached*

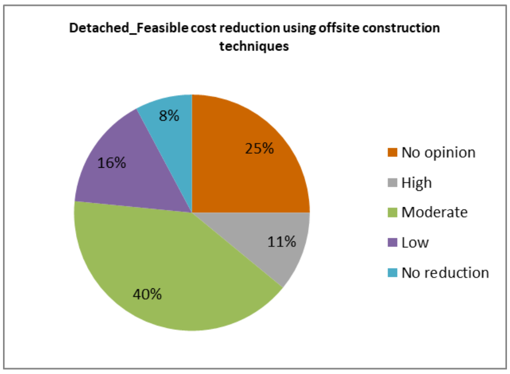


Figure 6.28 *Participants' feasible cost reduction estimation with offsite mechanisms-Detached*

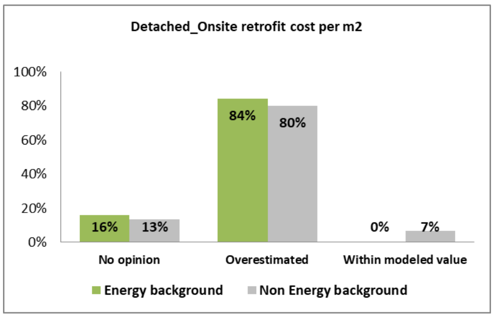


Figure 6.29 *Participants' cost estimation of Whole-House Retrofit/EnerPHit within the predetermined groups -Detached*

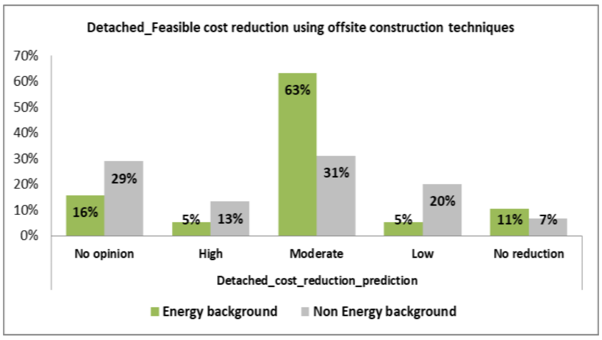


Figure 6.30 *Participants' feasible cost reduction estimation within the predetermined groups -Detached*

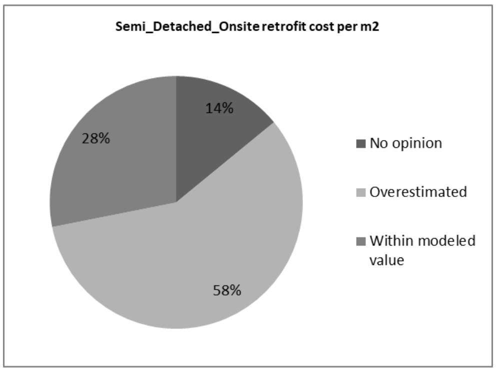


Figure 6.31 *Participants' cost estimation of Whole-House Retrofit/EnerPHit-Semi Detached*

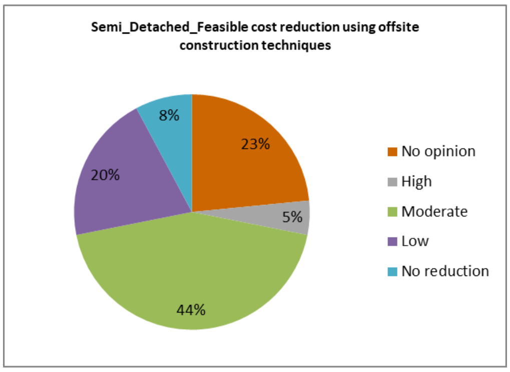


Figure 6.32 *Participants' feasible cost reduction estimation with offsite mechanisms-Semi Detached*

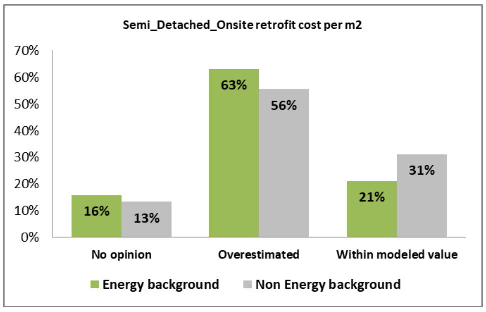


Figure 6.33 *Participants' cost estimation of Whole-House Retrofit/EnerPHit within the predetermined groups –Semi Detached*

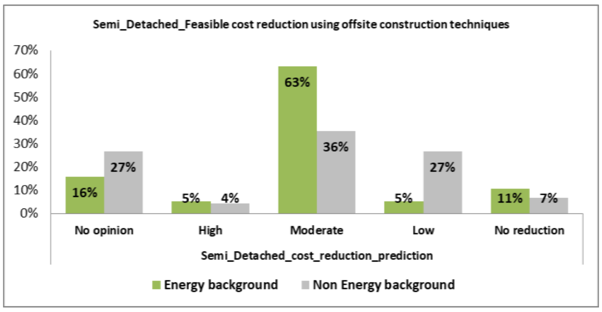


Figure 6.34 *Participants' feasible cost reduction estimation within the predetermined groups– Semi Detached*

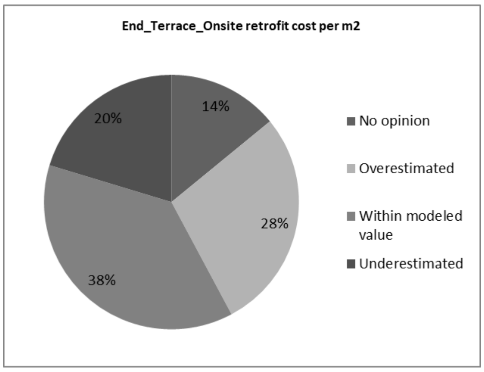


Figure 6.35 *Participants' cost estimation of Whole-House Retrofit/EnerPHit-End Terrace*

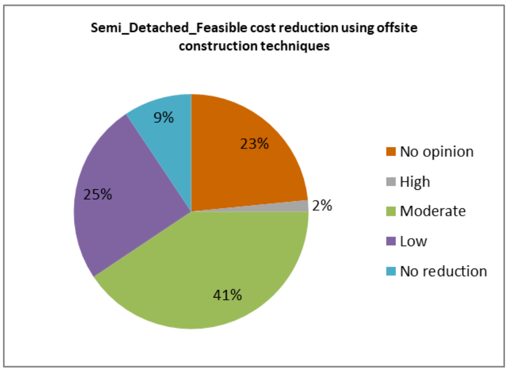


Figure 6.36 *Participants' feasible cost reduction estimation with offsite mechanisms-End Terrace*

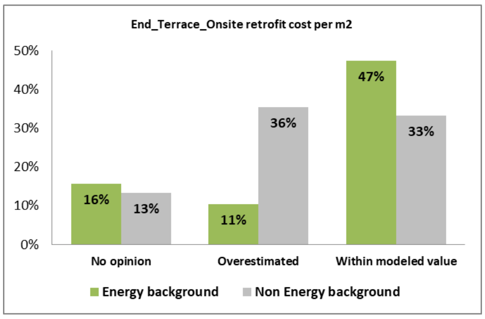


Figure 6.37 *Participants' cost estimation of Whole-House Retrofit/EnerPHit within the predetermined groups –End Terrace*

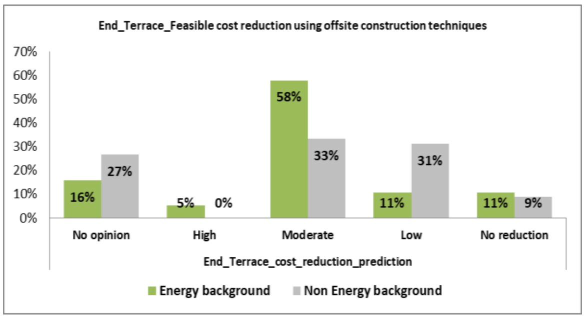


Figure 6.38 *Participants' feasible cost reduction estimation within the predetermined groups– End Terrace*

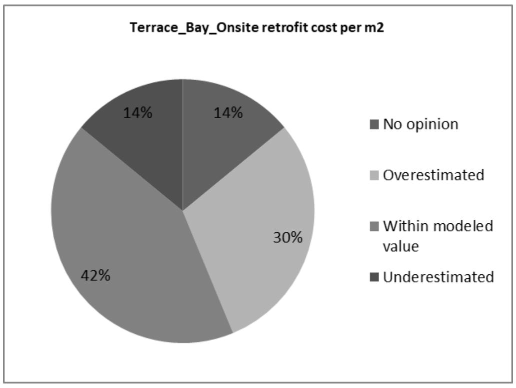


Figure 6.39 *Participants' cost estimation of Whole-House Retrofit/EnerPHit-Terrace Bay*

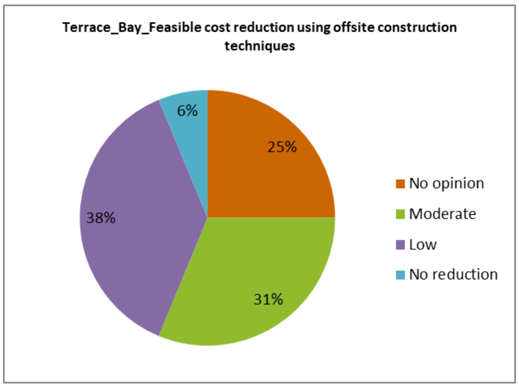


Figure 6.40 *Participants' feasible cost reduction estimation with offsite mechanisms-Terrace Bay*

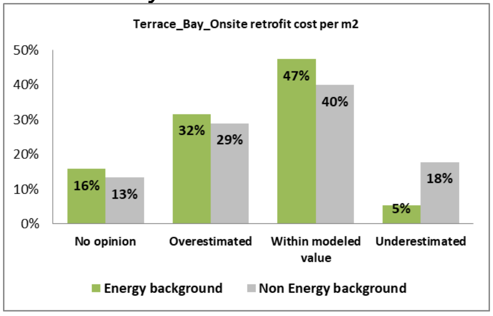


Figure 6.41 *Participants' cost estimation of Whole-House Retrofit/EnerPHit within the predetermined groups –Terrace Bay*

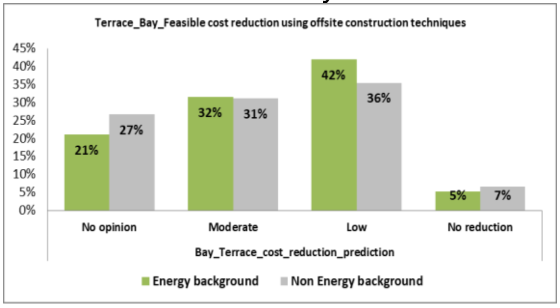


Figure 6.42 *Participants' feasible cost reduction estimation within the predetermined groups– Terrace Bay*

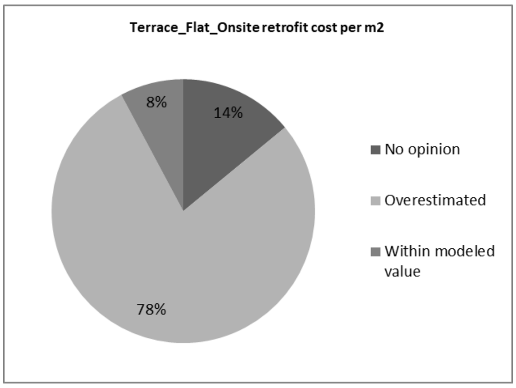


Figure 6.43 *Participants' cost estimation of Whole-House Retrofit/EnerPHit-Terrace Flat*

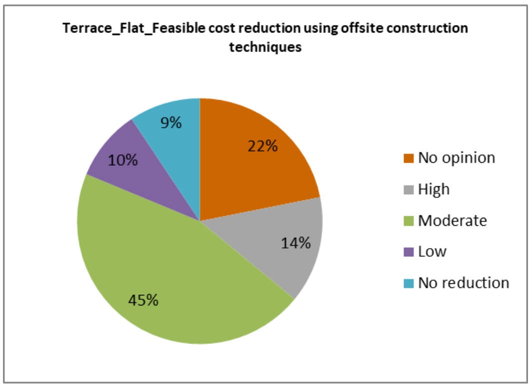


Figure 6.44 *Participants' feasible cost reduction estimation with offsite mechanisms-Terrace Flat*

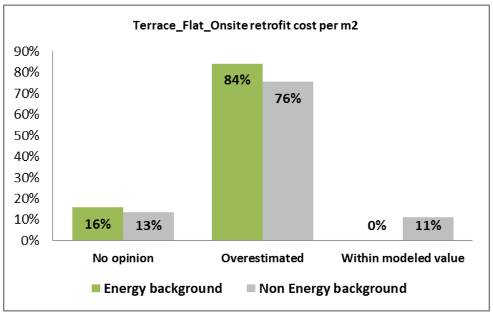


Figure 6.45 *Participants' cost estimation of Whole-House Retrofit/EnerPHit within the predetermined groups –Terrace Flat*

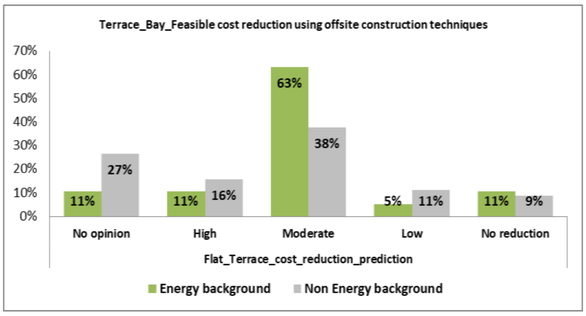


Figure 6.46 *Participants' feasible cost reduction estimation within the predetermined groups– Terrace Flat*

When the offsite feasible cost reduction perceptions are reviewed the analysis becomes more elaborate. As viewed from the offsite cost analysis comparison section the offsite mechanisms do differ significantly on a. the cost and b. on the "service" they provide. The majority of the responders considered that the offsite cost reduction would be in the "moderate" scale which is translated to 5-10%. The cost analysis showed that the "best case scenario" of offsite Internal Wall Insulation offered a reduction of >10% in all typologies (*Figure 5.24*) but also the other two, offsite roof and offsite package may not offer reduction on the capital need but they might be beneficial in the long run; i.e. additional space (Roof) or unforeseen construction cost/hassle "absorption" (Retrofit Package). This demonstrates a fundamental need of the offsite industry to able to demonstrate clearly the advantages of their mechanisms.

6.2.6 Offsite Incentives

To address the aim to investigate what feasible initiatives could stimulate the industry and by extension the market to take up offsite mechanisms in retrofit a multiple choice question was included in the survey asking what would influence the participant to choose offsite techniques in a housing retrofit project. The answers included a selection of general themes that are common in the construction industry (*Figure 6.47*) when the project mechanisms are selected i.e. from materials to services. In addition, the participants were asked to select one of the choices that has the strongest and least impact on their decision. As seen from *Figure 6.47* the “Better quality of build” holds the highest impact in comparison followed by “Shorter build times” and “If cost was lower”. The strongest impact percentage is seen on “Better quality of build” followed by “If cost was lower” (*Figure 6.49*) and the least impact was the “Easier” tendering process (Made to order). When the results are reviewed within the assigned groups (*Figure 6.48* , *Figure 6.51*, *Figure 6.52*) it is observed that the energy background has the strongest opinion in percentage (“strongly agree”) in the “Commissioning and guarantee” very close to “Better quality of build” but when asked to select the most influential factor, “Better quality of build” has the highest significance. Within the non-energy group the “Shorter build times” hold the highest percentage towards “strongly agree followed closely to “lower cost”. Even though similarly to the energy group the majority did select the “Better quality” as the most significant factor, the feasible “lower cost” had a substantial percentage (*Figure 6.51*) leading to a tentative conclusion that the energy background participants see higher value on the quality and guarantee while the non-energy give almost the same significance to monetary value. Both groups showed that an easier tendering process would have the least significant value to choosing offsite (*Figure 6.52*).

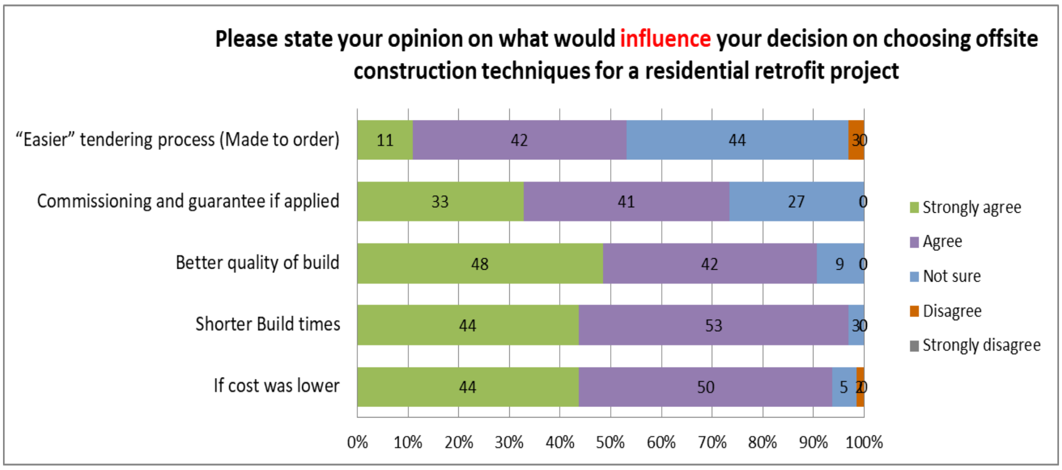


Figure 6.47 *Participants' incentives on choosing offsite mechanisms in housing retrofit*

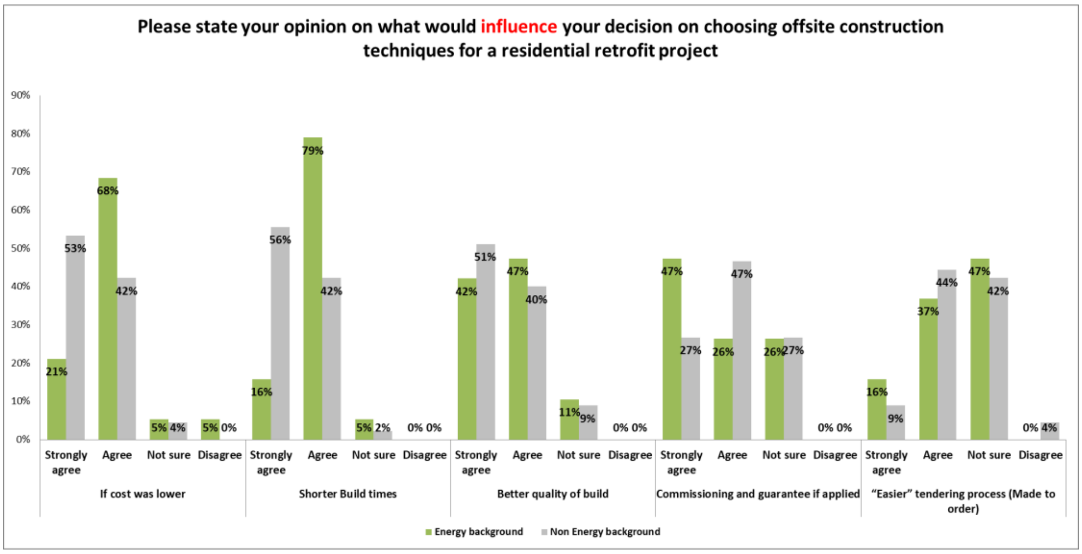


Figure 6.48 *Participants' incentives on choosing offsite mechanisms in housing retrofit within the predetermined groups*

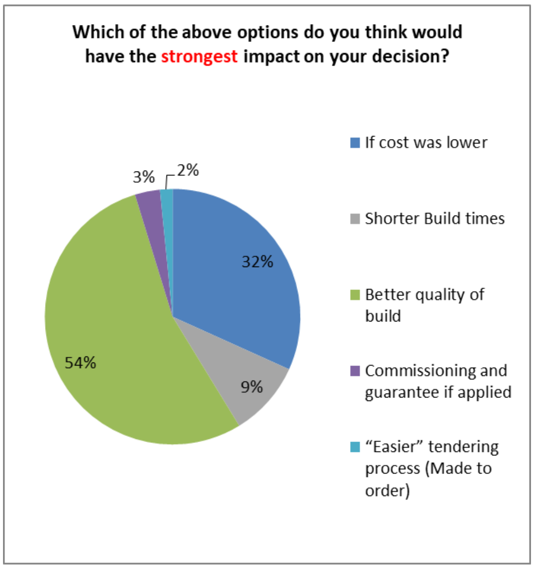


Figure 6.49 *Participants' stronger incentive on choosing offsite mechanisms in housing retrofit*

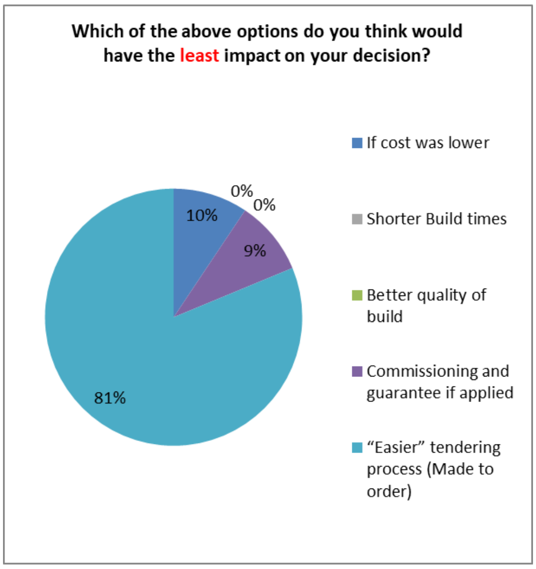


Figure 6.50 *Participants' incentive with the least impact on choosing offsite mechanisms in housing retrofit*

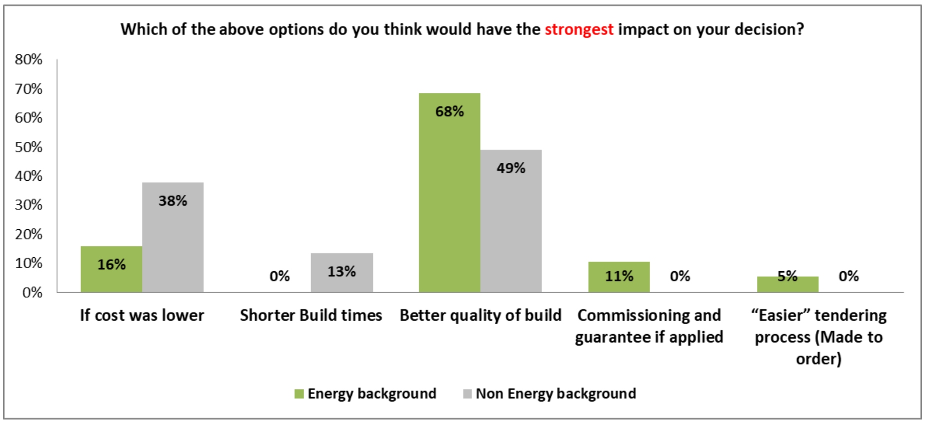


Figure 6.51 *Participants' stronger incentive on choosing offsite mechanisms in housing retrofit within the predetermined groups*

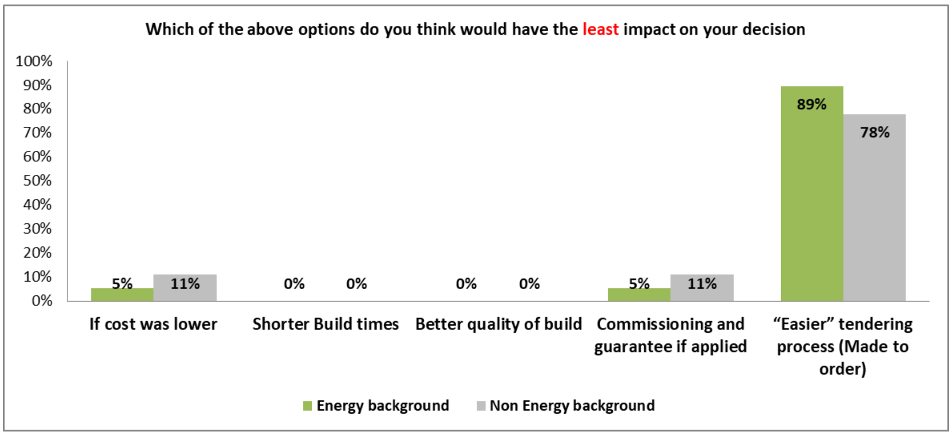


Figure 6.52 *Participants' incentive with the least impact on choosing offsite mechanisms in housing retrofit within the predetermined groups*

The cost reduction though seems to have a great impact in choosing offsite mechanisms (*Figure 6.49*). The cost model analysis showed that the reduction was relative to the offsite application along with the payback timescale. The onsite retrofit though has also unforeseen costs with delays or reworking and providing an open and integrated approach to communication across the design team, contractor, site team, and occupants showing that cost reduction is relevant and more complicated especially due to the variety of housing typologies in UK. The highest incentive being the quality of build correlates with the opinion that EnerPHit certification can deliver this guarantee (*Figure 6.17*) indicating that the offsite retrofit suppliers that associate their delivery with higher standards have better market opportunities. The quality assured investment and guarantee has been a major theme in retrofit as it is a high contributor to the "performance gap" as Johnston et. al, (2016) remarked in testing predicted and measured Passive House certified buildings: *“implementation of appropriate quality control systems, such as those required to attain Passive House Certification, may be conducive to delivering dwellings that begin to ‘bridge the gap’ between measured and predicted fabric performance”* (page 147).

6.2.7 Offsite Barriers

Similarly to inquiring what would be the incentives to selecting offsite mechanisms for a housing retrofit the participants were asked to provide their opinions on the feasible restrictions. The multiple choice answers included, lack of current regulatory requirements, insufficient market demands, insufficient access to relevant information on both product and feasible advantages and the perception that Whole-House retrofit could not be combined with offsite techniques.

In comparison to the incentives the answers were more dispersed (*Figure 6.53*) but the three predominant percentages showed that the strongest barriers are the lack of regulation motivating these types of market, market demand itself and not enough information which also was felt to have the strongest impact (*Figure 6.55*). The least impact correspondingly between the assigned groups seems to be the concept that Whole-House retrofit cannot be combined with offsite (*Figure 6.57* and *Figure 6.58*) showing that the participants accepted this combination (Offsite and Whole-House retrofit).

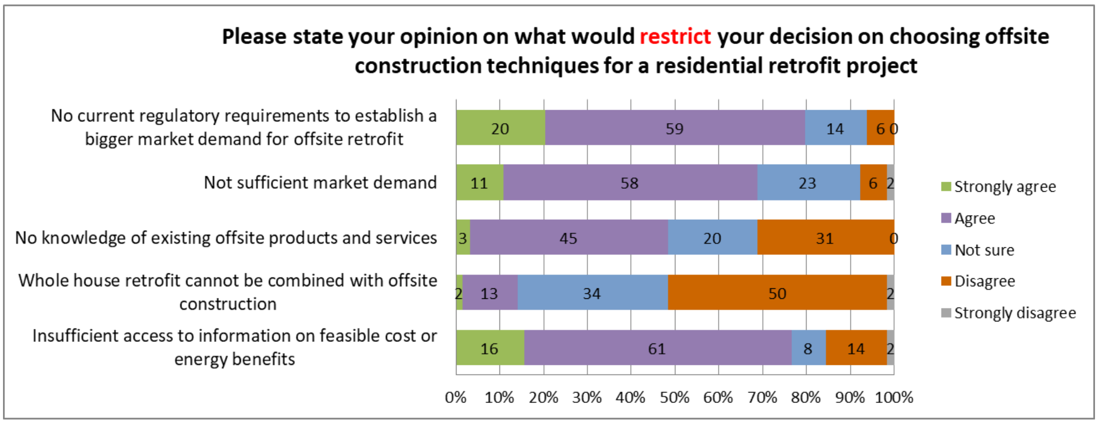


Figure 6.53 *Participants’ barriers on choosing offsite mechanisms in housing retrofit*

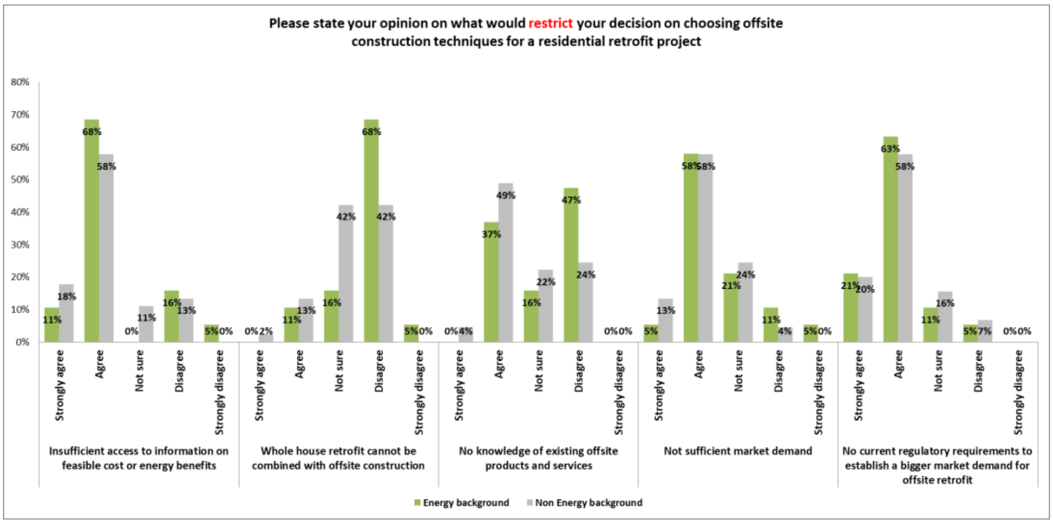


Figure 6.54 *Participants' barriers on choosing offsite mechanisms in housing retrofit within the predetermined groups*

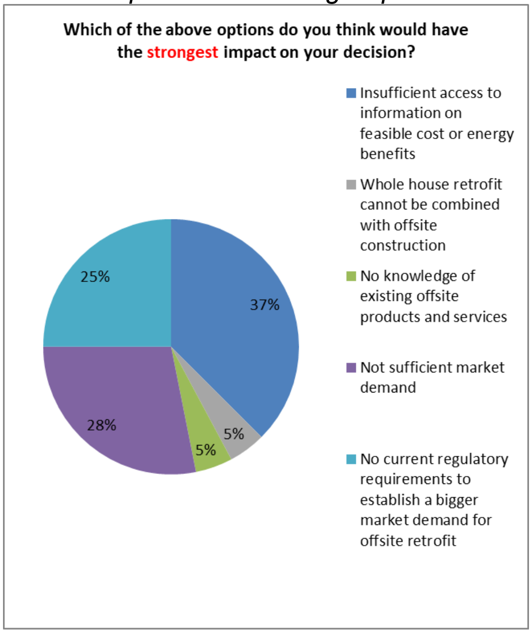


Figure 6.55 *Participants' stronger barrier on choosing offsite mechanisms in housing retrofit*

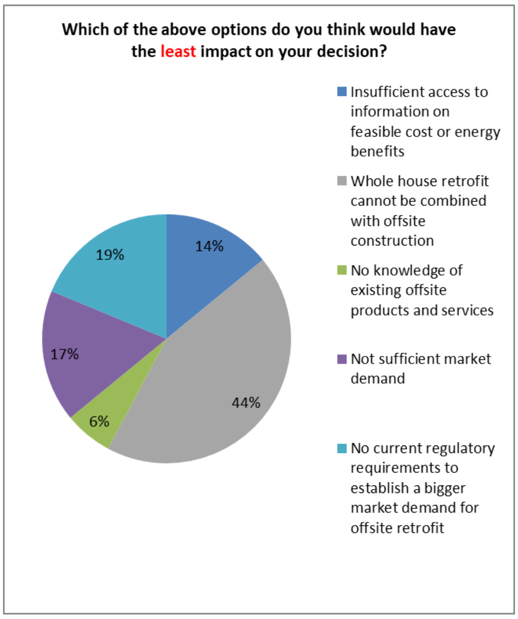


Figure 6.56 *Participants' barrier with the least impact on choosing offsite mechanisms in housing retrofit*

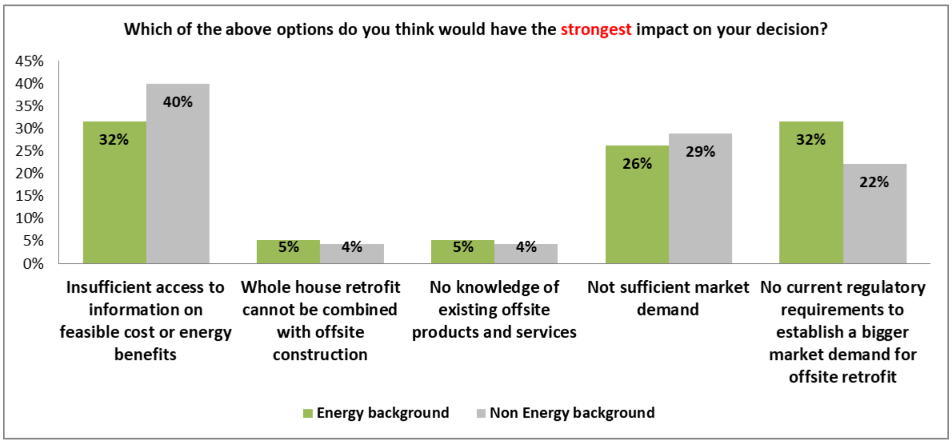


Figure 6.57 *Participants' stronger barrier on choosing offsite mechanisms in housing retrofit within the predetermined groups*

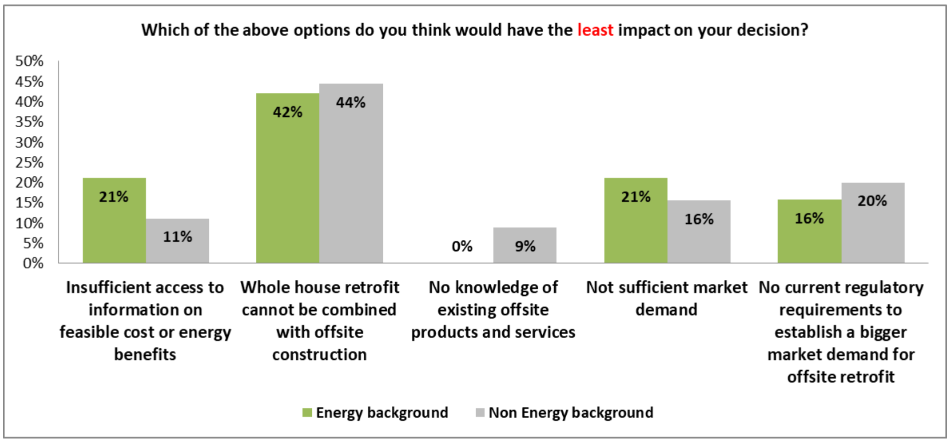


Figure 6.58 *Participants' barrier with the least impact on choosing offsite mechanisms in housing retrofit within the predetermined groups*

This raises the question whether the retrofit industry does not have preconceptions about offsite mechanisms but the need to have an external factor to dictate its market expansion (regulation, easier information access, market demand). The access to information was evident also in the research with cost data not always easy to get hold of. The lack of regulatory requirement or market demand has also been explored in other research in regards to retrofit supply chains. The "Ready for Retrofit" programme (Kenington *et al.,* 2014) reviewed specifically the retrofit market barriers and opportunities and revealed that within the barriers identified , demand vs. supply reactive behaviour: '*waiting for the opportunity to be realised'* before taking action, demand barriers: lack of costumer's awareness and interest were key. The same pattern seems to be realised on perception in regards to adopting offsite retrofit mechanisms in scale. The fact that offsite in new build is receiving a momentum currently could possibly influence the retrofit market as well but the same expectation had been anticipated when the Zero Carbon Homes was to be realized as a legislation drive but did not. Nonetheless, with the introduction of PAS2035 as described in section 2.5.7.5 focusing on quality and installer liability in retrofit it is safe to speculate that there could be a change in delivery and demand dynamics in the sector of retrofit through offsite mechanisms.

6.3 Thematic analysis

Throughout the survey the participants were encouraged to submit free text answers to elaborate on their answer. Due to the size of the received responses a basic thematic approach was considered the most appropriate route of analysis. Three main themes were derived from the questions/answers:

A. What are the practical challenges to achieving Passive House and EnerPHit standard in UK
B. Do Passive House and EnerPHit guarantee quality of build?
C. Offsite construction and retrofit combination challenges.

The free text answers provided a great opportunity for the research to investigate with a qualitative approach the responder's perceptions, in most cases grounded in project experience and thus providing a great insight for the research objective.

A. What are the practical challenges on achieving Passive House and EnerPHit standard in UK

The theme that was repeated the most within the answers was the "***competency"*** of the sub/contractors to deliver the project efficiently (*Table 6.1* and *Table 6.2*) with the main sub theme in *finding* and *ensuring* that could be translated into *finding* available contractors that would *ensure* the project would be to Passive House/EnerPHit standard quality. This is also reflected within the answers given to the question *"Please state your opinion on the following statement: "There is sufficient knowledge and experience across the UK's construction industry to deliver the EnerPHit standard on UK's existing housing stock"*(*Figure 6.29*). Within the energy group it was observed that a high proportion (40%), disagreed and 5%, highly disagreed. The skill shortage to deliver Whole-House retrofit and by implication EnerPHit is an issue that has been raised in previous research (Heffernan *et al.*, 2015; NEF and EEPB, 2014b; Stieß and Dunkelberg, 2013; Topouzi, Killip and Owen, 2017) and reviewed in the first chapter of the thesis as a major barrier to the retrofit industry revealing the challenge of delivering to higher energy standard housing.

The two other issues that were brought up as challenging issues in project delivery were the cost related detailing (*find a solution that would meet our budget… In particular zero cold bridges.) (Table 6.2)* and *elaborate design and changes late in the design process* (*Table 6.1*). Both remarks also have a direct connection to the standard's approach to careful detailing and an obvious increase in cost due to additional labour and material.

Table 6.1 *Free text answers from survey regarding involvement in Passive House projects*

I. Have you ever been involved in a residential Passive House project? **If yes please provide a few words on your involvement and what you found most challenging**
- *Finding a* ***competent contractor*** *to deliver.*
- *only a competition (BRE) Project architect. Not all the way through project. Fitting PH building in between existing houses.*
- *While I have not worked on a Passive House or EnerPHit scheme, I am a certified Passive House Designer.*
- *Passive House Designer for several projects. Most challenging area is* ***dealing with elaborate design and changes late in the design process.***
- *Ensuring suppliers /* ***sub contractors and site management understood*** *what they were providing*
- *finding* ***competent contractor***
- *post occupancy evaluation during my phd. Most challenging, the severity of the* ***unexpected consequences.***

Table 6.2. *Free text answers form survey regarding involvement in EnerPHit projects*

II. Have you ever been involved in a residential EnerPHit project? **If yes please provide a few words on your involvement and what you found most challenging**
- *Finding a **competent contractor** to deliver. Achieving air tightness was the biggest challenge.* - *Princedale Road retrofit. Most challenging was to find a **solution that would meet our budge**t and the stringent requirements of PH. **In particular zero cold bridges*** - *I have learnt from colleagues and their projects.* - *Only at design stage; challenges; lack **of skills/understanding by everyone**; money* - *finding **competent contractor*** - *Involved in early design discussions, but it didn't happen in the end* - *the one above. Passive House (EnerPHit) was the standard aimed.*

Very important to this research is whether offsite mechanisms could act as response and market opportunity that could control and guarantee the process of delivery. This probability can be debated with two examples; first that the general offsite building construction as a process has been reviewed as an opportunity to assist in dealing with skills constraints (Nanyam, Sawhney and Gupta, 2017; Taylor, 2009) mainly due to the control environment. Secondly, in the answers it is visible that the weight of “responsibility” on the “shortcomings” of the delivery falls on the contractor i.e. the coordinator of the onsite works. Current offsite construction companies such as the reviewed Beattie Passive has its own training academy[50] and ModCell® [51] which is an offsite straw panel construction company (Passive House Certified Building system) for

---

[50] Company’s official website: www.beattiepassivetrainingacademy.com/

[51] Company’s official website: www.modcell.com/

new build state that the construction can be made by “quick training of local labour”[52] . Both of these examples, even though ModCell® is not involved in retrofit (yet), show that their innovation of delivery does not fall on the innovation of technology per say as both methods of construction use straightforward timber frame. What they provide is the guarantee of overseeing a project through strategic management and this links to the cost analysis in the previous section (5.4.4) where the cost of retrofit package (Beattie Passive) showed to be more expensive in comparison but they seem to understand the market demand barrier in delivering guaranteed high energy efficient standard housing retrofit (EnerPHit).

The majority of the answers focused on a lack of “competence” in the site delivery with the responder’s actual experience informing the challenges of delivering Passive House or EnerPHit in the UK. These concerns may be focused on a voluntary “demanding” standard but the reality is that the retrofit regulations in regards to its quality are changing (PAS 2035[53]) thus contractors would be required to acquire the knowledge necessary. On the other hand it has to be considered that the participants may point out that the liability falls on the contractors’ part but it might be due to the overall industry fragmentation in knowledge sharing; something that Bonfield Review and PAS 2035 aim to tackle (Price *et al.,* 2017). Furthermore, research done by Killip,(2013) on the innovation potential for low-carbon housing refurbishment among SMEs in the UK construction industry showed that there might be a misconception on the fact that contractors only favour traditional approaches. Without claiming that this could have a assured prevalent effect the research showed that: “*Where the conditions are favourable (as determined by an informal process of multi-factor risk assessment), the response of contractors may be to take pride in learning new methods and solving new problem”* (Killip, 2013, page 528). So could it be argued that the issue of “competence” is really a

---

[52] idid

[53] https://standardsdevelopment.bsigroup.com/projects/2017-04146

lack of communication? The Retrofit Academy[54] for example has embedded in their training of a Retrofit Coordinator the importance of “toolbox talks” onsite that would focus on elements of detailing with the same standards of Passive House (continuity of insulation, airtightness, thermal bridging etc.).

B. Do Passive House and EnerPHit guarantee quality of build?

The overall census from the answers showed that that the participants had to some extent “**tentative**” opinions on the certainty of guarantee *Table 6.3*. Even though, it is recognised by almost all respondents that the necessity of rigorous testing for compliance leads to better construction quality they also pointed that *“'Guarantee'* is not necessarily a given. The delivery from a competent builder/team was remarked relating to the previous question but there is an overall confidence in the standard as shows that 80% of the respondents supported the standard’s assurance (*Figure 6.27* and *Figure 6.28*). This demonstrates that the responders recognise the qualities of required detailed design but also the challenges in actual project delivery.

Table 6.3 *Free text answers form survey regarding Passive House and EnerPHit construction quality*

III.	**Do you believe a Passive House or EnerPHit certified building guarantees the quality of construction? Please provide a few words for your opinion**
-	*The high levels of air tightness tend to ensure the rest of the construction has been **thought about and built well too but there is no guarantee.** The designer and certifier are likely to have avoided problems but the high levels of insulation in themselves create additional risk which has to be managed throughout the process.*
-	***doesn't guarantee but provide a strong 'likelihood' in comparison with not aiming for PH***
-	***Quality Assurance, Comfort, reduced performance gap***

---

[54] Retrofit Academy: www.retrofitacademy.org/wp-content/uploads/2016/02/Retrofit-Coordinator-Prospectus.pdf

- ***Requires more oversight on site,*** *which can only be good. However not applicable to* ***finishes etc so not a complete guarantee.*** *But covers most important aspects.*

- ***Airtightness testing provides quality assurance*** *regarding the construction approach. For other aspects, inspection is required to ensure compliance.*

- ***Because it is certified after construction is complete.***

- ***Yes to a certain extent, the standard is very rigorous and a great deal of photographic evidence is required.***

- ***to a certain level*** *but not totally as it does not guarantee quality of all fit out*

- *The certificate only covers the final result which was witnessed during construction -* ***it does not provide a guarantee that shortcuts were not taken throughout the build process*** *then masked with a band aid prior to final testing*

- *certain aspects of the build will* ***be to a higher standard and builders*** *who can do this are likely to be much better than the* ***average but not sure they guarantee the overall build quality***

- ***'Guarantees' is a strong word*** *- without a system which includes post-occupancy evaluation I don't think it can be justified. I think Passive House or EnerPHit makes it* ***much more likely construction will be of high quality****, as this is essential to deliver those challenging standards.*

- ***It's only one way to achieve quality and not the only way***

- ***fact it is verified/checked + all in team working towards a goal***

- *Must past certain tests to achieve Passive House or EnerPHit status, but* ***may still have design or build defects***

- ***Yes and no. No, because it is still a learning curve in this country. Yes, in the sense that constructions are learning to build with tests in mind.***

It was described in the literature review chapter that the Passive House standard, including EnerPHit has, through energy monitoring, demonstrated that the projects typically do perform as designed i.e. closing the performance gap. Specifically in the UK, the Passive House Trust[55] along with the annual conference offers a platform that provides practical evidence of the processes, challenges and limitations which offer a critical review and assist on the evolution of the standard to tailor the UK industry and vice versa. This critical review was also observed in the survey responses while remarking that the standard's "strength" stands on the fact(s) of "certification" and "testing" revealing that the industry recognises the need to a regulatory "Code of Practice". This is actually being addressed by the BSI Retrofit Standards Task Group[56] following the Bonlfield Review (PAS 2035: www.bsigroup.com) which has not come into force yet but is a confident response for the industry and the retrofit market needs. In comparison, the EnerPHit standard follows most of the aspects that are proposed PAS 2035 draft thus showing its feasible macroscale longevity.

One of the interesting findings in the exploration of the participants' opinions in the free text answers is the cautiousness of stating that the Passive House or EnerPHit guarantees quality of construction but at the same time acknowledging the technical rigour in the design, detailing and construction it requires for certification. This cautiousness is at some level understandable as the standard is not viewed blindly as the "only answer" but could also point to the cultural barriers that UK still has to overcome in terms of fully accepting the standard (Schoenefeldt, 2014). In UK, Passive House is still considered as "innovation" where as in other EU countries it has been adopted as the mainstream approach (Lynch, 2011) and even in neighbour Ireland[57] has been adopted in regional building legislation.

C. Offsite construction and retrofit combination challenges

Even though the multiple choice question showed that the least impact of restricting offsite was the statement that "Whole-House retrofit cannot be combined with offsite"

---

[55] Web site:www.passivhaustrust.org.uk

[56] PAS 2035:2018 Specification for the energy retrofit of domestic buildings

[57] Dublin local authority makes passive house mandatory in historic vote: https://phai.ie/news/dublin-local-authority-makes-passive-house-mandatory-in-historic-vote/

(*Figure 6.47*, *Figure 6.50*, *Figure 6.52*), the writing statements have pointed out significant views of the respondents in the feasible limitations of this combination. The main subject that was pointed out was that offsite applications on retrofit are highly “***conditional***” on each project combined by the requirement of extensive survey needed as the offsite could limit any modifications onsite. Some statements made are not actual accurate in regards to the environmental impact that has been studied and proven to be less intensive than onsite construction by organisations such as WRAP (Waste and Resources Action Programme (www.wrap.org.uk) which again raises the question of how informed industry is in regards to offsite. Additionally, it is observed that the industry’s perception barriers can be found within different aspects such as technological: “*offsite methods suffer from more poorer airtightness”,* and lack of research or even historical failures: *“offsite process needs to be proven as beneficial” (Table 6.4), “Whole-House retrofit not easily combined with offsite construction” (Table 6.5).*

Table 6.4. *Free text answers from survey regarding drivers of offsite mechanisms in housing retrofit*

IV. Please state your opinion on what would influence your decision on choosing offsite construction techniques for a residential retrofit project **Other:**
- ***Practicality. Offsite construction uses a lot of extra material which is unnecessary.*** *To externally insulate a wall you only actually need the insulation.* ***For offsite construction you need to create a frame for it,*** *and if the windows are included as well, a strong frame. Also I think* ***offsite methods suffer from more poorer airtightness*** *because there has to be a larger tolerance for manufacture.* - ***The application of the offsite process needs to be proven as beneficial for cost, quality and ease of installation****, the issue with retrofit is the quality of* ***initial survey information for the existing building*** *- any mistakes here will be amplified through the process and any modifications required due to error at this initial stage will then negate the quality, cost and speed of install.* - ***higher standards*** *(could fall under better build quality), and* ***more eco materials*** - ***depending*** *on if appropriate*

V. Which of the above options do you think would have the strongest impact on your decision?

Other:

- ***Practicality.***
- *it **depends** on the project and the client*
- ***whether applicable***
- *One of the first three **depending on circumstances***
- *the impact on indoor air quality and comfort*

Table 6.5. *Free text answers form survey regarding barriers of offsite mechanisms in housing retrofit*

VI. Which of the above options do you think would have the least impact on your decision?

Other:

- ***don't actually consider that tendering is likely to be easier - hard to nominate within contract***
- *it **depends** on the project and the client*

VII. Please state your opinion on what would restrict your decision on choosing offsite construction techniques for a residential retrofit project

Other:

- *When best to get manufacturer involved in process / complications with procurement. **You need to commit really early to a specific product**, but if it's a very large part of the build that can restrict competitiveness of tendering*
- *env. impact of offsite not well known/studied*
- ***Whole-House retrofit not easily combined with offsite construction***
- ***Market demand depends on price which is too high.** Regulatory requirement would cause outcry because of cost*

The participants' remarks showed that the offsite industry in retrofit still has a long way to go as most of the human perceptions are grounded in the fragmented industry structure. Similarities on how retrofit with offsite mechanisms and Passive House are perceived could be made through the prism of "innovation". Even though Passive House/EnerPHit becomes more popular the comments from *Table 6.3* showed both cautiousness but also recognition on what the standard brings in terms of quality. Equally, offsite needs to prove that it can respond to either misconceptions or include the same "principles" of delivery. One of the comments summarises those issues (*Table 6.4*): *The application of the offsite process needs to be proven as* ***beneficial for cost, quality and ease of installation****, the issue with retrofit is the* ***quality of initial survey information*** *for the existing building - any mistakes here will be amplified through the process and* ***any modifications required due to error at this initial stage will then negate the*** *quality, cost and speed of install.*

From the energy and cost modelling presented in the thesis it was demonstrated that **cost** benefit is highly dependable on typology location and offsite method applied. So those distinctions in benefits should be accessible and transparent similar to EnerPHit where the cost benefits derive in the long term and through careful design. In retrofit the initial **quality survey** and the unforeseen **modifications** are actions that are highly dependable on work done onsite as part of working with existing buildings. In the mechanisms reviewed in this thesis offsite Internal Wall Insulation (WHISCERS) and Beattie Passive include those elements in their service delivery. WHISCERS uses 3D laser survey ensuring the insulation panels are pre-cut and fitted accurately. The technology adopted ensures quality of installation while existing services are removed and refitted by the same provider warrants risk management. On the other hand the Beattie Passive approach is within the company name, as they have a Passive House certified building system. They do incorporate offsite techniques in their project delivery ensuring quality control in some elements while by understanding the complexities of airtightness and thermal bridging ensuring risk management on site works.

The responders showed that they are still very guarded in relation to offsite-retrofit approaches which are reasonably recent additions to the existing market. The question is though how much their restraint is due to their fear of leaving traditional approaches and how much further the offsite market needs to go to gain wider support.

6.4 Social significances and findings

The survey results provided an important insight to the industry's knowledge and perceptions in two main issues explored in the thesis, the high energy efficient standard Whole-House retrofit (EnerPHit) and the application of offsite mechanisms. The quantitative and qualitative data that the survey provided explored the attitudes of the industry which are invaluable to have a holistic understanding of the applicability of offsite in housing retrofit that spans beyond technical findings. Extending beyond previous research done to either focused deep retrofit or offsite techniques the research offers an original contribution on exploring the evidenced-based technical variables and then assesses them through the human attitude "lens". For this research, the questionnaire was influenced by the Theory of Reasoned Action (TRA) and Theory of planned behaviour (TPB)(Ajzen, 1991), but did not formally apply the models; specifically the questionnaire measured the "desire" to adopt energy efficiency standards and offsite mechanisms as well as the participants' "intent" to do so. For example participants would have confidence in higher energy standards or offsite mechanisms (desire) but possible onsite complexities would be an obstacle to do so (low intent). The free text answers provided a deeper insight and worked in some extend as market analysis on what the offsite industry has to overcome, adopt or demonstrate.

6.4.1 Standards

The majority of the participants were confident in their understanding of current regulations concerning energy efficient design in new and existing housing. In the following questions regarding high efficient energy standards and deep retrofit (Passive House and EnerPHit) the level of knowledge remained in high levels within both assign groups along with two main facts. The first is the number of participants, including the ones with “no energy background”, having participated in either Passive House or EnerPHit project and secondly the high level of confidence in the standard’s quality of construction. This is also somewhat confirmed by previous research (Hopfe and Mcleod, 2015) recognising that Passive House is the fastest growing energy performance standard and the most recognizable alternative to Zero Carbon (Pitts, 2017; Greenwood, Congreve and King, 2017) but opinions differ on whether the UK industry has the ability to deliver. That signifies that there is an opportunity for the future of offsite retrofit mechanisms to embrace the standard as has been done with Beattie Passive’s TCozy

6.4.2 Cost

When the questions centred on offsite construction the participants showed in general positive attitudes but when focused on its combination with retrofit the level of knowledge and confidence was significantly lower. This is an interesting remark when it also viewed in relation to the cost estimation responses. When estimations came to onsite retrofit the opinions on cost were relative to the size of the property while the modelling (energy and cost) demonstrated that this is not always case. In the case of inquiring about the feasible cost reduction (if any) that offsite applications could offer the opinions were varied but with an inclination towards “relative cost reduction” which is met (as the modelling demonstrated) with the Internal Wall Insulation as the offsite technique. As repeatedly mentioned in this thesis, in existing housing stock and especially in older typologies unforeseen onsite issues increasing the costs would almost always be the case. Thus offsite “standardisation” can only be applied in some elements of delivery possibly making the notion of just “upfront cost reduction” less important to the construction quality.

6.4.3 Incentives and Barriers

The exploration in the incentives and barriers that would influence the selection of offsite mechanisms in retrofit presents an insight not only into the current perceptions of the participants but also the prospects that the offsite industry could embrace for better quality of build followed by shorter building times and lower cost. Therefore, quality, time and cost would be main drivers similar to previous research done on offsite construction industry (Pan *et al.*, 2004a; Goodier and Gibb, 2005). In the case of exploring the opinions on what would constitute a barrier in the selection of offsite mechanisms the three predominant themes were: lack of regulation drivers, insufficient access and knowledge of product and techniques and lack of market demand. These are factors that are equally reflected in the research regarding UK housing retrofit in general (NEF, 2014; Killip, 2013a; Dowson *et al.*, 2012; Pelenur, 2013b).

Finally the thematic analysis from the open text answers somewhat provided a deeper insight to the participants’ opinions or experience to both energy standards and offsite. The main concerns that rose in delivering either Passive House or EnerPHit standard in UK was finding a competent contractor alongside general skill shortages an issue that is widely relevant in retrofit and has been extensively brought to the attention from other research along with the unintended consequences this entails (Marina Topouzi *et al.,* 2017). Still the responders recognise that the standard holds the element of assured quality delivery due to the rigorous path of certification needed.

In regards to the combination of offsite techniques the answers had a more tentative approach to the success their applicability. This presents an opportunity for the offsite/retrofit industry to “prove its worth” and links back to the need for making the information available more accessible. Previous research has showed negative public attitudes to prefabrication (Pan *et al.*, 2004) due to the mass prefabricated problematic housing during the 1960’s but more recent qualitative research within SMEs (Killip, 2013a) showed that there is room of implementation of innovation in retrofit where the “conditions are favourable”. Killip, (2013a) summarizes that contractors’ wiliness to embrace innovation depends*:” on an informal approach to risk assessment, taking account of cost, time efficiency, client demands, and installer confidence in the reliability of the resulting work”* (page 522). From this research similar issues derived in terms of perceptions on integrating offsite with retrofit but with the participants’ background ranging beyond the contractor “title”. This shows that there is a “standardisation” in the incentives of the wider construction industry where the offsite mechanisms need to deliver.

6.4.4 Survey and model results interrelated

The main question is how are these responses interrelating with the energy and cost research model? The EnerPHit standard modelled within the predetermined typologies showed a great reduction to the heating demand demonstrating the standard’s effect. Similarly, the survey results showed its popularity and confidence within the participants indicating an energy standard goal that the offsite manufacturers could aim to include in their market strategies. This is delivered by one of the offsite mechanisms modelled, the “Offsite Package” from Beattie Passive’s TCozy. In terms of cost the model showed high variation within each type of offsite mechanism modelled along with their long term payback and range of benefits such as lower upfront cost, additional living (and profitable) space and all-encompassing delivery services. When those results are looked at in comparison to the survey’s varying answers it is visible that there is a need for more transparency and accessibility on the possibilities that offsite mechanisms could offer. Even within the research process obtaining straightforward costings was highly challenging. It is obviously recognized that unforeseen costs could arise on site since existing house conditions could prove unpredictable. The relatively new RealCosting software for example, as used in this thesis has taken a step of “user-friendly” breakdown of the retrofit complexities and could be a good opportunity if offsite techniques could also be intergraded in the process.

Regulation and market demand were also recognised as prime barriers for offsite uptake in retrofit and are issues previously explored in the retrofit market and innovation in general with somewhat conflicting views on whether one drives the other (“bottom up or top down”) (Kenington *et al.,* 2014; Greenwood, Congreve and King, 2017).

Due to the ‘failures’ of previous mass retrofit ventures such as the Green Deal and unintended consequences of faulty installations the Bonfield Review (Bonfield, 2016) has sparked the expected mandatory building BSI (British Standards Institution) PAS2035[58] (2019) which will ensure quality assurance of retrofit applications. Thus, the regulation will set in motion the much needed guarantee in the retrofit products and services and possibly the industry will look at the offsite mechanisms to be a delivering force in the market.

In conclusion, the research by examining those available offsite mechanisms showed that there are more than technical implications, cost or energy paybacks. A focused analysis without an interdisciplinary method would not be comprehensive. The mixed method approach illuminated on both technical and non-technical complexities, benefits and possibilities this arising market could embrace, especially within the UK‘s typologies that are in greater need of being retrofitted.

---

[58] PAS 2035 PAS 2035:2018 Specification for the energy retrofit of domestic buildings: https://standardsdevelopment.bsigroup.com/projects/2017-04146

7 Conclusions, reflections and further research

This chapter summarises the overall research project, starting with the rationale and original research questions, followed by the results and discussion. The implications of the results and recommendations for policy and retrofit professionals are also presented; as well as future research guidance and final concluding remarks.

As evidenced in the literature review (Chapters 2 and 3), there is a social, economic and environmental need for housing retrofit in UK. Attempts made so far to address the issue collectively have not generated the desirable outcomes but have brought to the forefront the factors presented as barriers to the sector's growth.

On reviewing this evolution, this research aimed to understand how the latest efforts of the industry introducing offsite mechanisms in the retrofit market along with the voluntary high energy efficient standard EnerPHit correspond to the current industry needs.

The research focused on examining how this offsite mechanisms dovetail with aspects of regulation, technical implications, financial gain and social acceptance with an emphasis on the most challenging typologies found in UK housing stock of pre-1919. In pursuit of this analysis the following research questions were raised:

RQ .1 Can the cost of UK Whole-House retrofit to EnerPHit standard be reduced via current offsite mechanisms in pre 1919 UK house typologies?

RQ .2 Could the UK industry be confident in adopting this combination as common practice?

RQ .3 What innovations are needed by the industry for 'Whole-House' retrofit practice to have a macro-scale effect in the UK?

7.1 Summary of findings, discussion and recommendations

In response to these questions, the research took upon an interdisciplinary approach in its methodology with the regulatory, technical, financial and social interconnected aspects as its guide. Those were tested by undertaking energy and cost modelling of the most common pre-1919 typologies and conducting an online survey with target responders from construction industry professionals. The findings summaries are presented in the next sections according to the analysis methods.

7.2 Regulatory findings

The energy modelling tested three energy standards scenarios for each of the five most common pre-1919 typologies in four different climatic conditions in UK. This was the basis data collection and analysis that provided a clear comparison on energy results that by extension became the basis for the financial analysis.

The energy standards compared were the Base case where no retrofit has taken place, minimum Building Regulations Part L1B and EnerPHit. Those were chosen so there could be a parallel view of the results on an un-retrofitted dwelling (Base Case), a dwelling with the minimum “mandatory” standard (Building Regulations) and a “voluntary” high energy efficient standard (EnerPHit).

The results showed that there is a significant difference between typologies and within different UK locations (*Figure 5.1* and *Figure 5.2*). In average the differences from a non-retrofitted dwelling upgraded to minimum Building Regulations resulted to 40-50% reduction in heat demand and a staggering ~90% reduction when the equivalent typologies were retrofitted to EnerPHit standard. Additionally, the regional differences had an average 30% between “warm” (South UK) and “cool” climate (North UK) on the Base Case and Building Regulations scenarios.

This analysis was the initial critical understanding of the impact in energy reduction EnerPHit standard could provide throughout the range of typologies. While the Base

Case and the Building Regulations scenarios heating energy demand varied according to typology and location, the EnerPHit remained “invariable (≤20-25kWh/m2/a).

Nonetheless, the significant differences of heat demand between typologies and locations (Base Case) demonstrates that different amount of materials and labour is required to achieve EnerPHIt showing that a “fit for all” applications would be challenging through the pre-1919 housing stock. The variations and their impact in retrofit applications were explored in more detail in the next section allowing to understand the limitations and possibilities of offsite approaches.

Recommendations:

Even though the complexity of the pre-1919 housing stock makes the deep retrofit more challenging, energy standards such as EnerPHit provide a whole-house approach that takes those into consideration. Regulation on retrofit has shown no clear direction in the past but some changes such as the future implementation of PAS 2035 show that this would be the way forward for energy reduction and construction quality. The offsite supply chain therefore is required to have the same attitude approaches on energy standards to ensure their macroscale influence.

7.3 Technical findings

By using the novel software RealCosting that works in conjunction to the Passive House Planning Package (PHPP) the research managed to analyse in detail the elements that contribute on the energy demand (PHPP) and direct cost related factors (RealCosting). This dovetailing of energy and cost in retrofit as a “tool” proved that it could be of great significance in understanding retrofit and which factors or elements could impact any feasible offsite uptake.

In the research the cost and energy correlation was evident in the analysis as it was feasible to demonstrate heat loss per element, per typology and per location. This has an impact on the cost/amount of the necessary application to upgrade and understanding the limitations and feasible strengths of adopting offsite in retrofit. For example the End

Terrace typology heat loss through its walls accounts for almost 50% of its total elements in contrast to the Terrace Flat of 35%. When the same typologies are located in different climatic conditions within UK, the heat loss from the same element varies to almost 30% from a warm to a cool climate. Consequently to upgrade those elements different amounts of insulation is required in each corresponding typology when are located in different regions in UK. Additionally, heat losses through the windows and ventilation have the second greater impact in the total heat loss with the amount varying between typology and location. To upgrade those two elements (to EnerPHit) a great amount of onsite works is usually needed showing that applying offsite construction to retrofit could have its limitations. How those impact the upfront cost and payback over time was explored in detail in the next section of the analysis.

Recommendations:

The modelling showed that according to the typology and location the retrofit amount of materials and work differ significantly. This diversity of the housing of the pre-1919 stock means that offsite supply chains need to deploy bespoke and unique solutions that offer flexibility within their delivery services.

7.4 Financial findings

The financial analysis took three types of offsite approaches that were applied in the cost calculation; Offsite Internal Wall Insulation, Offsite Internal Wall Insulation with Offsite Roof and Offsite Package that includes offsite mechanisms in delivering Whole-House retrofit under a central coordinator/contractor. The upfront capital cost of the selected offsite approaches when compared with onsite construction was only reduced when the Internal Wall Insulation was introduced as an offsite element with cost reductions ranging between 11 to 19% (*Figure 5.24*). When the Roof was added as an offsite element in the calculation the upfront cost was increased by 18 to 23% (*Figure 5.25*) and finally the Offsite Package increased between 17 to 49% (*Figure 5.26*). The variations between typologies' morphology and location reflected the reduced or increased cost accordingly to each offsite measure tested. For example typologies with relatively larger amounts of external wall achieved greater cost reduction with the Internal Wall Insulation as the offsite element, typologies with relatively greater roof area had greater cost increase when the Offsite Roof element was applied and finally typologies with relatively greater floor area had greater cost increase when the Offsite Package was applied.

The upfront cost differences showed a clear monetary distinction but when analysed in terms of payback the cost efficiency determinants show to have a wider implication depending on the typology that could essentially amount to a. location and b. “comfort”. The *“location-energy”* determinant relates to the amount of materials need to be used in different climatic regions (Warm/Cool) to achieve the same standard. The *“location-energy labelled”* house determinant relates to the amount of the House Value increase (EPC rating) by the amount of energy efficient measures. Finally, the *“location-property value”* where in the case of additional space is introduced in the property, its value will automatically increase. The most evident example of the high impact of this effect can be seen when the two regions are compared (Warm/Cool); a dwelling in London (Warm) will need less amount of materials to be retrofitted (EnerPHit) than one in Borders (Cool). The payback time in Borders, due to harsher climatic conditions is faster and its better EPC rating “worth” 17 times more than the one in London (*Table 5.2*). But then again, when it is viewed from the “real estate” spectrum if the retrofit is combined with living space addition (Offsite Internal Wall Insulation with Offsite Roof) the asset value of the property, especially in the case of London, not only is equal to the cost of works but has more than double the return (*Figure 5.30*).

The “comfort” element in this aspect of the research is related to the services that offsite can offer. As the co-benefit of the increase in internal temperature has been applied in monetary terms in the model via previous research done by the RealCosting creators the same rationality can be applied in the offsite mechanisms reviewed in this thesis. The Internal Wall Insulation with offsite mechanisms includes in its price the cost related on removing and reapplying services under one “umbrella”, the Offsite Roof has the possibility to “deliver” an extra room in the property within hours and the Offsite package takes the responsibility of “absorbing” the unseen cost and “secure”/guarantee certification (EnerPHit).

The analysis in summary showed that in terms of cost either upfront or payback does not only depend on the amount of energy reduction but are other factors that could make the offsite construction in retrofit a desirable approach. Still the industry’s perceptions play a great role in materialising those approaches. The survey conducted in this research aimed to understand the barriers and incentives that could have an impact on the sector’s future.

Recommendations:

With the modelling showing that there are different aspects of “payback” (reduced time on the return of investment, additional space, direct increased house value and reliable return on investment due to commission guarantee) offsite supply chains can create business models incentivising on those aspects that focus on older housing stock. Per offsite examples such as Beattie Passive and Energiesprong that ensure delivery, investment mechanisms that support retrofit can provide finance aid to homeowners and therefore made retrofit more attractive to private markets. These are finance mechanisms (for low energy retrofit) are available in other countries such as grants and very low interest loans from a state own bank in Germany (KfW)[59] and finance programme in France (Picardie Pass Rénovation)[60] targeting homeowners that provides both finance aid and technical support. In UK even though the Ecology Building Society[61] provides mortgage discount rates for low energy retrofits (not as low as the German KfW) but offsite mechanisms with the provision of guarantee can make financing retrofit more attractive to invest (public and private).

---

[59] Kreditanstalt für Wiederaufbau (KfW): www.kfw.de/inlandsfoerderung/Privatpersonen/Bestandsimmobilie/Energieeffizient-Sanieren/Das-KfW-Effizienzhaus/

[60] Picardie Pass Rénovation: www.pass-renovation.picardie.fr/project-funded-by-europe/

[61] Ecology Building Society: www.ecology.co.uk/mortgages/c-change-discounts/

7.5 Social findings

The survey objective was to understand the industry's perceptions on both high energy efficient standards on housing retrofit and the integration of offsite mechanisms. The survey structure and consequently the results could almost be summarized thematically as *knowledge*, *trust* and *aspiration*.

The *knowledge* of the Passive House/EnerPHit standard has a high percentage in responders with and without a professional energy background demonstrating its increasing popularity in the industry. When industry's knowledge though is examined in terms on the costs related to the standard the answers varied and in their majority were overestimated. The same diversity of knowledge was evident when the offsite elements were questioned; a high majority felt confident on understanding offsite construction but when feasible cost reductions were asked about in relation to retrofit the answers highly varied. This cost variation is also evident from the energy and cost analysis where different offsite approaches showed different results.

When the question of *trust* was posed which relates to guarantee or confidence the answers provided a great insight to the industry's perceptions and experience in regards to both EnerPHit and offsite mechanisms. The EnerPHit standard, with a high majority in both energy and non-energy background groups; was considered to be able to guarantee quality of construction. Still, when the free text answers were reviewed it seems that there is a tentative constrain in "dogmatically" connect guarantee with EnerPHit standard in connection with concerns on current skill sets in the industry to deliver (contractors' competency). In the case of offsite there is clear shift in opinion from when it is applied in new build which has a high percentage of confidence but in the case of retrofit there is an evident decline demonstrating that there is a constraint in adopting these measures.

The *aspiration* relates to the incentive and barriers considered in choosing offsite mechanisms. The stronger incentives were in expressions of higher quality, reduced cost and fast application with the quality having the highest impact. In terms of barriers the lack of regulation requirement, market demand and lack of accessible information were on the highest percentages with lack of accessible information having a moderate higher impact.

In summary the survey results showed that even though there is support in better energy standards such as EnerPHit due to the rigorous design required there is still a level of distrust in the industry to deliver. Similarly, the offsite measures in retrofit are viewed at some level with “suspicion” meaning that the sector still needs to be established.

Recommendations:

The survey showed that participants had a sufficient level of knowledge and trust in energy standards, both mandatory and voluntary Passive House/EnerPHit even within the group that did not have an energy background. This suggests that even though regulation in low energy retrofit is yet undeveloped, voluntary energy standards are becoming more accustomed and possibly more trustworthy. The offsite construction in retrofit could possibly follow the route in proving that can deliver those standards with fast application, reduce cost and more accessible information.

7.6 Research questions

This section presents an overview on how the research answered the questions raised.

RQ .1 Can the cost of UK Whole-House retrofit to EnerPHit standard be reduced via current offsite mechanisms in pre 1919 UK house typologies?

The research reviewed and compared three types of offsite approaches of retrofit in typical pre-1919 UK housing typologies. The findings showed that the “cost reduction” per say is more complicated and depends on various factors:

- Shape: the initial difference is understandably within the different morphology of the typologies. With the shape of any building having a vital role in its heating energy demand, the upfront cost with either onsite or offsite constructions approaches differ significantly demonstrating that one price “fit for all” would be very challenging at the least for this UK stock.

- Location: Adding to the variation is the location the equivalent dwelling typology is situated within the UK, where the climatic conditions differ significantly. This also has an effect on the energy heat demand and subsequent materials or works needed for retrofit. Apart from the climatic conditions, the location has an impact on the property value of the equivalent typology.
- Payback: The upfront cost comparison from onsite construction to the three offsite approaches analysed showed that only the Internal Wall Insulation with offsite measures presented a capital cost reduction in comparison and the cost increased when the Offsite Roof is added or the Offsite Package applied, with the latter having the highest increase. Due to the morphology of each typology in combination to the related cost there is an interconnected impact; high external wall (IWI offsite), roof size (IWI offsite and Offsite roof) and floor area (Retrofit Package). While it would be expected the same logic would apply when considering payback time and Return On Investment additional factors were consider to have a great effect such as when taking into account the increase of property value due to feasible additional space, access to lower mortgage rates due to EnerPHiit certification and reduced snagging and defects due to the quality of construction assurance.

RQ .2 Could the UK industry be confident in adopting this combination as common practice?

The research conducted the survey to investigate and identify the industry’s perspectives on energy standards, offsite mechanisms and their practical combination.

- Energy standards: The findings showed that in terms of energy standards, the majority of responders had a high level of knowledge with current Building Regulations but equal knowledge and confidence was shown for the voluntary

Passive Houses and EnerPHit standards of higher energy efficiency. Still, further analysis on open text answers showed barriers on existing skills to deliver.

- Offsite: In regards to offsite the participants suggested both high levels of knowledge and confidence in its applications but this was declined in comparison when asked for its combination on retrofit.
- Retrofit with offsite measures: The exploration of incentives on retrofit with offsite measures uptake showed that feasible higher quality would have the highest impact followed with feasible lower cost and faster delivery in comparison to onsite construction. On the other hand the main barriers considered were the lack of accessible information on measures followed by regulation and market demand.

RQ .3 What innovations are needed by the industry for 'Whole-House' retrofit practice to have a macro-scale effect in the UK?

There is a current shift momentum on legislation (Bonfield Review and PAS 2035) that focuses more on the quality of delivery in UK housing retrofit than just the set of energy targets. Taking into account the Whole-House approach is the foundation to achieve these objectives; voluntary high energy efficient standards such as EnerPHit encompassing Whole-House retrofit demonstrate that energy reduction and quality go hand-in-hand. It can then be presumed that this is the reason for its stronger presence as the survey demonstrated.

The offsite approaches are also becoming more present in the retrofit sector but as this research showed by exploring their applicability in the pre-1919 housing stock and through the exploration of the industry's perceptions there are barriers but also great potential. Building from existing knowledge and from the main findings of this research a number of recommendations could be made for offsite in retrofit to have a feasible macro-scale effect in the UK housing retrofit sector:

- Accessible data: Accessing data even for this research (apart from the ones used) was challenging and it was also identified as the barrier with the highest impact in the survey. With the introduction of software like RealCosting there is a recognisable beginning on interactive modelling that could be a tool to access retrofit possibilities to be used by designers, retrofit co-ordinators and clients. Offsite construction has an opportunity to take advantage of such tools.
- Clearer focus on feasible benefits: Through the energy and cost modelling in the pre-1919 typologies it was discovered that there could be a series of benefits (cost reduction, payback, comfort, reduced disruption, guarantee of quality construction etc.) that could be tailored on different typologies and locations being incentives for wider uptake.
- Compliance with legislation and clear standards: With the legislation requirements changing (PAS 2035) the offsite market has an excellent opportunity to take advantage of in-house or coordination of specialists that guarantee that the delivery is compliant. Additionally, as per Energiesprong's and Beattie Passive's examples, setting a target (zero bills) or standard (Passive House/EnerPHit) provides a clearer objective on the on feasible benefits.
- Focus on older stock: As stated in the beginning of the thesis there are very few examples of offsite approaches on pre-1919 UK stock. Being the most challenging the one in greater need retrofit more examples of offsite approaches focus on those typologies could provide access to wider markets.
- Economies of scale and economies of scope: Social housing is the most usual starting point for large-scale programmes of deep retrofit. This is practical as retrofit can be done in volume and offsite practices such Beattie Passive and Energiesprong have started their applications with this housing stock. This is a strategy that also reduces the cost i.e. economies of scale that both those examples are aiming for (3.2.1 and 3.2.2) and aspire that this will eventually be replicated in the private sector. Nonetheless, the data shows that the private

occupied and rented sector has the highest percentage of pre-1919 properties that are in the highest need of retrofit (majority of the least efficient properties and fuel poverty). This begs the question whether better policy and funding mechanisms need to for a kick start in this housing stock. Programmes such as Green Deal that targeted homeowners did not succeed because of its over-complexity, high loan interest rates that did not reflect the energy and cost payback from the retrofit upgrades. The cost and energy modelling of this research showed that there are different types of payback along with the fact that offsite mechanisms with consistent standards such as EnerPHit can have reliable results. Therefore if government would subsidize supply led initiatives such offsite mechanisms in retrofit the capital cost would be reduced, these approaches would be more attractive to the private market and their energy assurance would guarantee quality, payback and by extension macro scale impact in the reduction of fuel poverty and carbon emissions. Finally, offsite mechanisms have evolved with technology and examples such as Retrofit for the Future Cottesmore and WHISCERS (3.2.3) show that economies of scope can be applied to meet customised solutions that retrofit requires and especially in older stock that planning restrictions are more usual. This shows that offsite could overcome barriers such as planning or ownership (i.e. visual impact to neighbours from external wall insulation in rows of terrace houses).

7.7 Conclusions

In summary, this research contributed to an increased understanding of the complexities and future possibilities of offsite approaches in the UK industry in conjunction with the high energy efficient standard of EnerPHit applied to pre-1919 dwellings.

In terms of policy implications there has been a shift in beginning to regulate housing retrofit delivery in UK stemming from the Bonfield Review (PAS 2035) that has been a result of previous failures and lessons. The EnerPHit standard as demonstrated in the research modelling has the potential of achieving great energy reductions and monetary payback even if it is in the long run. In terms of how the EnerPHit standard and offsite mechanisms correspond to the future national regulation could be summed up; in transparency and in guarantee.

The research tested first-hand the software RealCosting that stemmed and work in conjunction with the Passive House Planning Package. The standard and by extension its software offers the user the ability to trace inputs and the physics behind them. The RealCosting works with the same principle as PHPP and most importantly is a novel approach in retrofit cost as there is no current equivalent in the UK retrofit market. This is important as it will be able to correspond to the access and awareness of the industry and by extension the consumer on the cost of retrofit in both more detail and in clearer representations.

The guarantee that the offsite mechanisms can offer is the absorption of the unforeseen costs and technical complexities that any energy model cannot actually predict especially in old typologies such as the pre-1919. The quality mark and the consumer protection is an issue that has been at the forefront in the Bonfield Review and will be strongly presented in the future legislation of PAS 2035. So offsite mechanisms have a great opportunity in adapting to this future demand and their presence even if it is still in post 1950’s properties has a sense of “smart regulation” approach. As presented in Greenwood, Congreve and King, (2017) in assessing the UK energy policies: *“Non-mandatory, industry-defined standards of the kind advocated by ‘smart regulation’ are widely viewed as having an important potential supplementary role in driving innovation and fostering consumer engagement, especially in those localities and markets most receptive to environmental sustainability concerns”* (page 496).

7.8 Research limitations and further research

After assessing the energy cost and implications on social/technical aspect of the high energy efficient standard retrofit and its relation to the offsite construction approach there were clear diverse results on cost payback and their determinants. The wide regional differences that expand further from just climatic conditions that effect heat demand have a direct effect not only on actual monetary gain and investment but also on the prospect of regional sustainable markets.

The research acknowledged the limitations of the modelling versus actual implications found on live projects but also understood that the offsite mechanisms could absorb those even if their cost is higher. Therefore, with the same mind-set of previous research (RealCosting co-benefits) of people placing a monetary value on comfort of better/higher internal temperatures would they also be willing to pay more in return of a certified/guarantee energy efficient and fast delivering retrofit that would be come from single coordinator/supplier? How would that differ between UK regions?

With offsite mechanisms in retrofit having a stronger presence in UK with examples such as Energiesprong and Beattie Passive along with software creation such as RealCosting more data and tools are becoming available to quantify the impact offsite has in housing retrofit. Further research with modelling and information from existing and live projects could ensure to realise more transparent quantifiable data of offsite especially in the challenging older UK housing stock.

References

AECB. (2014). *Excess winter deaths and illnesses – guideline consultation*. Retrieved from https://www.aecb.net/publications/aecb-response-nice-national-institute-health-care-excellence-excess-winter-deaths-illnesses-guideline-consultation/

AECB. (2016). BREXIT anyone ? In *AECB 2016 Annual Conference*. Retrieved from https://www.aecb.net/publications/brexit-anyone/

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*. https://doi.org/10.1016/0749-5978(91)90020-T

Association for the Conservation of Energy. (2015). Chilled to Death : The human cost of cold homes, (March), 1–8. Retrieved from http://www.ukace.org/wp-content/uploads/2015/03/ACE-and-EBR-fact-file-2015-03-Chilled-to-death.pdf

Baeli, M. (2013). *Residential Retrofit: 20 Case Studies*. London: RIBA Publishing.

Banks, N., & White, V. (2012). *Evaluation of solid wall insulation in fuel poor households in the private sector Final Report to eaga Charitable Trust*.

Barker, T., Ekins, P., & Foxon, T. (2007). The macro-economic rebound effect and the UK economy. *Energy Policy*, *35*(10), 4935–4946. https://doi.org/10.1016/j.enpol.2007.04.009

BBC. (2018). Grenfell Tower: What happened. Retrieved November 20, 2018, from https://www.bbc.co.uk/news/uk-40301289

Berry, S., Sharp, A., Hamilton, J., & Killip, G. (2014). Inspiring low-energy retrofits: The influence of open home events. *Building Research and Information*, *42*(4), 422–433. https://doi.org/10.1080/09613218.2014.894747

Boardman, B. (2007). *Home truths*. Retrieved from https://www.eci.ox.ac.uk/research/energy/downloads/boardman07-hometruths.pdf

Bonfield, P. (2016). Each Home Counts, (December), 68. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/578749/Each_Home_Counts__December_20

Braun, V., & Clarke, V. (2006). Braun, V ., Clarke, V .Using thematic analysis in psychology., 3:2 (2006), 77-101. *Qualitative Research in Psychology*. https://doi.org/10.1191/1478088706qp063oa

BRE. (2015). *Report on failure rates and remediation costs for External and Cavity Wall Insulation – BRE Client Report 303-500 prepared for Wales Low and Zero Carbon Hub*. Retrieved from http://www.cavityclaimuk.com/bre-report.pdf

BRE. (2016). *Post Installation Performance of Cavity Wall & External Wall Insulation*. Retrieved from http://www.cewales.org.uk/files/3014/7671/0110/Post_Installation_Performance_of_Cavity_Wall__External_Wall_Insulation.pdf

Britnell, J., & Dixon, T. (2011). Retrofitting in the private residential and commercial property sectors – survey findings. *Retrofit 2050 Working Paper*, (November), 1–15.

Brown, D., Kivimaa, P., Sorrell, S., Rogge, K., Nightingale, P., Martin, B., & Bloom, M. (2018). SWPS 2018-19 (October) How Can Intermediaries Promote Business Model Innovation : The Case of ‘ Energiesprong ’ Whole-House Retrofits in the United Kingdom Editorial Assistance, *19*.

Brown, P., Swan, W., & Chahal, S. (2014). Retrofitting social housing: Reflections by tenants on adopting and living with retrofit technology. *Energy Efficiency*, *7*(4), 641–653. https://doi.org/10.1007/s12053-013-9245-3

Bryman, A. (2012). *Social research methods.* (Fifth). Oxford University Press.

BS 5250. (2011). Code of practice for control of condensation in buildings, *3*(1), 100. Retrieved from www.bsigroup.com/standards

BSI. (2017). *PAS 2030:2017 Improving the energy efficiency of existing buildings. Specification for installation process, process management and service provision* (4th ed.). Retrieved from https://shop.bsigroup.com/ProductDetail/?pid=000000000030353572

BSRIA. (2014). *The Soft Landings Framework for better briefing, design, handover and building performance in-use, Building Services Research and Information Association. Bsria Bg 54/2014*. Retrieved from https://www.bsria.co.uk/services/design/soft-landings/

CCC. (2016). *Meeting Carbon Budgets - 2016 Progress Report to Parliament*. Retrieved from https://www.theccc.org.uk/publication/meeting-carbon-budgets-2016-progress-report-to-parliament/

Chiu, L., Lowe, R., Raslan, R., Altamirano-Medina, H., & Wingfield, J. (2014). A socio-technical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit. *Building Research and Information*, *42*(5), 574. https://doi.org/10.1080/09613218.2014.912539

CIBSE. (2005). Guide B : Heating, ventilating, air conditioning and refrigeration. *Chartered Institution of Building Services Engineers*. https://doi.org/10.1016/0016-0032(58)90363-6

CIBSE. (2015). Guide A: Environmental Design. *Chartered Institution of Building Services Engineers*. https://doi.org/10.1016/0360-1323(94)00059-2

Corbetta, P. (2003). *Social Research: Theory, Methods and Techniques*. (PiergiorgioCorbetta, Ed.), *Social research: Theory, methods and techniques*. London: England, London: SAGE Publications, Ltd. https://doi.org/10.4135/9781849209922

Creswell, J. W., & Clark, V. L. P. (2007). *Designing and conducting mixed methods research. Designing and conducting mixed methods research.* Thousand Oaks, CA, US: Sage Publications, Inc.

Crilly, M., & Lemon, M. (2012a). *PreFabhaus-MMC and low carbon housing Modern methods appropriate for hybrid construction*.

Crilly, M., & Lemon, M. (2012b). PreFabhaus – MMC and low carbon housing Modern methods appropriate for hybrid construction-Presentation. Retrieved from file:///C:/Users/user/Downloads/PreFabhausmmcandlowcarbonhousing.pdf

Crilly, M., Lemon, M., Wright, A., Cook, M., & Shaw, D. (2012). Retrofitting Homes for Energy Efficiency: An Integrated Approach to Innovation in the Low-Carbon Overhaul of UK Social Housing. *Energy & Environment*, *23*, 1027–1056. https://doi.org/10.1260/0958-305X.23.6-7.1027

Cross, L. (2016, April). EIB builds HA pipeline Japan closes first HA in face of Brexit debate bilateral deal. *Social Housing*. Retrieved from https://www.socialhousing.co.uk/news/news/european-investment-bank-ha-loans-safe-in-event-of-brexit-25670

DBEIS. (2018). *ECO3 : 2018 - 2022 Final Stage Impact Assessment*. Retrieved from https://www.gov.uk/government/consultations/energy-company-obligation-eco3-2018-to-2022

De-Selincourt, K. (2015). The risks of retrofit. *Green Building*, 28–37. Retrieved from http://www.katedeselincourt.co.uk/wp-content/uploads/2016/01/risks-of-retrofit.pdf

De-Selincourt, K. (2017, August). Grenfell Tower How did it happen? *Passive House Plus Issue 22*, 78–89. Retrieved from https://passivehouseplus.ie/issuu/previous-digital-editions

Deakin, M., Campbell, F., Alasdair, R., & Orsinger, J. (2014). *The Mass Retrofitting of an Energy Efficient— Low Carbon Zone*. SpringerBriefs in Energy.

DECC. (2009). *Five point plan The UK Government has a five point plan*. *Climate Change Act 2008*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/228752/9780108508394.pdf

DECC. (2013). *Housing Energy Fact File*. Retrieved from https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013

DECC. (2014a). *Annual Fuel Poverty Statistics Report , 2014*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/319280/Fuel_Poverty_Report_Final.pdf

DECC. (2014b). *DECC fossil fuel price projections*. Retrieved from https://www.gov.uk/government/publications/fossil-fuel-price-projections-2014

DECC. (2015a). *Annual Fuel Poverty Statistics Report, 2015*. Retrieved from www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2015

DECC. (2015b). *Fuel Poverty Advisory Group (for England), ￼12th Annual Report, 2013-14.* Retrieved from www.gov.uk/government/publications/fuel-poverty-advisory-group-for-england-12th-annual-report-2013-14

DECC. (2015c). *Green Deal and Energy Company Obligation (ECO): headline statistics (November 2015)*. Retrieved from https://www.gov.uk/government/statistics/green-deal-and-energy-company-obligation-eco-headline-statistics-november-2015

DECC. (2015d). *Impact Assessment Summary : Intervention and Options Summary : Analysis & Evidence Policy*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/398546/Warm_Home_Discount_Final_Stage_Impact_Assessment_FINAL.pdf

DECC. (2016). Energy Consumption. *Department for Business Energy & Industrial Stratergy*, (July), 1–39. https://doi.org/10.1016/j.enbuild.2011.12.037

DECC & BRE. (2011). Appendix S : Reduced Data SAP for existing dwellings S, *90*(March), 106–141. Retrieved from http://www.bre.co.uk/filelibrary/accreditation/rdsap_conventions/v4/SAP-2009_9-90_Appendix_S_only_March2011.pdf

DECC & NAO. (2014). *English Housing Survey ENERGY EFFICIENCY OF ENGLISH HOUSING 2012*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/284648/English_Housing_Survey_Headline_Report_2012-13.pdf

DECC & NAO. (2016a). *Green Deal and Energy Company Obligation*. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/477288/Headline_Release_-_GD___ECO_in_GB_19_Nov_Final.pdf

DECC, & National Statistics. (2015). *English Housing Survey*. *English Housing Survey Headline Report 2013-14*. Retrieved from https://www.gov.uk/government/statistics/english-housing-survey-2013-to-2014-headline-report

Departament for Business, E. & I. S. (2017). Annual Fuel Poverty Statistics Report (2015 Data), *2017*(June), 46–55. https://doi.org/10.1007/s10910-011-9944-y

Dowson, M., Poole, A., Harrison, D., & Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy*, *50*, 294–305. https://doi.org/10.1016/j.enpol.2012.07.019

Ecology Building Society. (2017). C-Change Mortgage Discounts | Ecology Building Society. Retrieved November 5, 2017, from https://www.ecology.co.uk/mortgages/c-change-discounts/

Economidou, M., Laustsen, J., Ruyssevelt, P., & Staniaszek, D. Europe's Buildings Under the Microscope, Executive Summary, Buildings Performance Institute Europe (BPIE) § (2011). https://doi.org/ISBN: 9789491143014

Energiesprong. (2015). *Transition Zero Energiesprong*. Retrieved from https://uploads-ssl.webflow.com/59944999990f53000134107e/5bc8766a33d973180b34d58c_ESUK-Transition_Zero_document.pdf

Energiesprong. (2018). SMEs plan for growth as market for Energiesprong retrofits expands. Retrieved December 3, 2018, from https://www.energiesprong.uk/newspage/smes-plan-for-growth-energiesprong

Energiesprong UK. (2018). Nottingham's Energiesprong homes win UK Housing Award for Innovation. Retrieved September 30, 2018, from https://www.energiesprong.uk/newspage/nottinghams-ultra-low-energy-homes-win-national-innovation-award-nch

Episcope. (2014). *Building Typology Brochure England*. Retrieved from http://episcope.eu/fileadmin/tabula/public/docs/brochure/GB_TABULA_TypologyBrochure_BRE.pdf

EST. (2010). *Sustainable Refurbishment*. *Sustainable refurbishment: Towards an 80% reduction in CO2 emissions, water efficiency, waste reduction, and climate change adaptation*. London. https://doi.org/10.1002/9781118387894

EST. (2011). Trigger points: a convenient truth. *EST*, 1–28. Retrieved from http://www.energysavingtrust.org.uk/reports/trigger-points-convenient-truth

Farah, Y. (2015). Government scraps zero carbon target | News | Building. *Building*. Retrieved from https://www.building.co.uk/news/government-scraps-zero-carbon-target/5076456.article

Farmer, M. (2016). The Farmer Review of the UK Construction Labour Model: Modernise or Die. *Construction Leadership Council*, 76. Retrieved from http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf

Fawcett, J. (2014). South West Retrofit Market Analysis Study South West Retrofit Market Analysis Study Project Director : Report Author : David Kenington, (February).

Fawcett, T., & Killip, G. (2014). Anatomy of low carbon retrofits: Evidence from owner-occupied Superhomes. *Building Research and Information*, *42*(4), 434–445. https://doi.org/10.1080/09613218.2014.893162

Fellows, R., & Liu, A. (2015). *Research Methods for Construction* (Fourth edi). United Kingdom: John Wiley & Sons Inc.

Fischer, J., & Guy, S. (2009). Re-interpreting regulations: Architects as intermediaries for low-carbon buildings. *Urban Studies*, *46*(12), 2577–2594. https://doi.org/10.1177/0042098009344228

Foxon, T. (2003). *Inducing innovation for a low-carbon future : Drivers, barriers and policies*. London.

Galvin, R. (2014). Making the “rebound effect” more useful for performance evaluation of thermal retrofits of existing homes: Defining the “energy savings deficit” and the “energy performance gap.” *Energy and Buildings*, *69*, 515–524. https://doi.org/10.1016/j.enbuild.2013.11.004

Gardiner, J. (2015). The Green Deal: “A catastrophe from start to finish” | Magazine Features | Building. *Building*. Retrieved from https://www.building.co.uk/the-green-deal-a-catastrophe-from-start-to-finish/5076906.article

Gaze, C., Ross, K., & Nolan, E. (2007). IP 3/07, Part 3. *BRE*, (Modern methods of construction (MMC) in housing: Designing for manufacture).

Gaze, C., Ross, K., Nolan, E., Novakovic, O., & Cartwright, P. (2007). IP 3/07, Part 1. *BRE*, (Modern methods of construction (MMC) in housing: Drivers and barriers to their use).

Gibb, A. G. F. (1999). *Off-site Fabrication: Prefabrication, Pre-assembly and Modularisation*. John Wiley & Sons. Retrieved from https://books.google.co.uk/books?id=uTiN_aGtXzwC

Gillott, M. C., Loveday, D. L., White, J., Wood, C. J., Chmutina, K., & Vadodaria, K. (2016). Improving the airtightness in an existing UK dwelling: The challenges, the measures and their effectiveness. *Building and Environment*, *95*, 227–239. https://doi.org/10.1016/j.buildenv.2015.08.017

Goodier, C. I., & Gibb, A. G. F. (2005). Barriers and Opportunities for Offsite in the UK. *Abdul Samed Kazi (Ed). Systematic Innovation in the Management of Project and Processes, Cib Helsinki International Joint Symposium*, 148–158. https://doi.org/10.1080/01446190601071821

Gray, D. E. (2014). *Doing Research in the Real World (3rd ed.)*. *SAGE*. https://doi.org/10.1007/s13398-014-0173-7.2

Greenwood, D., Congreve, A., & King, M. (2017). Streamlining or watering down? Assessing the “smartness” of policy and standards for the promotion of low and zero carbon homes in England 2010–15. *Energy Policy*, *110*(December 2016), 490–499. https://doi.org/10.1016/j.enpol.2017.08.033

Guermanova, M., & Arora, P. (2015). Whole-life carbon: Retrofit vs EnerPHit, (June). Retrieved from http://sturgiscarbonprofiling.com/wp-content/uploads/2015/06/Whole-life-carbon-Retrofit-vs-EnerPHit.pdf

Guerra-Santin, O., Tweed, C., Jenkins, H., & Jiang, S. (2013). Monitoring the performance of low energy dwellings: Two UK case studies. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2013.04.002

Gupta, R., & Gregg, M. (2016). Do deep low carbon domestic retrofits actually work? *Energy and Buildings*, *129*, 330–343. https://doi.org/10.1016/j.enbuild.2016.08.010

Gupta, R., Gregg, M., Passmore, S., & Stevens, G. (2015). Intent and outcomes from the Retrofit for the Future programme: Key lessons. *Building Research and Information*, *43*(4), 435–451. https://doi.org/10.1080/09613218.2015.1024042

Guy, S., & Shove, E. (2000). *The Sociology of Energy, Buildings and the Environment: Constructing Knowledge, Designing Practice*. Routledge. Retrieved from https://books.google.co.uk/books?id=FMKAqdv-gWIC

Haas, R., Auer, H., & Biermayr, P. (1998). The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings*. https://doi.org/10.1016/S0378-7788(97)00034-0

Hairstans, R. (2014). *Building offsite: an introduction*. Retrieved from https://www.napier.ac.uk/research-and-innovation/research-search/outputs/building-offsite-an-introduction

Hartman, H. (2014). Code for sustainable homes scrapped. *Architects' Journal*, *240*(23).

Heffernan, E., Pan, W., Liang, X., & de Wilde, P. (2015). Zero carbon homes: Perceptions from the UK construction industry. *Energy Policy*, *79*(2015), 23–36. https://doi.org/10.1016/j.enpol.2015.01.005

Hill, S., & Lorenz, D. (2011). Rethinking professionalism: guardianship of land and resources. *Building Research & Information*, *39*(3), 314–319. https://doi.org/10.1080/09613218.2011.563051

HM Government. The UK Renewable Energy Strategy (2009). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228866/7686.pdf

HM Government. (2013). L1B - Conservation of Fuel and Power in Existing Dwellings. *UK Building Regulations*, 31.

HM Treasury. (2013). The Green Book : Appraisal and Evaluation in Central Government. *Evaluation*, (October 2013), 118. https://doi.org/http://greenbook.treasury.gov.uk/index.htm

HM Treasury. (2017). *Autumn Budget 2017*. Retrieved from https://www.gov.uk/government/publications/autumn-statement-2016-documents/autumn-statement-2016

HM Treasury & BIS. (2015). *Fixing the foundations: creating a more prosperous nation*. Retrieved from https://www.gov.uk/government/publications/fixing-the-foundations-creating-a-more-prosperous-nation

Hope, A. J., & Booth, A. (2014). Attitudes and behaviours of private sector landlords towards the energy efficiency of tenanted homes. *Energy Policy*, *75*, 369–378. https://doi.org/10.1016/j.enpol.2014.09.018

Hopfe, C., & Mcleod, R. (2015). *The Passivhaus Designer's Manual: A technical guide to low and zero energy buildings*. Routledge.

House, W. (2015). Chilled to Death : The human cost of cold homes, (March), 1–8.

Institute for Sustainability. (2012). *Retrofit insights : perspectives for an emerging industry*. Retrieved from http://bob.instituteforsustainability.org.uk/knowledgebank/integratedfindingsreport/Pages/default.aspx

Jackson, T. (2005). *Motivating Sustainable Consumption*. *Sustainable Development Research Network as part of the ESRC Sustainable Technologies Programme Centre for Environmental Strategy*. https://doi.org/10.1260/0958305043026573

Janda, K. (1999). Re-inscribing design work : architects , engineers , and efficiency advocates . In *In Proceedings of the European Council for an Energy Efficient Economy (ECEEE) Summer Study, Mandelieu, France*. Retrieved from https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/1999/Panel_3/p3_11/

Janda, K. B., & Parag, Y. (2013). A middle-out approach for improving energy performance in buildings. *Building Research and Information*, *41*(1), 39–50. https://doi.org/10.1080/09613218.2013.743396

Janda, K., Killip, G., & Fawcett, T. (2014). Reducing Carbon from the "Middle-Out": The Role of Builders in Domestic Refurbishment. *Buildings*, *4*(4), 911–936. https://doi.org/10.3390/buildings4040911

Johnston, D., Farmer, D., Brooke-Peat, M., & Miles-Shenton, D. (2016). Bridging the domestic building fabric performance gap. *Building Research & Information*, *44*(2), 147–159. https://doi.org/10.1080/09613218.2014.979093

Jones, P., Lannon, S., & Patterson, J. (2013). Retrofitting existing housing: how far, how much? *Building Research & Information*, *41*(5), 532–550. https://doi.org/10.1080/09613218.2013.807064

Kaiser, F., Wölfing, S., & Fuhrer, U. (1999). Environmental Attitude and Ecological Behavior. *Journal of Environmental Psychology*. https://doi.org/10.1108/17471111311307787

Kalafatis, S. P., Pollard, M., East, R., & Tsogas, M. H. (1999). Green marketing and Ajzen’s theory of planned behaviour: A cross-market examination. *Journal of Consumer Marketing*, *16*(5), 441–460. https://doi.org/10.1108/07363769910289550

Karvonen, A. (2013). Towards systemic domestic retrofit: a social practices approach. *Building Research & Information*, *41*(5), 563–574. https://doi.org/10.1080/09613218.2013.805298

Kenington, D., Fawcett, J., & Bell, A. (2014). South West Retrofit Market Analysis Study South West Retrofit Market Analysis Study Project Director : Report Author : David Kenington, (February). Retrieved from https://www.winningmoves.com/publications/south-west-retrofit-market-analysis-study-regensw

Killip, G. (2011a). Implications of an 80% CO2 emissions reduction target for small and medium- sized enterprises (SMEs) in the UK housing refurbishment industry. *Environmental Change Institute*, *PhD thesis*(April).

Killip, G. (2011b). Latent market opportunities for low-carbon housing refurbishment. *Energy and People: Futures, Complexity and Challenges (20-21 September 2011)*, (September), 1–12. https://doi.org/http://dx.doi.org/

Killip, G. (2013a). Products, practices and processes: Exploring the innovation potential for low-carbon housing refurbishment among small and medium-sized enterprises (SMEs) in the UK construction industry. *Energy Policy*, *62*, 522–530. https://doi.org/10.1016/j.enpol.2013.06.024

Killip, G. (2013b). Transition management using a market transformation approach: Lessons for theory, research, and practice from the case of low-carbon housing refurbishment in the UK. *Environment and Planning C: Government and Policy*, *31*(5), 876–892. https://doi.org/10.1068/c11336

Krug, D., & Miles, J. (2013). Offsite construction: sustainability characteristics. *Buildoffsite*, (June), 1–18. Retrieved from http://www.buildoffsite.com/outputs/publications/?id=190

Lewis, S. (2014). *PHPP Illustrated: A Designer’s Companion to the Passive House Planning Package*. RIBA Publishing. Retrieved from https://books.google.co.uk/books?id=Aqr8oAEACAAJ

Lomas, K. J. (2010). Carbon reduction in existing buildings: a transdisciplinary approach. *Building Research & Information*, *38*(1), 1–11. https://doi.org/10.1080/09613210903350937

Loveday, D. L., & Vadodaria, K. (2013). *Institutional Repository Project CALEBRE : Consumer Appealing Low Energy technologies for Building REtrofitting : a summary of the project and its findings This item was submitted to Loughborough ' s Institutional Repository (https://dspace.lboro.ac.uk/)*. Retrieved from https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/13132

Lynch, H. (2011). Passivhaus in the UK: The Challenges of an Emerging Market A Case Study of Innovation using Mixed Methods Research, 267–278. Retrieved from http://discovery.ucl.ac.uk/1418470/1/Lynch_Henrietta_Thesis.pdf. Combined.pdf

Macalister, T. (2015). UK solar panel subsidy cuts branded "huge and misguided." *The Guardian*. Retrieved from https://www.theguardian.com/business/2015/dec/17/uk-solar-panel-subsidies-slashed-paris-climate-change

MacLeod, G. (2018). The Grenfell Tower atrocity: Exposing urban worlds of inequality, injustice, and an impaired democracy. *City*, *22*(4), 460–489. https://doi.org/10.1080/13604813.2018.1507099

Madlener, R., & Alcott, B. (2009). Energy rebound and economic growth: A review of the main issues and research needs. *Energy*, *34*(3), 370–376. https://doi.org/10.1016/j.energy.2008.10.011

Mark, L. (2016). Zero carbon homes policy scrapped – again | News | Architects Journal. Retrieved December 24, 2016, from https://www.architectsjournal.co.uk/news/zero-carbon-homes-policy-scrapped-again/10006475.article

Martel, T. (2017). *REALcosting Manual*. Retrieved from http://optimalretrofit.co.uk/

McLeod, E., & Milne, K. (2016). *Brexit Analysis Bulletin Construction & Infrastructure*. Retrieved from https://shepwedd.com/sites/default/files/Construction_Infrastructure_PostRef_Brexit.pdf

Monahan, J., & Powell, J. C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, *43*(1), 179–188. https://doi.org/10.1016/j.enbuild.2010.09.005

Nanyam, V. P. S. N., Sawhney, A., & Gupta, P. A. (2017). Evaluating Offsite Technologies for Affordable Housing. *Procedia Engineering*, *196*(June), 135–143. https://doi.org/10.1016/j.proeng.2017.07.183

NEF. (2015). *Whole House In Situ Carbon and Energy Reduction Solution*. Retrieved from http://www.nef.org.uk/themes/site_themes/agile_records/images/uploads/WHISCERS_Promotional_Leaflet_V9_May_15_One_page_per_sheet.pdf

NEF & EEPB. (2014a). *Breaking barriers. An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan. Literature review and full list of barriers and solutions, March 2014* (Vol. 14). Retrieved from http://www.nef.org.uk/about-us/press-releases/retrofit-industry-task-group-devises-action-plan-to-meet-energy-efficiency

NEF & EEPB. (2014b). *Breaking the barriers: An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan. Summary Report* (Vol. 86). Retrieved from http://www.nef.org.uk/about-us/press-releases/retrofit-industry-task-group-devises-action-plan-to-meet-energy-efficiency

Neroutsou, T. I. (2016). Lifecycle costing of low energy housing refurbishment: A case study of a 7 year retrofit in Chester Road, London. *Energy and Buildings*, *128*, 178–189. https://doi.org/10.1016/j.enbuild.2016.06.040

NHBC. (2015). *Homes through the decades*. NHBC Foundation. Retrieved from http://www.nhbc.co.uk/cms/publish/consumer/NewsandComment/HomesThroughTheDecades.pdf

NHBC. (2016). *Modern Methods of Construction: views from the industry*. *IHS BRE Press*. Retrieved from http://www.nhbcfoundation.org/Publications/Primary-Research/Modern-methods-of-construction-NF70

NICE. (2016). *Preventing excess winter deaths and illness associated with cold homes: Quality Standard*. https://doi.org/ISBN: 978-1-4731-1759-4

Odell, M., & O'Murchu, C. (2017, June 16). What we know and what we do not know about the Grenfell Tower fire. *Financial Times*. Retrieved from https://www.ft.com/content/33a32fec-52b3-11e7-bfb8-997009366969

ONS. (2015). Statistical Bulletin Output in the Construction Industry , February 2015, (April), 1–23.

Pan, W., Dainty, A. R. J., & Gibb, A. G. F. (2004). Managing Innovation : a Focus on Off-Site Production (OSP) in the UK Housebuilding Industry. In *20th Annual ARCOM Conference* (Vol. 2, pp. 823–830). Retrieved from http://www.arcom.ac.uk/-docs/proceedings/ar2004-0823-0830_Pan_Dainty_and_Gibb.pdf

Parag, Y., & Janda, K. B. (2014). More than filler: Middle actors and socio-technical change in the energy system from the "middle-out." *Energy Research and Social Science*, *3*(C), 102–112. https://doi.org/10.1016/j.erss.2014.07.011

Passive House Institute. (2016). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard. *Passive House Institute*, 1–25.

Pelenur, M. (2013a). Retrofitting the domestic built environment : investigating household perspectives towards energy efficiency technologies and behaviour, 1–332. https://doi.org/10.1007/s12053-018-9624-x

Pelenur, M. (2013b). Retrofitting the domestic built environment : investigating household perspectives towards energy efficiency technologies and behaviour.

Pelsmakers, S. (2015). *The Environmental Design Pocketbook*. London: RIBA Publishing.

Pettifor, H., Wilson, C., & Chryssochoidis, G. (2015). The appeal of the green deal: Empirical evidence for the influence of energy efficiency policy on renovating homeowners. *Energy Policy*, *79*, 161–176. https://doi.org/10.1016/j.enpol.2015.01.015

Piroozfar, P. A. E., & Piller, F. T. (2013). *Mass Customisation and Personalisation in Architecture and Construction* (Vol. 9780203437). London: Routledge.

Pitts, A. (2017). Passive House and Low Energy Buildings: Barriers and Opportunities for Future Development within UK Practice. *Sustainability*, *9*(2), 272. https://doi.org/10.3390/su9020272

Powell, J., Monahan, J. L., & Foulds, C. (2015). *Building Futures: Managing energy in the built environment*. Routledge Ltd.

Price, C., Rickaby, P., & Palmer, J. (2017). Energy Efficiency in Buildings Update on Standards development and "Each Home Counts." Retrieved from https://www.bsigroup.com/PageFiles/549554/energy efficiency.pdf

Price, S., & Marincioni, V. (2014). Building Physics A presentation for The Retrofit Academy.

Ransome-Croker, L. (2018). Five ways to cut the cost of your loft conversion – Which? News. Retrieved April 27, 2018, from https://www.which.co.uk/news/2018/04/five-ways-to-cut-the-cost-of-your-loft-conversion/?wgu=5665_116019_15486130706579_7953a42ac9&wgexpiry=1556389070&utm_source=webgains&utm_medium=affiliates&utm_content=49483&source_code=314AGJ

RIBA. (2013). *RIBA plan of work 2013. RIBA: London* (Vol. 6). https://doi.org/ISBN 978 1 85946 519 6

Rickaby, P. (2015, August). Could the death of zero carbon help passive house bloom? *Passive House Plus Issue 12*, 76–77. Retrieved from https://issuu.com/passivehouseplus/docs/passive_house_plus_issue_12__uk_edi

Rickaby, P. (2017a). *Specification for the installation of energy efficiency measures (EEM) in existing buildings*. Retrieved from https://www.nhmf.co.uk/files/dmfile/170501 NHR 03.pdf

Rickaby, P. (2017b, August). GRENFELL TOWER: the end of high rise retrofit? *Passive House Plus Issue 22*, 8. Retrieved from https://passivehouseplus.ie/issuu/previous-digital-editions

Ross, K., Cartwright, P., & Novakovic, O. (2006). *A guide to modern methods of construction. NHBC*. Retrieved from https://www.nhbcfoundation.org/publication/a-guide-to-modern-methods-of-construction/

Royston, S. (2013). *Fact - file : The Cold Man of Europe*. Retrieved from https://www.ukace.org/wp-content/uploads/2013/03/ACE-and-EBR-fact-file-2013-03-Cold-man-of-Europe.pdf

Saint-Gobain. (2016). The UK Home, Health and Wellbeing Report 2016. Retrieved from https://multicomfort.saint-gobain.co.uk/media/1163/saint-gobain-research-home-health-and-wellbeing-report-2016-full-report.pdf

Schiellerup, P., & Gwilliam, J. (2009). Social Production of Desirable Space: An Exploration of the Practice and Role of Property Agents in the UK Commercial Property Market. *Environment and Planning C: Government and Policy*, *27*(5), 801–814. https://doi.org/10.1068/c08102

Schoenefeldt, H. (2014). Interrogating the technical, economic and cultural challenges of delivering the PassivHaus standard in the UK. Retrieved from https://kar.kent.ac.uk/44559/1/PassivHaus_UK_eBook.pdf

Shrubsole, C., Macmillan, a., Davies, M., & May, N. (2014). 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock. *Indoor and Built Environment*, *23*(3), 340–352. https://doi.org/10.1177/1420326X14524586

Simpson, J. (2016, August 2). Brexit fallout: construction activity drops to seven-year low. *The Architect's Journal*. Retrieved from https://www.architectsjournal.co.uk/news/brexit-fallout-construction-activity-drops-to-seven-year-low/10009436.article

Simpson, S., Banfill, P., Haines, V., Mallaband, B., & Mitchell, V. (2015). Energy-led domestic retrofit: impact of the intervention sequence. *Building Research & Information*, *3218*(February 2015), 1–19. https://doi.org/10.1080/09613218.2014.996360

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect : A review, *37*, 1356–1371. https://doi.org/10.1016/j.enpol.2008.11.026

Stafford, A., Gorse, C. A., & Shao, L. (2011). *The Retrofit Challenge: Delivering Low Carbon Buildings*. *Research Insights into Building Retrofit for the UK*. Retrieved from https://www.leedsbeckett.ac.uk/as/cebe/projects/retrofit_challenge.pdf

Stieß, I., & Dunkelberg, E. (2013). Objectives, barriers and occasions for energy efficient refurbishment by private homeowners. *Journal of Cleaner Production*, *48*, 250–259. https://doi.org/10.1016/j.jclepro.2012.09.041

Stone, A., Shipworth, D., Biddulph, P., & Oreszczyn, T. (2014). Key factors determining the energy rating of existing English houses. *Building Research and Information*, *42*(6), 725–738. https://doi.org/10.1080/09613218.2014.905383

Swan, W., Ruddock, L., & Smith, L. (2013). Low carbon retrofit: attitudes and readiness within the social housing sector. *Engineering, Construction and Architectural Management*, *20*(5), 522–535. https://doi.org/10.1108/ECAM-12-2012-0112

Tahir, F., Walker, I., & Rivers, W. (2015). *Review of potential for carbon savings from residential energy efficiency - Final report for The Committee on Climate Change*. Retrieved from www.theccc.org.uk/publication/fourth-carbon-budget-review/review-of-potential-for-carbon-savings-from-residential-energy-efficiency-final-report-a-160114/

Taylor, S. (2009). *Offsite Production in the UK Construction Industry, a brief overview*. Retrieved from https://www.buildoffsite.com/content/uploads/2015/04/HSE-off-site_production_june09.pdf

The Technology Strategy Board. (2013). Retrofit Revealed, 32. Retrieved from http://www.retrofitanalysis.org/

The Technology Strategy Board. (2014). Retrofit for the Future - analysis of cost data report 2014. Retrieved from https://www.innovateuk.org/documents/1524978/1866952/Retrofit for the Future - analysis of cost data report 2014

Thompson, M., Cooper, I., Gething, B., Gale, J. F., Architects, S., Gale, D. G., & Architects, S. (2015). *The business case for adapting buildings to climate change : Niche or mainstream ?*

Thorpe, D. (2010). *Sustainable home refurbishment: The earthscan expert guide to retrofitting homes for efficiency*. *Sustainable Home Refurbishment: The Earthscan Expert Guide to Retrofitting Homes for Efficiency*. Routledge. https://doi.org/10.4324/9781849776523

Thorpe, D. (2016). English parliament at war over zero carbon homes - The Fifth Estate. Retrieved September 29, 2016, from https://www.thefifthestate.com.au/business/government/english-parliament-at-war-over-zero-carbon-homes/

Thu, L., & Kaufmann, B. (2016). Economic Passive House buildings. In *International Financial Workshop in Frankfurt, Germany*. Retrieved from https://europhit.eu/downloads

Topouzi, M. (2015). *Occupants' interaction with low-carbon retrofitted homes and its impact on energy use. Unpublished DPhil, Environmental Change Institute, University of Oxford, Oxford*. https://doi.org/http://dx.doi.org/

Topouzi, Marina. (2013). Low-carbon refurbishments : How passive or active are technologies , users and their interaction ? *Eceee*, (December), 2297–2309.

Topouzi, Marina. (2016). *Occupants' interaction with low-carbon retrofitted homes and its impact on energy use*. University of Oxford.

Topouzi, Marina, Killip, G., & Owen, A. (2017). *`Learning from "horror" stories: a plan of work to reduce the performance gap in deep retrofit Marina*. *PLEA Conference Proceedings: Design to Thrive* (Vol. I).

Torgal et al. (2013). *Nearly Zero Energy Building Refurbishment*. *Springer*. https://doi.org/10.1007/978-1-4471-5523-2

Trochim, W. M. (2016). Social Research Methods Knowledge Base. Retrieved October 31, 2017, from http://www.socialresearchmethods.net/kb/dedind.php

Tweed, C. (2013). Socio-technical issues in dwelling retrofit. *Building Research & Information*, *41*(5), 551–562. https://doi.org/10.1080/09613218.2013.815047

UK Green Building Council. (2018, June 25). Nottingham first to adopt revolutionary energiesprong housing approach. Retrieved September 30, 2018, from https://www.ukgbc.org/news/nottingham-first-to-adopt-revolutionary-energiesprong-housing-approach/

UKGBC. (2013). Retrofit Incentives, Boosting take-up of energy efficiency measures in domestic properties. Retrieved from https://www.ukgbc.org/sites/default/files/130705%2520Retrofit%2520Incentives%2520Task%2520Group%2520-%2520Report%2520FINAL_1.pdf

Vaughan, A. (2016). UK solar power installations plummet after government cuts | Environment | The Guardian. *The Guardian*. Retrieved from https://www.theguardian.com/environment/2016/apr/08/solar-installation-in-british-homes-falls-by-three-quarters-after-subsidy-cuts

Venables, T., Barlow, J., & Gann, D. (2004). The Housing Forum Manufacturing Excellence Building Performance Group.

Washan, P., & Cole, C. (2012). *Financial modelling in-depth findings*. Retrieved from file:///C:/Users/Will/SkyDrive/4. Research, Reports and Documents/Policy and Guidance/Affinity Sutton - April 2012 - Future Fit - Detailed finance report.pdf

Washan, P., Stenning, J., & Goodman, M. (2014). Building the Future: The economic and fiscal impacts of making homes energy efficient, 44.

Waterson, E. (2005). How can whole house fiscal measures encourage consumers to improve the energy efficiency of their homes ?, 1507–1513. Retrieved from http://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2005c/Panel_7/7166waterson/paper

World Health Organization. (1987). *Health Impact of Low Indoor Temperatures: Report on a WHO Meeting : Copenhagen, 11-14 November 1985*. World Health Organization, Regional Office for Europe. Retrieved from www.theclaymoreproject.com/uploads/associate/365/file/Health Documents/WHO%0A -%0A health impact of low indoor temperatures (WHO, 1985).pdf

WRAP. (2016). *Survey using laser measurement*. Retrieved from http://www.wrap.org.uk/system/files/private/Refurbishment Resource Efficiency Case Study_Residential_United House.pdf

WRAP. (2009). *Benefits of off site manufacture*. Retrieved from http://www.wrap.org.uk/sites/files/wrap/APS - FINAL.pdf

Zero Carbon Hub. (2014). *Closing the gap between Design & As Built Performance Evidence Review Report. Zero Carbon Hub*. https://doi.org/10.1136/bmj.a1770

Zimmermann, M. (2012). *Project Summary Report Prefabricated Systems for Low Energy Renovation of Residential Buildings*. ECBCS.

Appendices

Appendix A – Typology Examples

Below are plans and front elevation examples of the typologies used in the energy and cost modelling. The drawings are not to scale.

Figure A.1 *Detached example*

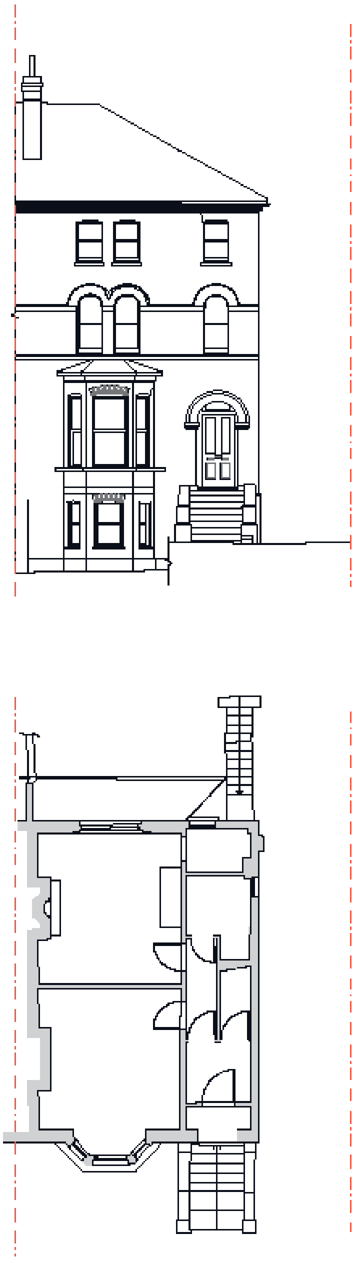


Figure A.2 Semi-Detached example

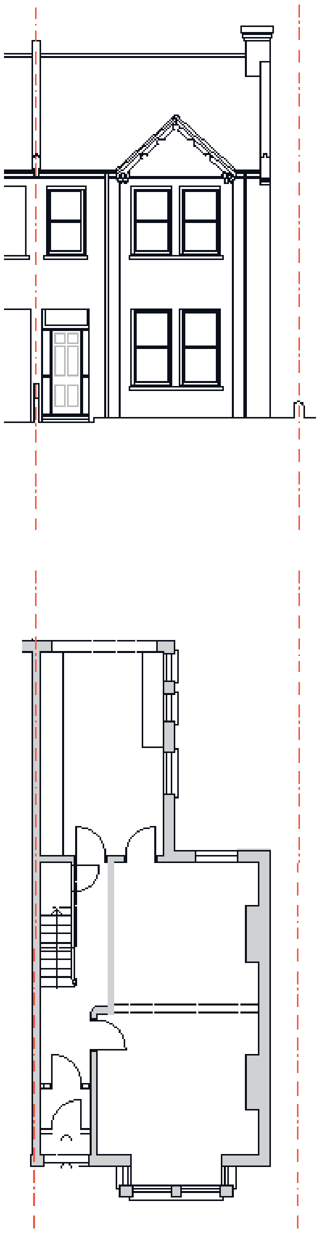


Figure A.3 *End-Terrace example*

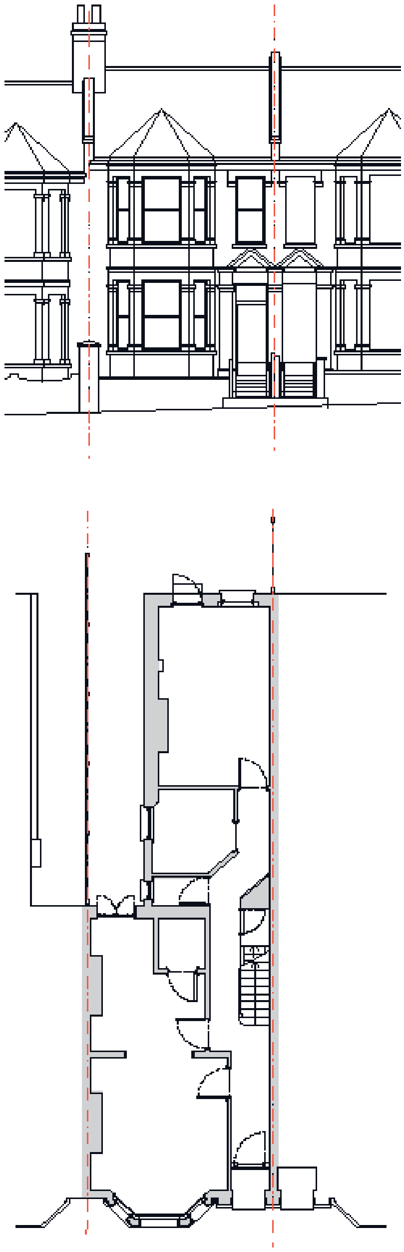


Figure A.4 *Terrace-Bay example*

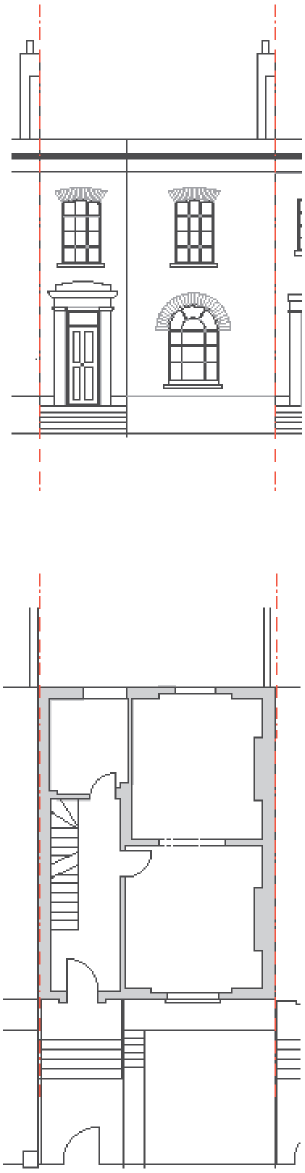
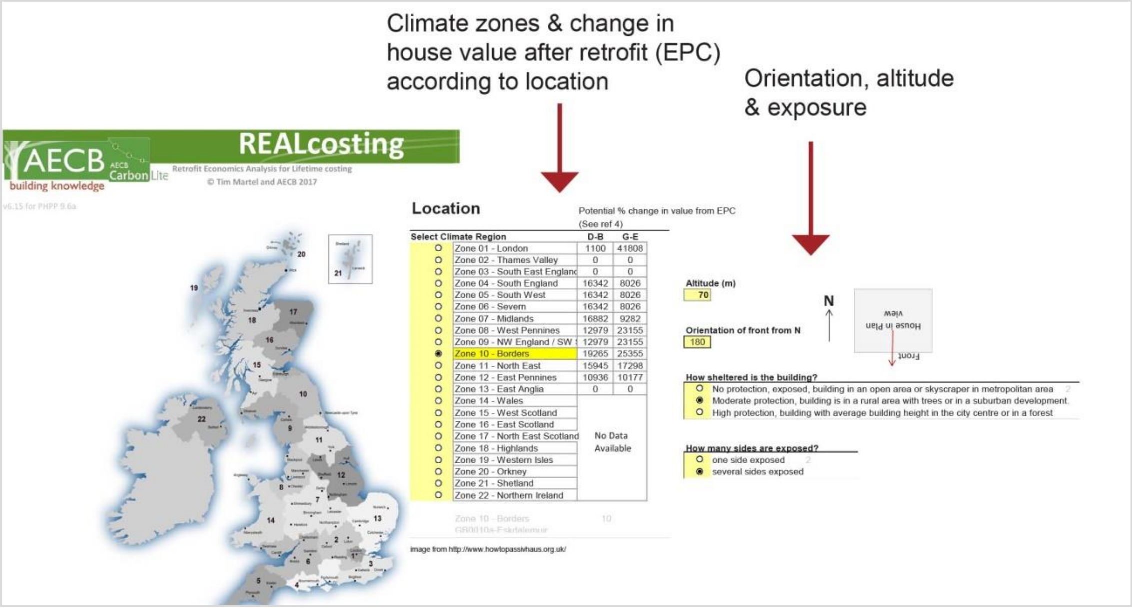


Figure A.5 *Terrace-Flat example*

Appendix B – RealCosting modelling process



Climate zones & change in house value after retrofit (EPC) according to location

Orientation, altitude & exposure

Retrofit Economics Analysis for Lifetime costing

© Tim Martel and AECB 2017

v6.15 for PHPP 9.6a

Location

Potential % change in value from EPC (See ref 4)

Select Climate Region		D-B	G-E
○	Zone 01 - London	1100	41808
○	Zone 02 - Thames Valley	0	0
○	Zone 03 - South East England	0	0
○	Zone 04 - South England	16342	8026
○	Zone 05 - South West	16342	8026
○	Zone 06 - Severn	16342	8026
○	Zone 07 - Midlands	16882	9282
○	Zone 08 - West Pennines	12979	23155
○	Zone 09 - NW England / SW S	12979	23155
●	Zone 10 - Borders	19265	25355
○	Zone 11 - North East	15945	17298
○	Zone 12 - East Pennines	10936	10177
○	Zone 13 - East Anglia	0	0
○	Zone 14 - Wales	No Data Available	
○	Zone 15 - West Scotland		
○	Zone 16 - East Scotland		
○	Zone 17 - North East Scotland		
○	Zone 18 - Highlands		
○	Zone 19 - Western Isles		
○	Zone 20 - Orkney		
○	Zone 21 - Shetland		
○	Zone 22 - Northern Ireland		

Zone 10 - Borders 10
GB0010a-Eskdalemuir

image from http://www.howtopassivhaus.org.uk/

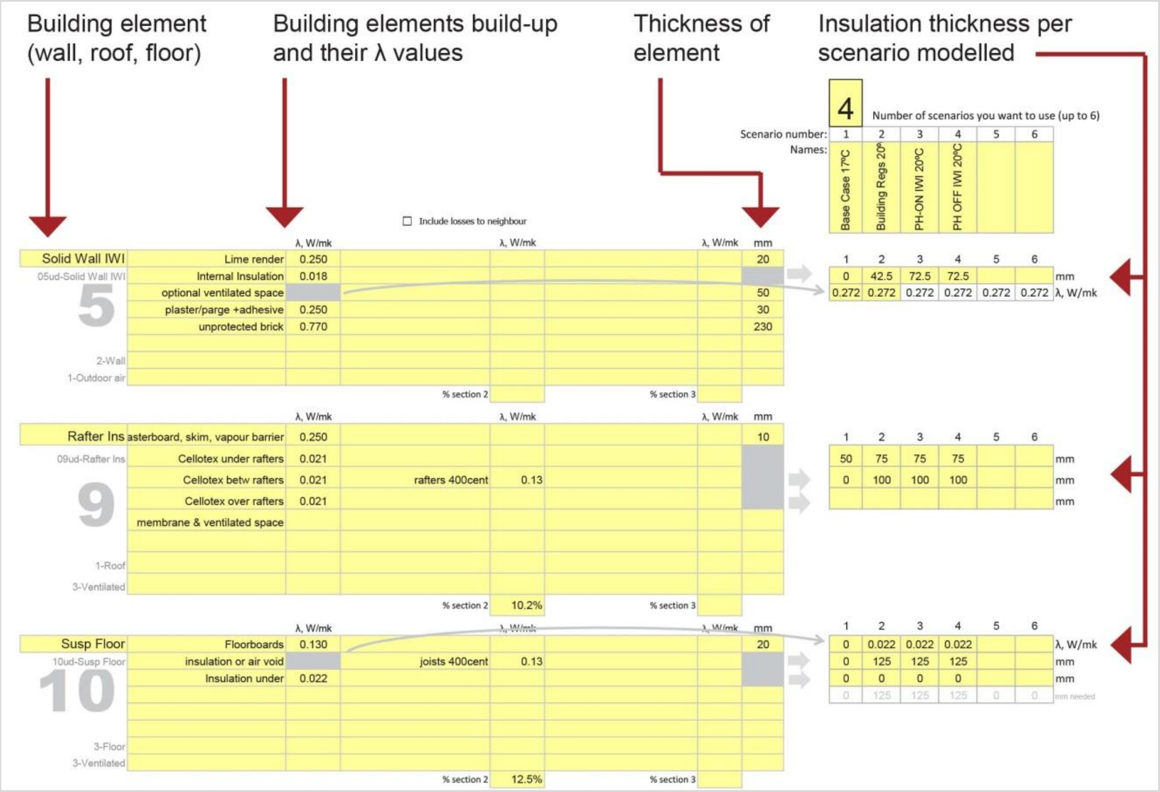
Altitude (m)
70

Orientation of front from N
180

How sheltered is the building?
- ○ No protection, exposed, building in an open area or skyscraper in metropolitan area 2
- ● Moderate protection, building is in a rural area with trees or in a suburban development.
- ○ High protection, building with average building height in the city centre or in a forest

How many sides are exposed?
- ○ one side exposed 2
- ● several sides exposed

Figure B.1 *Location & Climate data input*



Building element (wall, roof, floor)

Building elements build-up and their λ values

Thickness of element

Insulation thickness per scenario modelled

4 Number of scenarios you want to use (up to 6)

Scenario number:	1	2	3	4	5	6
Names:	Base Case 17ºC	Building Regs 20º	PH-ON IWI 20ºC	PH OFF IWI 20ºC		

☐ Include losses to neighbour

		λ, W/mk		λ, W/mk		λ, W/mk	mm
Solid Wall IWI	Lime render	0.250					20
05ud-Solid Wall IWI	Internal Insulation	0.018					
5	optional ventilated space						50
	plaster/parge +adhesive	0.250					30
	unprotected brick	0.770					230
2-Wall							
1-Outdoor air							

% section 2 % section 3

1	2	3	4	5	6	
0	42.5	72.5	72.5			mm
0.272	0.272	0.272	0.272	0.272	0.272	λ, W/mk

		λ, W/mk		λ, W/mk		λ, W/mk	mm
Rafter Ins	asterboard, skim, vapour barrier	0.250					10
09ud-Rafter Ins	Cellotex under rafters	0.021					
9	Cellotex betw rafters	0.021	rafters 400cent	0.13			
	Cellotex over rafters	0.021					
	membrane & ventilated space						
1-Roof							
3-Ventilated							

% section 2 10.2% % section 3

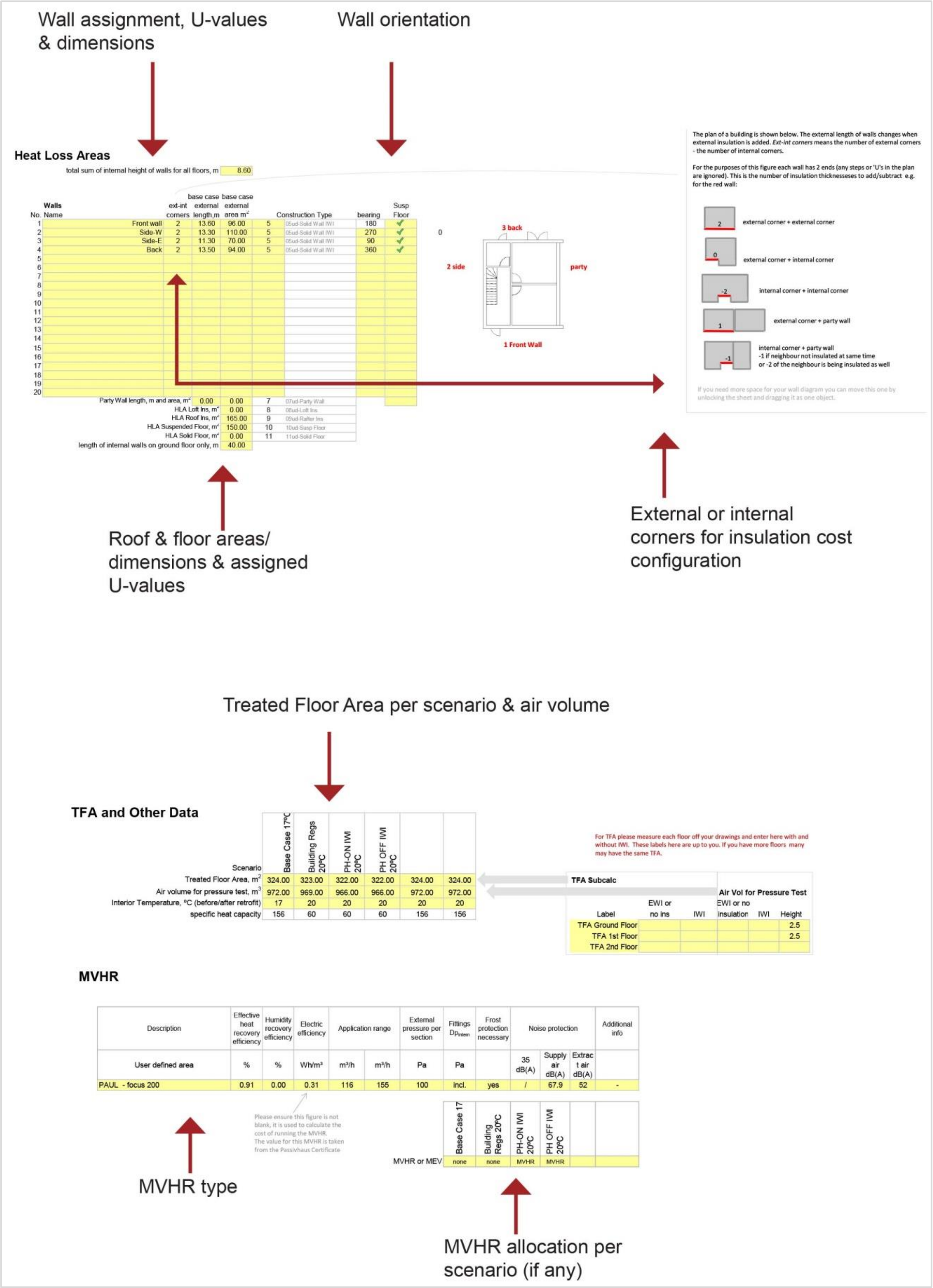
1	2	3	4	5	6	
50	75	75	75			mm
0	100	100	100			mm
						mm

		λ, W/mk		λ, W/mk		λ, W/mk	mm
Susp Floor	Floorboards	0.130					20
10ud-Susp Floor	insulation or air void		joists 400cent	0.13			
10	Insulation under	0.022					
3-Floor							
3-Ventilated							

% section 2 12.5% % section 3

1	2	3	4	5	6	
0	0.022	0.022	0.022			λ, W/mk
0	125	125	125			mm
0	0	0	0			mm
0	125	125	125	0	0	mm needed

Figure B.2 *U-values input*



Heat Loss Areas

total sum of internal height of walls for all floors, m 8.60

Walls No.	Name	ext-int corners	base case external length,m	base case external area m²		Construction Type	bearing	Susp Floor
1	Front wall	2	13.60	96.00	5	05ud-Solid Wall IWI	180	✓
2	Side-W	2	13.30	110.00	5	05ud-Solid Wall IWI	270	✓
3	Side-E	2	11.30	70.00	5	05ud-Solid Wall IWI	90	✓
4	Back	2	13.50	94.00	5	05ud-Solid Wall IWI	360	✓
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
	Party Wall length, m and area, m²		0.00	0.00	7	07ud-Party Wall		
	HLA Loft Ins, m²			0.00	8	08ud-Loft Ins		
	HLA Roof Ins, m²			165.00	9	09ud-Rafter Ins		
	HLA Suspended Floor, m²			150.00	10	10ud-Susp Floor		
	HLA Solid Floor, m²			0.00	11	11ud-Solid Floor		
	length of internal walls on ground floor only, m			40.00				

The plan of a building is shown below. The external length of walls changes when external insulation is added. *Ext-int corners* means the number of external corners - the number of internal corners.

For the purposes of this figure each wall has 2 ends (any steps or 'U's in the plan are ignored). This is the number of insulation thicknesseses to add/subtract e.g. for the red wall:

external corner + external corner

external corner + internal corner

internal corner + internal corner

external corner + party wall

internal corner + party wall
-1 if neighbour not insulated at same time
or -2 of the neighbour is being insulated as well

If you need more space for your wall diagram you can move this one by unlocking the sheet and dragging it as one object.

TFA and Other Data

Scenario	Base Case 17ºC	Building Regs 20ºC	PH-ON IWI 20ºC	PH OFF IWI 20ºC		
Treated Floor Area, m²	324.00	323.00	322.00	322.00	324.00	324.00
Air volume for pressure test, m³	972.00	969.00	966.00	966.00	972.00	972.00
Interior Temperature, ºC (before/after retrofit)	17	20	20	20	20	20
specific heat capacity	156	60	60	60	156	156

For TFA please measure each floor off your drawings and enter here with and without IWI. These labels here are up to you. If you have more floors many may have the same TFA.

TFA Subcalc			**Air Vol for Pressure Test**		
Label	EWI or no ins	IWI	EWI or no insulation	IWI	Height
TFA Ground Floor					2.5
TFA 1st Floor					2.5
TFA 2nd Floor					

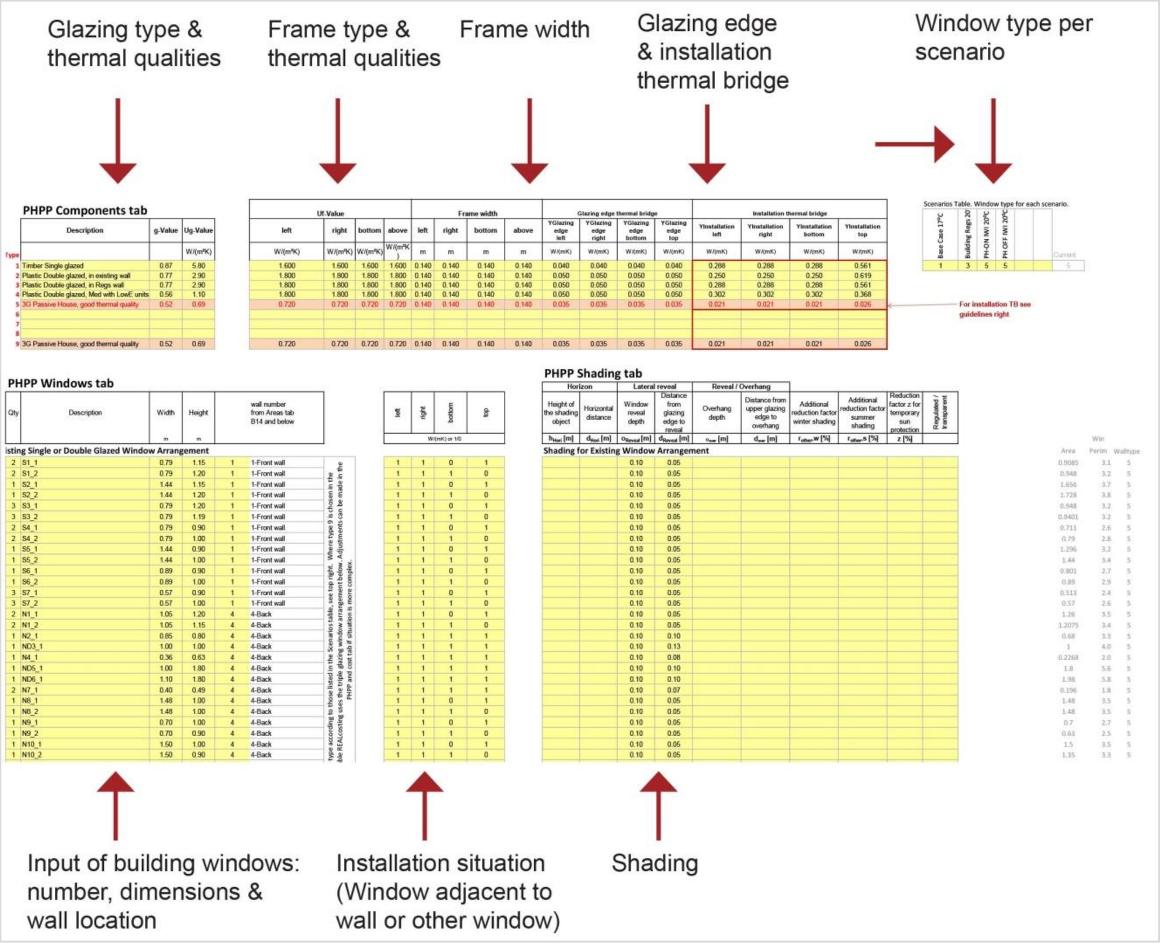
MVHR

Description	Effective heat recovery efficiency	Humidity recovery efficiency	Electric efficiency	Application range		External pressure per section	Fittings Dp_{intern}	Frost protection necessary	Noise protection			Additional info
User defined area	%	%	Wh/m³	m³/h	m³/h	Pa	Pa		35 dB(A)	Supply air dB(A)	Extract air dB(A)	
PAUL - focus 200	0.91	0.00	0.31	116	155	100	incl.	yes	/	67.9	52	-

Please ensure this figure is not blank, it is used to calculate the cost of running the MVHR.
The value for this MVHR is taken from the Passivhaus Certificate

	Base Case 17	Building Regs 20ºC	PH-ON IWI 20ºC	PH OFF IWI 20ºC		
MVHR or MEV	none	none	MVHR	MVHR		

***Figure B.3** Areas input*



PHPP Components tab

Type	Description	g-Value	Ug-Value	Uf-Value left	Uf-Value right	Uf-Value bottom	Uf-Value above	Frame width left	Frame width right	Frame width bottom	Frame width above	Glazing edge thermal bridge: YGlazing edge left	YGlazing edge right	YGlazing edge bottom	YGlazing edge top	Installation thermal bridge: YInstallation left	YInstallation right	YInstallation bottom	YInstallation top
			W/(m²K)	W/(m²K)	W/(m²K)	W/(m²K)	W/(m²K)	m	m	m	m	W/(mK)	W/(mK)	W/(mK)	W/(mK)	W/(mK)	W/(mK)	W/(mK)	W/(mK)
1	Timber Single glazed	0.87	5.80	1.600	1.600	1.600	1.600	0.140	0.140	0.140	0.140	0.040	0.040	0.040	0.040	0.288	0.288	0.288	0.561
2	Plastic Double glazed, in existing wall	0.77	2.90	1.800	1.800	1.800	1.800	0.140	0.140	0.140	0.140	0.050	0.050	0.050	0.050	0.250	0.250	0.250	0.619
3	Plastic Double glazed, in Regs wall	0.77	2.90	1.800	1.800	1.800	1.800	0.140	0.140	0.140	0.140	0.050	0.050	0.050	0.050	0.288	0.288	0.288	0.561
4	Plastic Double glazed, Med with LowE units	0.56	1.10	1.800	1.800	1.800	1.800	0.140	0.140	0.140	0.140	0.050	0.050	0.050	0.050	0.302	0.302	0.302	0.368
5	3G Passive House, good thermal quality	0.52	0.69	0.720	0.720	0.720	0.720	0.140	0.140	0.140	0.140	0.035	0.035	0.035	0.035	0.021	0.021	0.021	0.026
6																			
7																			
8																			
9	3G Passive House, good thermal quality	0.52	0.69	0.720	0.720	0.720	0.720	0.140	0.140	0.140	0.140	0.035	0.035	0.035	0.035	0.021	0.021	0.021	0.026

For installation TB see guidelines right

Scenarios Table. Window type for each scenario.

Base Case 17ºC	Building Regs 20'	PH-ON IWI 20ºC	PH OFF IWI 20ºC			Current
1	3	5	5			5

PHPP Windows tab

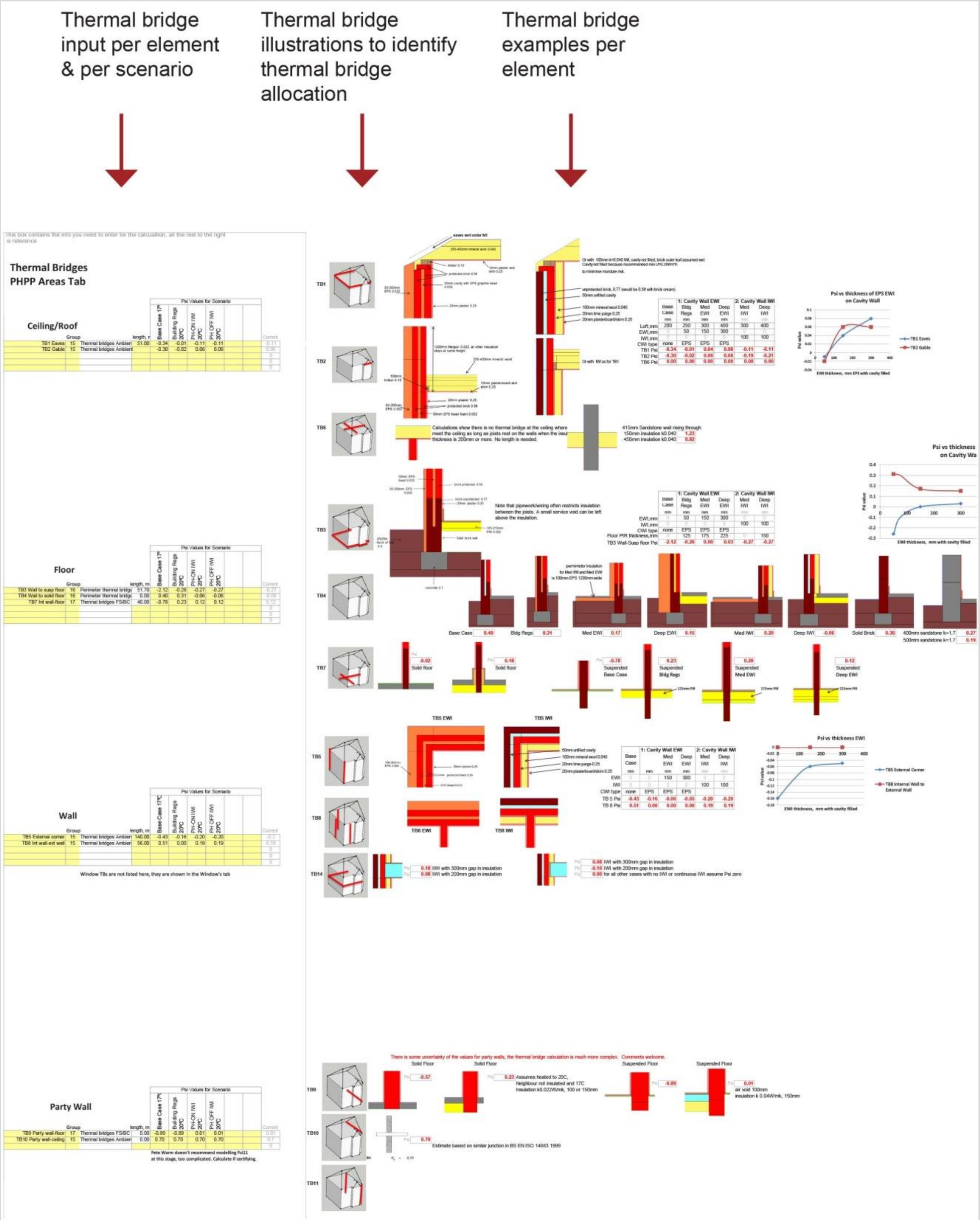
Qty	Description	Width m	Height m	wall number from Areas tab B14 and below		left	right	bottom	top
						W/(mK) or 1/0			
isting Single or Double Glazed Window Arrangement									
2	S1_1	0.79	1.15	1	1-Front wall	1	1	0	1
2	S1_2	0.79	1.20	1	1-Front wall	1	1	1	0
1	S2_1	1.44	1.15	1	1-Front wall	1	1	0	1
1	S2_2	1.44	1.20	1	1-Front wall	1	1	1	0
3	S3_1	0.79	1.20	1	1-Front wall	1	1	0	1
3	S3_2	0.79	1.19	1	1-Front wall	1	1	1	0
2	S4_1	0.79	0.90	1	1-Front wall	1	1	0	1
2	S4_2	0.79	1.00	1	1-Front wall	1	1	1	0
1	S5_1	1.44	0.90	1	1-Front wall	1	1	0	1
1	S5_2	1.44	1.00	1	1-Front wall	1	1	1	0
1	S6_1	0.89	0.90	1	1-Front wall	1	1	0	1
1	S6_2	0.89	1.00	1	1-Front wall	1	1	1	0
3	S7_1	0.57	0.90	1	1-Front wall	1	1	0	1
3	S7_2	0.57	1.00	1	1-Front wall	1	1	1	0
2	N1_1	1.05	1.20	4	4-Back	1	1	0	1
2	N1_2	1.05	1.15	4	4-Back	1	1	1	0
1	N2_1	0.85	0.80	4	4-Back	1	1	1	1
1	ND3_1	1.00	1.00	4	4-Back	1	1	1	1
1	N4_1	0.36	0.63	4	4-Back	1	1	1	1
1	ND5_1	1.00	1.80	4	4-Back	1	1	1	1
1	ND6_1	1.10	1.80	4	4-Back	1	1	1	1
2	N7_1	0.40	0.49	4	4-Back	1	1	1	1
1	N8_1	1.48	1.00	4	4-Back	1	1	0	1
1	N8_2	1.48	1.00	4	4-Back	1	1	1	0
1	N9_1	0.70	1.00	4	4-Back	1	1	0	1
1	N9_2	0.70	0.90	4	4-Back	1	1	1	0
1	N10_1	1.50	1.00	4	4-Back	1	1	0	1
1	N10_2	1.50	0.90	4	4-Back	1	1	1	0

type according to those listed in the Scenarios table, see top right. Where type 9 is chosen in the
ble REALcosting uses the triple glazing window arrangement below. Adjustments can be made in the
PHPP and cost tab if situation is more complex.

PHPP Shading tab

Horizon: Height of the shading object	Horizon: Horizontal distance	Lateral reveal: Window reveal depth	Lateral reveal: Distance from glazing edge to reveal	Reveal / Overhang: Overhang depth	Reveal / Overhang: Distance from upper glazing edge to overhang	Additional reduction factor winter shading	Additional reduction factor summer shading	Reduction factor z for temporary sun protection	Regulated / transparent		Area	Win Perim	Walltype
h_{Hori} [m]	d_{Hori} [m]	o_{Reveal} [m]	d_{Reveal} [m]	o_{over} [m]	d_{over} [m]	$r_{other,w}$ [%]	$r_{other,s}$ [%]	z [%]					
Shading for Existing Window Arrangement													
		0.10	0.05								0.9085	3.1	5
		0.10	0.05								0.948	3.2	5
		0.10	0.05								1.656	3.7	5
		0.10	0.05								1.728	3.8	5
		0.10	0.05								0.948	3.2	5
		0.10	0.05								0.9401	3.2	5
		0.10	0.05								0.711	2.6	5
		0.10	0.05								0.79	2.8	5
		0.10	0.05								1.296	3.2	5
		0.10	0.05								1.44	3.4	5
		0.10	0.05								0.801	2.7	5
		0.10	0.05								0.89	2.9	5
		0.10	0.05								0.513	2.4	5
		0.10	0.05								0.57	2.6	5
		0.10	0.05								1.26	3.5	5
		0.10	0.05								1.2075	3.4	5
		0.10	0.10								0.68	3.3	5
		0.10	0.13								1	4.0	5
		0.10	0.08								0.2268	2.0	5
		0.10	0.10								1.8	5.6	5
		0.10	0.10								1.98	5.8	5
		0.10	0.07								0.196	1.8	5
		0.10	0.05								1.48	3.5	5
		0.10	0.05								1.48	3.5	5
		0.10	0.05								0.7	2.7	5
		0.10	0.05								0.63	2.5	5
		0.10	0.05								1.5	3.5	5
		0.10	0.05								1.35	3.3	5

***Figure B.4** Window type, morphology & location input*


Thermal bridge input per element & per scenario

Thermal bridge illustrations to identify thermal bridge allocation

Thermal bridge examples per element

This box contains the info you need to enter for the calcuation, all the rest to the right is reference

Thermal Bridges
PHPP Areas Tab

Ceiling/Roof

	Group		length, m	Psi Values for Scenario Base Case 17°C	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C			Current
TB1 Eaves	15	Thermal bridges Ambien	51.00	-0.34	-0.01	-0.11	-0.11			-0.11
TB2 Gable	15	Thermal bridges Ambient		-0.30	-0.02	0.06	0.06			0.06
										0
										0
										0

Floor

	Group		length, m	Psi Values for Scenario Base Case 17°C	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C			Current
TB3 Wall to susp floor	16	Perimeter thermal bridge	51.70	-2.12	-0.26	-0.27	-0.27			-0.27
TB4 Wall to solid floor	16	Perimeter thermal bridge	0.00	0.40	0.31	-0.06	-0.06			-0.06
TB7 Int wall-floor	17	Thermal bridges FS/BC	40.00	-0.78	0.23	0.12	0.12			0.12
										0
										0
										0

Wall

	Group		length, m	Psi Values for Scenario Base Case 17°C	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C			Current
TB5 External corner	15	Thermal bridges Ambien	140.00	-0.43	-0.16	-0.20	-0.20			-0.2
TB8 Int wall-ext wall	15	Thermal bridges Ambien	56.00	0.51	0.00	0.19	0.19			0.19
										0
										0
										0

Window TBs are not listed here, they are shown in the Window's tab

Party Wall

	Group		length, m	Psi Values for Scenario Base Case 17°C	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C			Current
TB9 Party wall-floor	17	Thermal bridges FS/BC	0.00	-0.89	-0.89	0.01	0.01			0.01
TB10 Party wall-ceiling	15	Thermal bridges Ambien	0.00	0.70	0.70	0.70	0.70			0.7
										0

Pete Warm doesn't recommend modelling Psi11 at this stage, too complicated. Calculate if certifying.

TB1

Or with 100mm k=0.040 IWI, cavity not filled, brick outer leaf assumed wet
Cavity not filled because recommended min U=0.3W/m²K
to minimise moisture risk

unprotected brick, 0.77 (would be 0.56 with brick cream)
50mm unfilled cavity
100mm mineral wool 0.040
20mm lime parge 0.25
20mm plasterboard/skim 0.25

TB2

Or with IWI as for TB1

	Base Case	1: Cavity Wall EWI Bldg Regs	Med EWI	Deep EWI	2: Cavity Wall IWI Med IWI	Deep IWI
	mm	mm	mm	mm	mm	mm
Loft,mm	200	250	300	400	300	400
EWI,mm	0	50	150	300	0	0
IWI,mm	0	0	0	0	100	100
CWI type	none	EPS	EPS	EPS		
TB1 Psi	-0.34	-0.01	0.04	0.08	-0.11	-0.11
TB2 Psi	-0.30	-0.02	0.06	0.06	-0.19	-0.21
TB6 Psi	0.00	0.00	0.00	0.00	0.00	0.00

TB6

Calculations show there is no thermal bridge at the ceiling where meet the ceiling as long as joists rest on the walls when the insul thickness is 200mm or more. No length is needed.

415mm Sandstone wall rising through
150mm insulation k0.040 1.23
450mm insulation k0.040 0.82

TB3

Note that pipework/wiring often restricts insulation between the joists. A small service void can be left above the insulation.

	Base Case	1: Cavity Wall EWI Bldg Regs	Med EWI	Deep EWI	2: Cavity Wall IWI Med IWI	Deep IWI
	mm	mm	mm	mm	mm	mm
EWI,mm	0	50	150	300	0	0
IWI,mm	0	0	0	0	100	100
CWI type	none	EPS	EPS	EPS		
Floor PIR thickness,mm	0	125	175	225	0	150
TB3 Wall-Susp floor Psi	-2.12	-0.26	0.00	0.03	-0.27	-0.27

TB4

perimeter insulation for Med IWI and Med EWI is 100mm EPS 1200mm wide

Base Case	0.40
Bldg Regs	0.31
Med EWI	0.17
Deep EWI	0.15
Med IWI	0.20
Deep IWI	-0.06
Solid Brick	0.36
400mm sandstone k=1.7	0.27
500mm sandstone k=1.7	0.19

TB7

Psi	
-0.02	Solid floor
0.18	Solid floor
-0.78	Suspended Base Case
0.23	Suspended Bldg Regs
0.20	Suspended Med EWI
0.12	Suspended Deep EWI

TB5 EWI

TB5 IWI

TB5

50mm unfilled cavity
100mm mineral wool 0.040
20mm lime parge 0.25
20mm plasterboard/skim 0.25

	Base Case	1: Cavity Wall EWI	Med EWI	Deep EWI	2: Cavity Wall IWI Med IWI	Deep IWI
	mm	mm	mm	mm	mm	mm
EWI	0	0	150	300	0	0
IWI	0	0	0	0	100	100
CWI type	none	EPS	EPS	EPS		
TB 5 Psi	-0.43	-0.16	-0.06	-0.05	-0.20	-0.20
TB 8 Psi	0.51	0.00	0.00	0.00	0.19	0.19

TB8

TB8 EWI

TB8 IWI

TB14

Psi	
0.18	IWI with 300mm gap in insulation
0.08	IWI with 200mm gap in insulation

Psi	
0.08	IWI with 300mm gap in insulation
-0.10	IWI with 200mm gap in insulation
0.00	for all other cases with no IWI or continuous IWI assume Psi zero

There is some uncertainty of the values for party walls, the thermal bridge calculation is much more complex. Comments welcome.

TB9

Solid Floor: Psi -0.57

Solid Floor: Psi 0.23 Assumes heated to 20C,
Neighbour not insulated and 17C
Insulation k0.022W/mk, 100 or 150mm

Suspended Floor: Psi -0.89

Suspended Floor: Psi 0.01 air void 100mm
insulation k 0.04W/mk, 150mm

TB10

Psi 0.70 Estimate based on similar junction in BS EN ISO 14683 1999

TB11

Figure B.5 Thermal bridges input

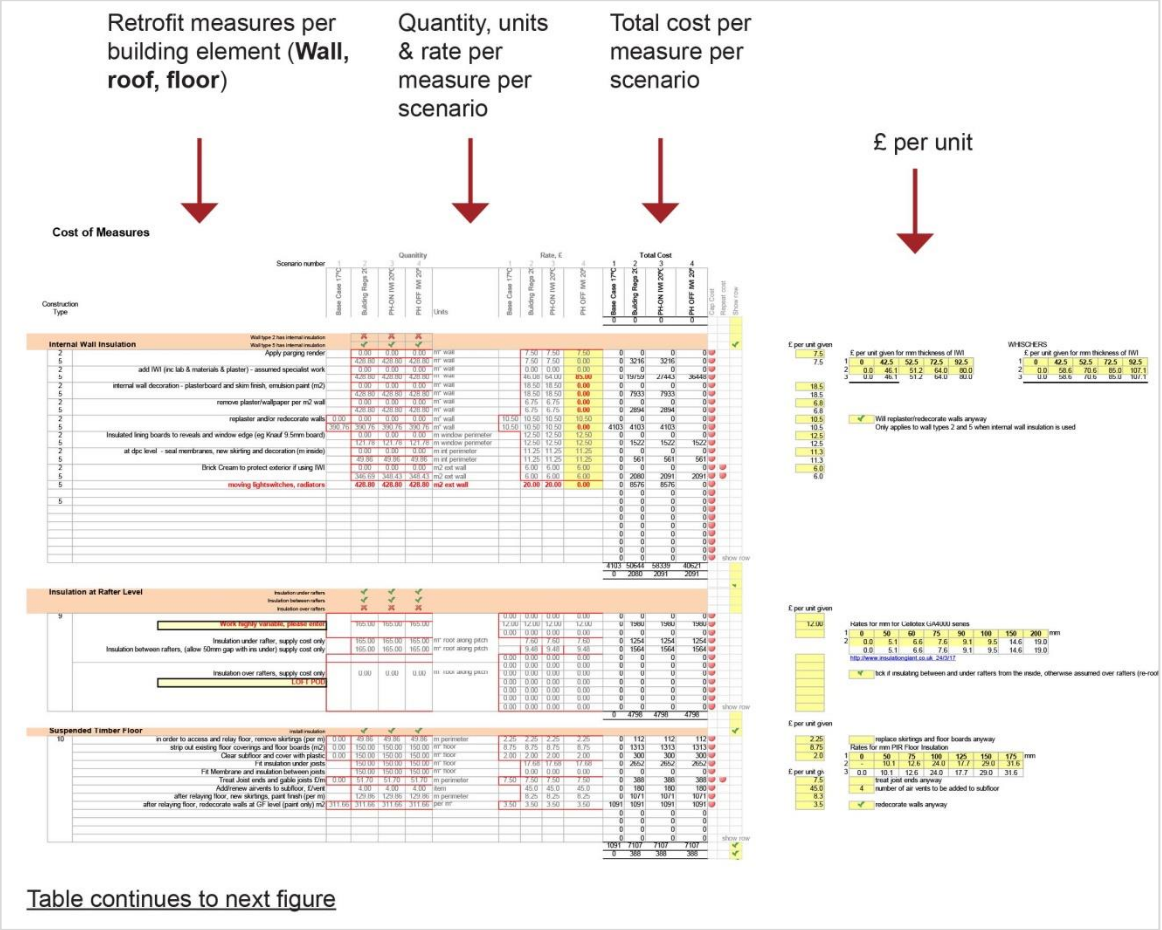
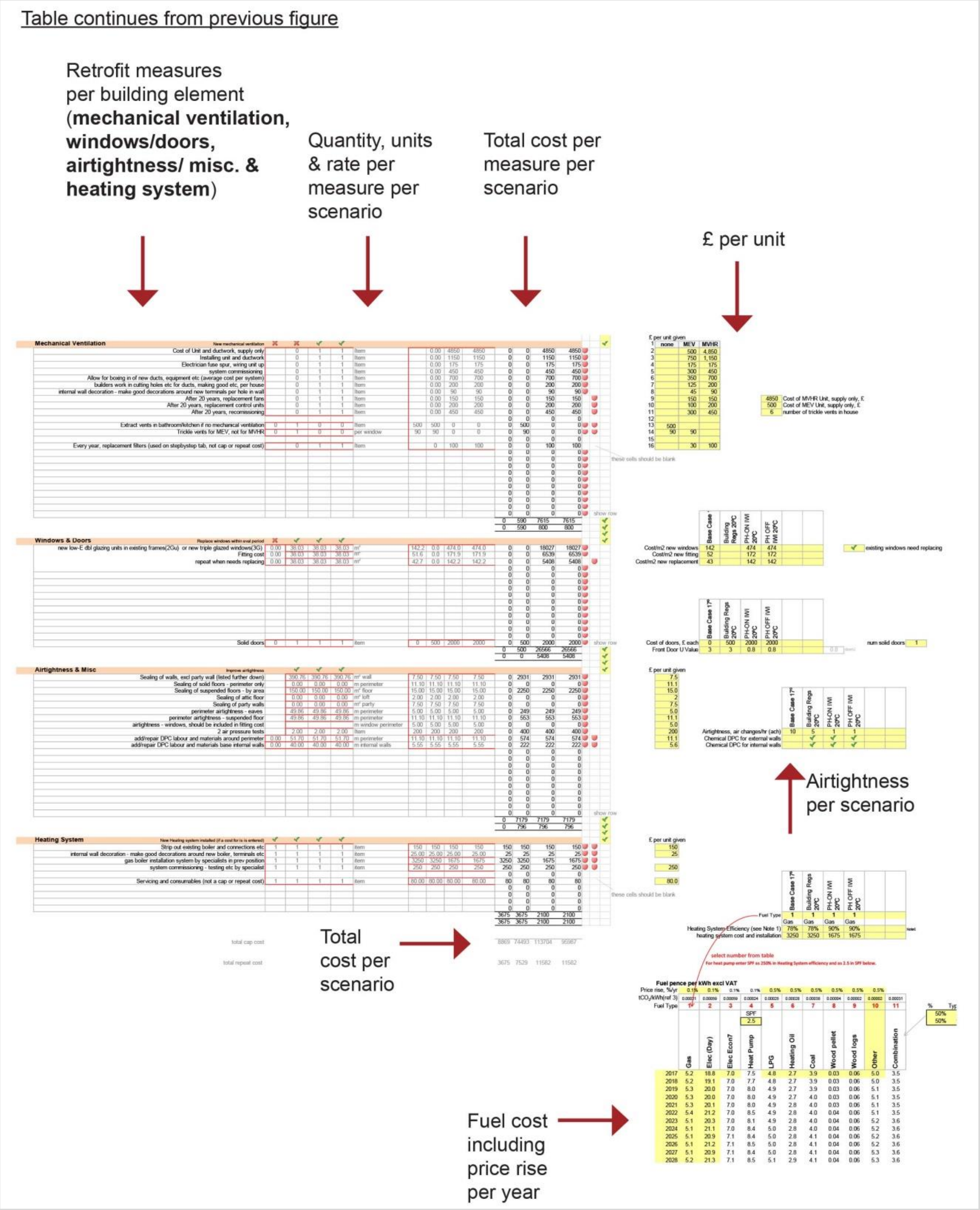


Table continues to next figure

Figure B.6 *Cost allocation & breakdown input part 1*



Mechanical Ventilation New mechanical ventilation	✗	✗	✓	✓									
Cost of Unit and ductwork, supply only		0	1	1	Item		0.00	4850	4850	0	0	4850	4850
Installing unit and ductwork		0	1	1	Item		0.00	1150	1150	0	0	1150	1150
Electrician fuse spur, wiring unit up		0	1	1	Item		0.00	175	175	0	0	175	175
system commissioning		0	1	1	Item		0.00	450	450	0	0	450	450
Allow for boxing in of new ducts, equipment etc (average cost per system)		0	1	1	Item		0.00	700	700	0	0	700	700
builders work in cutting holes etc for ducts, making good etc, per house		0	1	1	Item		0.00	200	200	0	0	200	200
internal wall decoration - make good decorations around new terminals per hole in wall		0	1	1	Item		0.00	90	90	0	0	90	90
After 20 years, replacement fans		0	1	1	Item		0.00	150	150	0	0	150	150
After 20 years, replacement control units		0	1	1	Item		0.00	200	200	0	0	200	200
After 20 years, recomissioning		0	1	1	Item		0.00	450	450	0	0	450	450
										0	0	0	0
Extract vents in bathroom/kitchen if no mechanical ventilation	0	1	0	0	Item	500	500	0	0	0	500	0	0
Trickle vents for MEV, not for MVHR	0	1	0	0	per window	90	90	0	0	0	90	0	0
										0	0	0	0
Every year, replacement filters (used on stepbystep tab, not cap or repeat cost)		0	1	1	Item		0	100	100	0	0	100	100
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	590	7615	7615
										0	590	800	800

these cells should be blank

show row

Windows & Doors Replace windows within eval period	✗	✓	✓	✓									
new low-E dbl glazing units in existing frames(2Gu) or new triple glazed windows(3G)	0.00	38.03	38.03	38.03	m²	142.2	0.0	474.0	474.0	0	0	18027	18027
Fitting cost	0.00	38.03	38.03	38.03	m²	51.6	0.0	171.9	171.9	0	0	6539	6539
repeat when needs replacing	0.00	38.03	38.03	38.03	m²	42.7	0.0	142.2	142.2	0	0	5408	5408
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
Solid doors	0	1	1	1	item	0	500	2000	2000	0	500	2000	2000
										0	500	26566	26566
										0	0	5408	5408

show row

Airtightness & Misc Improve airtightness		✓	✓	✓									
Sealing of walls, excl party wall (listed further down)		390.76	390.76	390.76	m² wall	7.50	7.50	7.50	7.50	0	2931	2931	2931
Sealing of solid floors - perimeter only		0.00	0.00	0.00	m perimeter	11.10	11.10	11.10	11.10	0	0	0	0
Sealing of suspended floors - by area		150.00	150.00	150.00	m² floor	15.00	15.00	15.00	15.00	0	2250	2250	2250
Sealing of attic floor		0.00	0.00	0.00	m² loft	2.00	2.00	2.00	2.00	0	0	0	0
Sealing of party walls		0.00	0.00	0.00	m² party	7.50	7.50	7.50	7.50	0	0	0	0
perimeter airtightness - eaves		49.86	49.86	49.86	m perimeter	5.00	5.00	5.00	5.00	0	249	249	249
perimeter airtightness - suspended floor		49.86	49.86	49.86	m perimeter	11.10	11.10	11.10	11.10	0	553	553	553
airtightness - windows, should be included in fitting cost					m window perimeter	5.00	5.00	5.00	5.00	0	0	0	0
2 air pressure tests		2.00	2.00	2.00	Item	200	200	200	200	0	400	400	400
add/repair DPC labour and materials around perimeter	0.00	51.70	51.70	51.70	m perimeter	11.10	11.10	11.10	11.10	0	574	574	574
add/repair DPC labour and materials base internal walls	0.00	40.00	40.00	40.00	m internal walls	5.55	5.55	5.55	5.55	0	222	222	222
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	7179	7179	7179
										0	796	796	796

show row

Heating System New Heating system installed (if a cost for is is entered)	✓	✓	✓	✓									
Strip out existing boiler and connections etc	1	1	1	1	item	150	150	150	150	150	150	150	150
internal wall decoration - make good decorations around new boiler, terminals etc	1	1	1	1	item	25.00	25.00	25.00	25.00	25	25	25	25
gas boiler installation system by specialists in prev position	1	1	1	1	item	3250	3250	1675	1675	3250	3250	1675	1675
system commissioning - testing etc by specialist	1	1	1	1	item	250	250	250	250	250	250	250	250
										0	0	0	0
Servicing and consumables (not a cap or repeat cost)	1	1	1	1	item	80.00	80.00	80.00	80.00	80	80	80	80
										0	0	0	0
										0	0	0	0
										0	0	0	0
										0	0	0	0
										3675	3675	2100	2100
										3675	3675	2100	2100
total cap cost										8869	74493	113704	95987
total repeat cost										3675	7529	11582	11582

these cells should be blank

£ per unit given

1	none	MEV	MVHR
2		500	4,850
3		750	1,150
4		175	175
5		300	450
6		350	700
7		125	200
8		45	90
9		150	150
10		100	200
11		300	450
12			
13	500		
14	90	90	
15			
16		30	100

4850	Cost of MVHR Unit, supply only, £
500	Cost of MEV Unit, supply only, £
6	number of trickle vents in house

	Base Case	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C		
Cost/m2 new windows	142		474	474		
Cost/m2 new fitting	52		172	172		
Cost/m2 new replacement	43		142	142		

✓ existing windows need replacing

	Base Case 17°	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C		
Cost of doors, £ each	0	500	2000	2000		
Front Door U Value	3	3	0.8	0.8		

num solid doors 1

£ per unit given

7.5
11.1
15.0
2
7.5
5.0
11.1
5.0
200
11.1
5.6

	Base Case 17°	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C		
Airtightness, air changes/hr (ach)	10	5	1	1		
Chemical DPC for external walls		✓	✓	✓		
Chemical DPC for internal walls		✓	✓	✓		

£ per unit given

150
25

250

80.0

these cells should be blank

	Base Case 17°	Building Regs 20°C	PH-ON IWI 20°C	PH OFF IWI 20°C		
Fuel Type	1	1	1	1		
	Gas	Gas	Gas	Gas		
Heating System Efficiency (see Note 1)	78%	78%	90%	90%		
heating system cost and installation	3250	3250	1675	1675		

select number from table

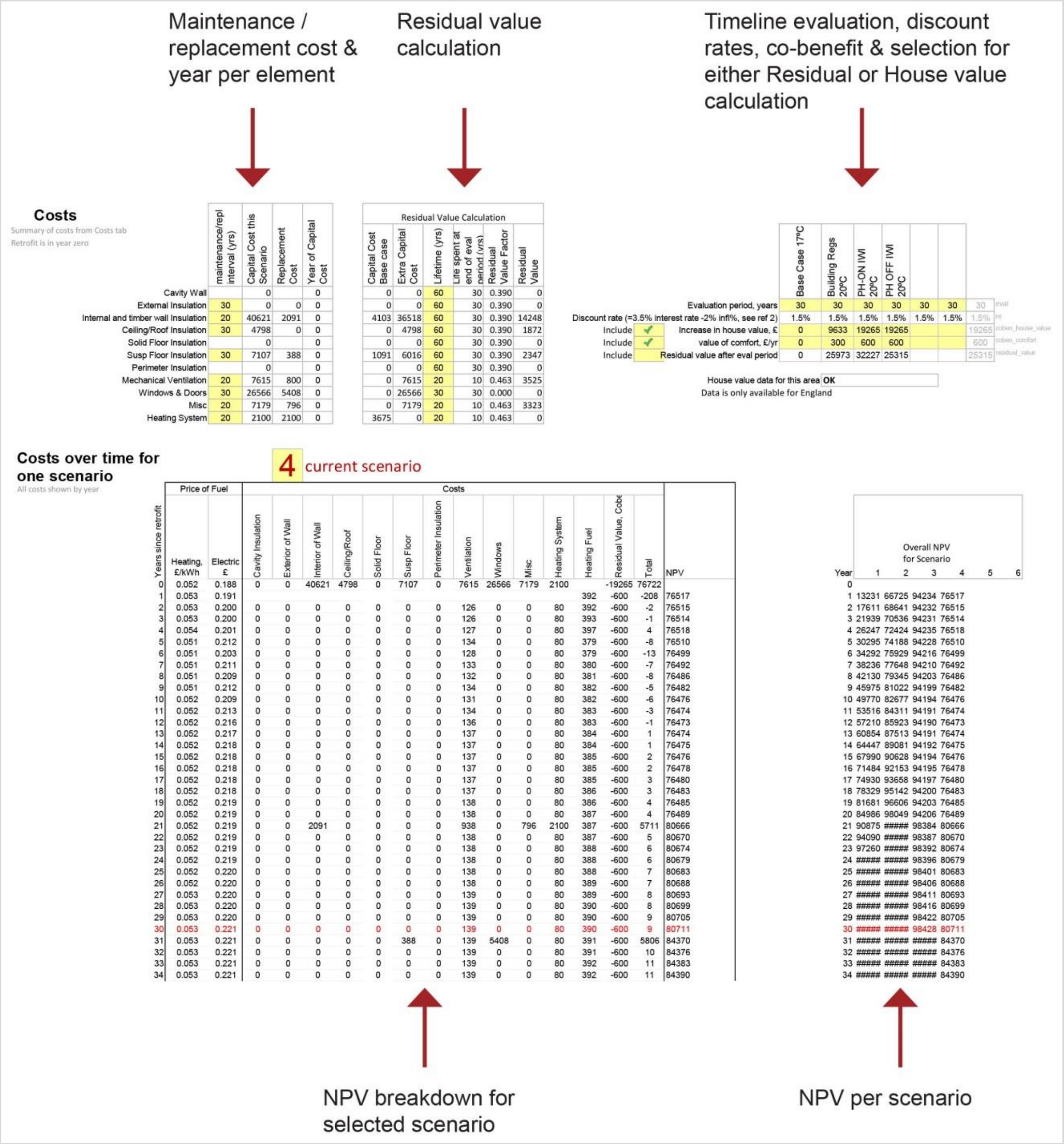
For heat pump enter SPF as 250% in Heating System efficiency and as 2.5 in SPF below.

Fuel pence per kWh excl VAT

	Gas	Elec (Day)	Elec Econ7	Heat Pump	LPG	Heating Oil	Coal	Wood pellet	Wood logs	Other	Combination
Price rise, %/yr	0.1%	0.1%	0.1%	0.1%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	
tCO_2/kWh(ref 3)	0.00021	0.00059	0.00059	0.00024	0.00025	0.00028	0.00038	0.00004	0.00002	0.00002	0.00031
Fuel Type	1	2	3	4	5	6	7	8	9	10	11
				SPF 2.5							
2017	5.2	18.8	7.0	7.5	4.8	2.7	3.9	0.03	0.06	5.0	3.5
2018	5.2	19.1	7.0	7.7	4.8	2.7	3.9	0.03	0.06	5.0	3.5
2019	5.3	20.0	7.0	8.0	4.9	2.7	3.9	0.03	0.06	5.1	3.5
2020	5.3	20.0	7.0	8.0	4.9	2.7	4.0	0.03	0.06	5.1	3.5
2021	5.3	20.1	7.0	8.0	4.9	2.8	4.0	0.03	0.06	5.1	3.5
2022	5.4	21.2	7.0	8.5	4.9	2.8	4.0	0.04	0.06	5.1	3.5
2023	5.1	20.3	7.0	8.1	4.9	2.8	4.0	0.04	0.06	5.2	3.6
2024	5.1	21.1	7.0	8.4	5.0	2.8	4.0	0.04	0.06	5.2	3.6
2025	5.1	20.9	7.1	8.4	5.0	2.8	4.1	0.04	0.06	5.2	3.6
2026	5.1	21.2	7.1	8.5	5.0	2.8	4.1	0.04	0.06	5.2	3.6
2027	5.1	20.9	7.1	8.4	5.0	2.8	4.1	0.04	0.06	5.3	3.6
2028	5.2	21.3	7.1	8.5	5.1	2.9	4.1	0.04	0.06	5.3	3.6

%
50%
50%

Figure B.7 *Cost allocation & breakdown input part 2*



Costs

Summary of costs from Costs tab
Retrofit is in year zero

	maintenance/repl interval (yrs)	Capital Cost this Scenario	Replacement Cost	Year of Capital Cost	Residual Value Calculation					
					Capital Cost Base case	Extra Capital Cost	Lifetime (yrs)	Life spent at end of eval period (yrs)	Residual Value Factor	Residual Value
Cavity Wall		0		0	0	0	60	30	0.390	0
External Insulation	30	0	0	0	0	0	60	30	0.390	0
Internal and timber wall Insulation	20	40621	2091	0	4103	36518	60	30	0.390	14248
Ceiling/Roof Insulation	30	4798	0	0	0	4798	60	30	0.390	1872
Solid Floor Insulation		0		0	0	0	60	30	0.390	0
Susp Floor Insulation	30	7107	388	0	1091	6016	60	30	0.390	2347
Perimeter Insulation		0		0	0	0	60	30	0.390	0
Mechanical Ventilation	20	7615	800	0	0	7615	20	10	0.463	3525
Windows & Doors	30	26566	5408	0	0	26566	30	30	0.000	0
Misc	20	7179	796	0	0	7179	20	10	0.463	3323
Heating System	20	2100	2100	0	3675	0	20	10	0.463	0

			Base Case 17ºC	Building Regs 20ºC	PH-ON IWI 20ºC	PH OFF IWI 20ºC				
		Evaluation period, years	30	30	30	30	30	30	30	eval
		Discount rate (=3.5% interest rate -2% infl%, see ref 2)	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	re
Include	✓	Increase in house value, £	0	9633	19265	19265			19265	coben_house_value
Include	✓	value of comfort, £/yr	0	300	600	600			600	coben_comfort
Include		Residual value after eval period	0	25973	32227	25315			25315	residual_value

House value data for this area **OK**
Data is only available for England

Costs over time for one scenario

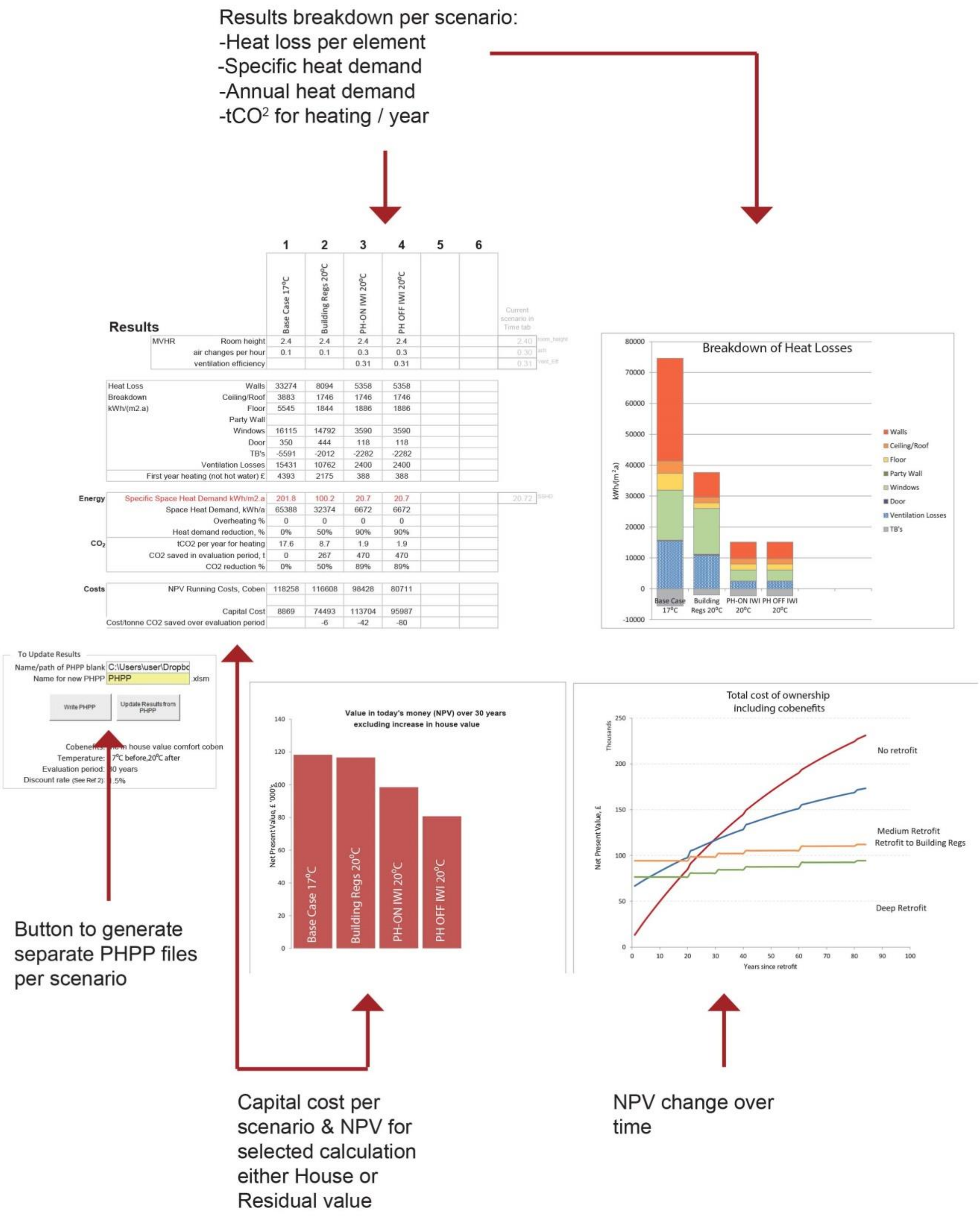
All costs shown by year

4 current scenario

	Price of Fuel		Costs														
Years since retrofit	Heating, £/kWh	Electric £	Cavity Insulation	Exterior of Wall	Interior of Wall	Ceiling/Roof	Solid Floor	Susp Floor	Perimeter Insulation	Ventilation	Windows	Misc	Heating System	Heating Fuel	Residual Value, Cobe	Total	NPV
0	0.052	0.188	0	0	40621	4798	0	7107	0	7615	26566	7179	2100		-19265	76722	
1	0.053	0.191												392	-600	-208	76517
2	0.053	0.200	0	0	0	0	0	0	0	126	0	0	80	392	-600	-2	76515
3	0.053	0.200	0	0	0	0	0	0	0	126	0	0	80	393	-600	-1	76514
4	0.054	0.201	0	0	0	0	0	0	0	127	0	0	80	397	-600	4	76518
5	0.051	0.212	0	0	0	0	0	0	0	134	0	0	80	379	-600	-8	76510
6	0.051	0.203	0	0	0	0	0	0	0	128	0	0	80	379	-600	-13	76499
7	0.051	0.211	0	0	0	0	0	0	0	133	0	0	80	380	-600	-7	76492
8	0.051	0.209	0	0	0	0	0	0	0	132	0	0	80	381	-600	-8	76486
9	0.051	0.212	0	0	0	0	0	0	0	134	0	0	80	382	-600	-5	76482
10	0.052	0.209	0	0	0	0	0	0	0	131	0	0	80	382	-600	-6	76476
11	0.052	0.213	0	0	0	0	0	0	0	134	0	0	80	383	-600	-3	76474
12	0.052	0.216	0	0	0	0	0	0	0	136	0	0	80	383	-600	-1	76473
13	0.052	0.217	0	0	0	0	0	0	0	137	0	0	80	384	-600	1	76474
14	0.052	0.218	0	0	0	0	0	0	0	137	0	0	80	384	-600	1	76475
15	0.052	0.218	0	0	0	0	0	0	0	137	0	0	80	385	-600	2	76476
16	0.052	0.218	0	0	0	0	0	0	0	137	0	0	80	385	-600	2	76478
17	0.052	0.218	0	0	0	0	0	0	0	137	0	0	80	385	-600	3	76480
18	0.052	0.218	0	0	0	0	0	0	0	137	0	0	80	386	-600	3	76483
19	0.052	0.219	0	0	0	0	0	0	0	138	0	0	80	386	-600	4	76485
20	0.052	0.219	0	0	0	0	0	0	0	138	0	0	80	387	-600	4	76489
21	0.052	0.219	0	0	2091	0	0	0	0	938	0	796	2100	387	-600	5711	80666
22	0.052	0.219	0	0	0	0	0	0	0	138	0	0	80	387	-600	5	80670
23	0.052	0.219	0	0	0	0	0	0	0	138	0	0	80	388	-600	6	80674
24	0.052	0.219	0	0	0	0	0	0	0	138	0	0	80	388	-600	6	80679
25	0.052	0.220	0	0	0	0	0	0	0	138	0	0	80	388	-600	7	80683
26	0.052	0.220	0	0	0	0	0	0	0	138	0	0	80	389	-600	7	80688
27	0.053	0.220	0	0	0	0	0	0	0	139	0	0	80	389	-600	8	80693
28	0.053	0.220	0	0	0	0	0	0	0	139	0	0	80	390	-600	8	80699
29	0.053	0.220	0	0	0	0	0	0	0	139	0	0	80	390	-600	9	80705
30	0.053	0.221	0	0	0	0	0	0	0	139	0	0	80	390	-600	9	80711
31	0.053	0.221	0	0	0	0	0	388	0	139	5408	0	80	391	-600	5806	84370
32	0.053	0.221	0	0	0	0	0	0	0	139	0	0	80	391	-600	10	84376
33	0.053	0.221	0	0	0	0	0	0	0	139	0	0	80	392	-600	11	84383
34	0.053	0.221	0	0	0	0	0	0	0	139	0	0	80	392	-600	11	84390

	Overall NPV for Scenario					
Year	1	2	3	4	5	6
0						
1	13231	66725	94234	76517		
2	17611	68641	94232	76515		
3	21939	70536	94231	76514		
4	26247	72424	94235	76518		
5	30295	74188	94228	76510		
6	34292	75929	94216	76499		
7	38236	77648	94210	76492		
8	42130	79345	94203	76486		
9	45975	81022	94199	76482		
10	49770	82677	94194	76476		
11	53516	84311	94191	76474		
12	57210	85923	94190	76473		
13	60854	87513	94191	76474		
14	64447	89081	94192	76475		
15	67990	90628	94194	76476		
16	71484	92153	94195	76478		
17	74930	93658	94197	76480		
18	78329	95142	94200	76483		
19	81681	96606	94203	76485		
20	84986	98049	94206	76489		
21	90875	#####	98384	80666		
22	94090	#####	98387	80670		
23	97260	#####	98392	80674		
24	#####	#####	98396	80679		
25	#####	#####	98401	80683		
26	#####	#####	98406	80688		
27	#####	#####	98411	80693		
28	#####	#####	98416	80699		
29	#####	#####	98422	80705		
30	#####	#####	98428	80711		
31	#####	#####	#####	84370		
32	#####	#####	#####	84376		
33	#####	#####	#####	84383		
34	#####	#####	#####	84390		

Figure B.8 *Retrofit evaluation period, co-benefits & calculation method*



Results breakdown per scenario:
-Heat loss per element
-Specific heat demand
-Annual heat demand
-tCO² for heating / year

Results

		1 Base Case 17°C	2 Building Regs 20°C	3 PH-ON IWI 20°C	4 PH OFF IWI 20°C	5	6	Current scenario in Time tab	
MVHR	Room height	2.4	2.4	2.4	2.4			2.40	room_height
	air changes per hour	0.1	0.1	0.3	0.3			0.30	ach
	ventilation efficiency			0.31	0.31			0.31	vent_Eff
Heat Loss Breakdown kWh/(m2.a)	Walls	33274	8094	5358	5358				
	Ceiling/Roof	3883	1746	1746	1746				
	Floor	5545	1844	1886	1886				
	Party Wall								
	Windows	16115	14792	3590	3590				
	Door	350	444	118	118				
	TB's	-5591	-2012	-2282	-2282				
	Ventilation Losses	15431	10762	2400	2400				
	First year heating (not hot water) £	4393	2175	388	388				
Energy	Specific Space Heat Demand kWh/m2.a	201.8	100.2	20.7	20.7			20.72	SSHD
	Space Heat Demand, kWh/a	65388	32374	6672	6672				
	Overheating %	0	0	0	0				
	Heat demand reduction, %	0%	50%	90%	90%				
CO_2	tCO2 per year for heating	17.6	8.7	1.9	1.9				
	CO2 saved in evaluation period, t	0	267	470	470				
	CO2 reduction %	0%	50%	89%	89%				
Costs	NPV Running Costs, Coben	118258	116608	98428	80711				
	Capital Cost	8869	74493	113704	95987				
	Cost/tonne CO2 saved over evaluation period		-6	-42	-80				

To Update Results

Name/path of PHPP blank: C:\Users\user\Dropbc
Name for new PHPP: PHPP .xlsm

Cobenefits: in house value comfort coben
Temperature: 7°C before,20°C after
Evaluation period: 0 years
Discount rate (See Ref 2): .5%

Button to generate separate PHPP files per scenario

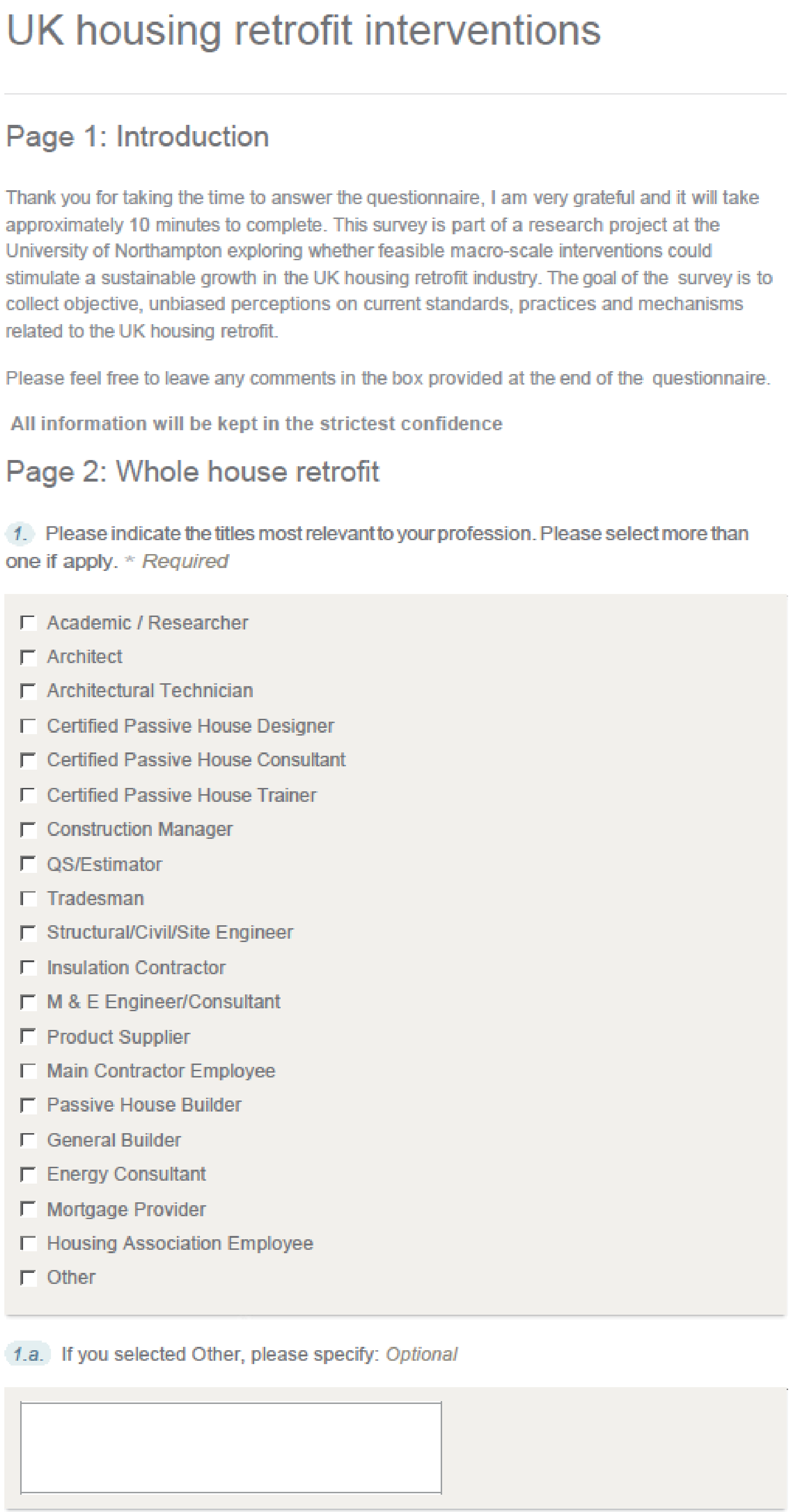
Capital cost per scenario & NPV for selected calculation either House or Residual value

NPV change over time

Figure B.9 Results

Appendix C – Survey

Below is the example of the online survey used in the research



UK housing retrofit interventions

Page 1: Introduction

Thank you for taking the time to answer the questionnaire, I am very grateful and it will take approximately 10 minutes to complete. This survey is part of a research project at the University of Northampton exploring whether feasible macro-scale interventions could stimulate a sustainable growth in the UK housing retrofit industry. The goal of the survey is to collect objective, unbiased perceptions on current standards, practices and mechanisms related to the UK housing retrofit.

Please feel free to leave any comments in the box provided at the end of the questionnaire.

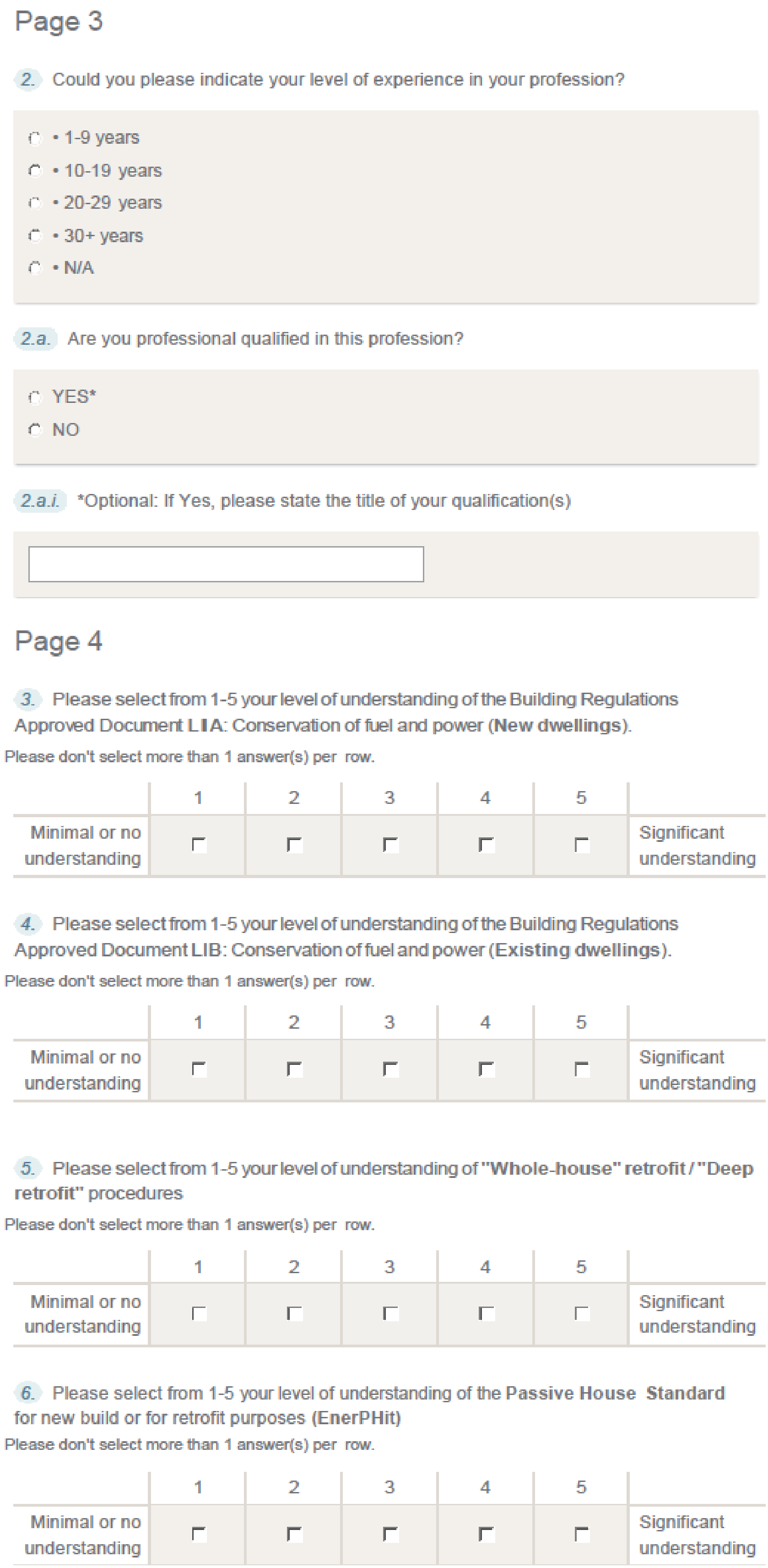
All information will be kept in the strictest confidence

Page 2: Whole house retrofit

1. Please indicate the titles most relevant to your profession. Please select more than one if apply. * *Required*

☐ Academic / Researcher
☐ Architect
☐ Architectural Technician
☐ Certified Passive House Designer
☐ Certified Passive House Consultant
☐ Certified Passive House Trainer
☐ Construction Manager
☐ QS/Estimator
☐ Tradesman
☐ Structural/Civil/Site Engineer
☐ Insulation Contractor
☐ M & E Engineer/Consultant
☐ Product Supplier
☐ Main Contractor Employee
☐ Passive House Builder
☐ General Builder
☐ Energy Consultant
☐ Mortgage Provider
☐ Housing Association Employee
☐ Other

1.a. If you selected Other, please specify: *Optional*



Page 3

2. Could you please indicate your level of experience in your profession?

○ • 1-9 years
○ • 10-19 years
○ • 20-29 years
○ • 30+ years
○ • N/A

2.a. Are you professional qualified in this profession?

○ YES*
○ NO

2.a.i. *Optional: If Yes, please state the title of your qualification(s)

Page 4

3. Please select from 1-5 your level of understanding of the Building Regulations Approved Document LIA: Conservation of fuel and power (**New dwellings**).

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or no understanding	☐	☐	☐	☐	☐	Significant understanding

4. Please select from 1-5 your level of understanding of the Building Regulations Approved Document LIB: Conservation of fuel and power (**Existing dwellings**).

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or no understanding	☐	☐	☐	☐	☐	Significant understanding

5. Please select from 1-5 your level of understanding of **"Whole-house" retrofit / "Deep retrofit"** procedures

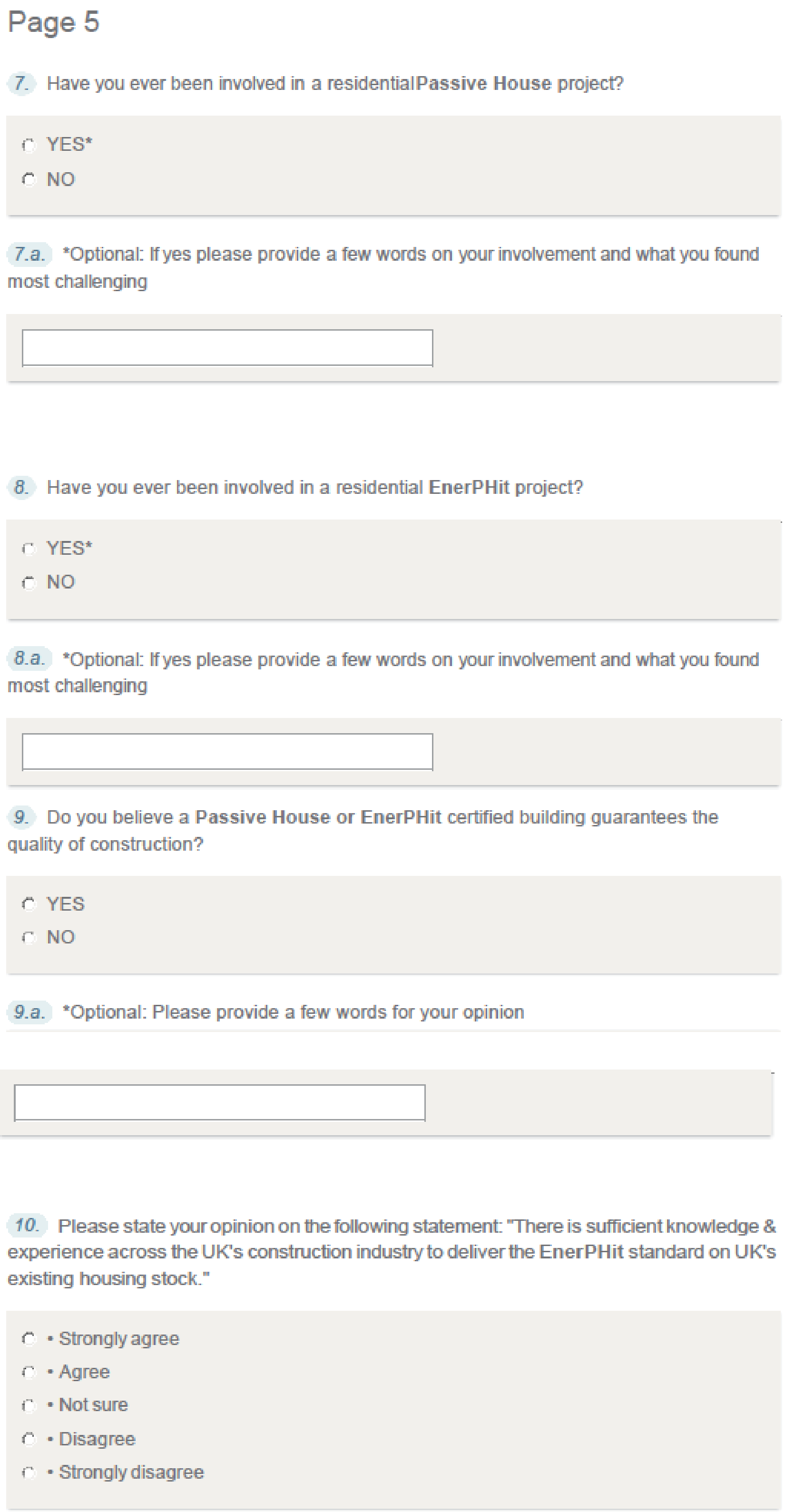
Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or no understanding	☐	☐	☐	☐	☐	Significant understanding

6. Please select from 1-5 your level of understanding of the **Passive House Standard** for new build or for retrofit purposes (**EnerPHit**)

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or no understanding	☐	☐	☐	☐	☐	Significant understanding



Page 5

7. Have you ever been involved in a residential **Passive House** project?

○ YES*
○ NO

7.a. *Optional: If yes please provide a few words on your involvement and what you found most challenging

8. Have you ever been involved in a residential **EnerPHit** project?

○ YES*
○ NO

8.a. *Optional: If yes please provide a few words on your involvement and what you found most challenging

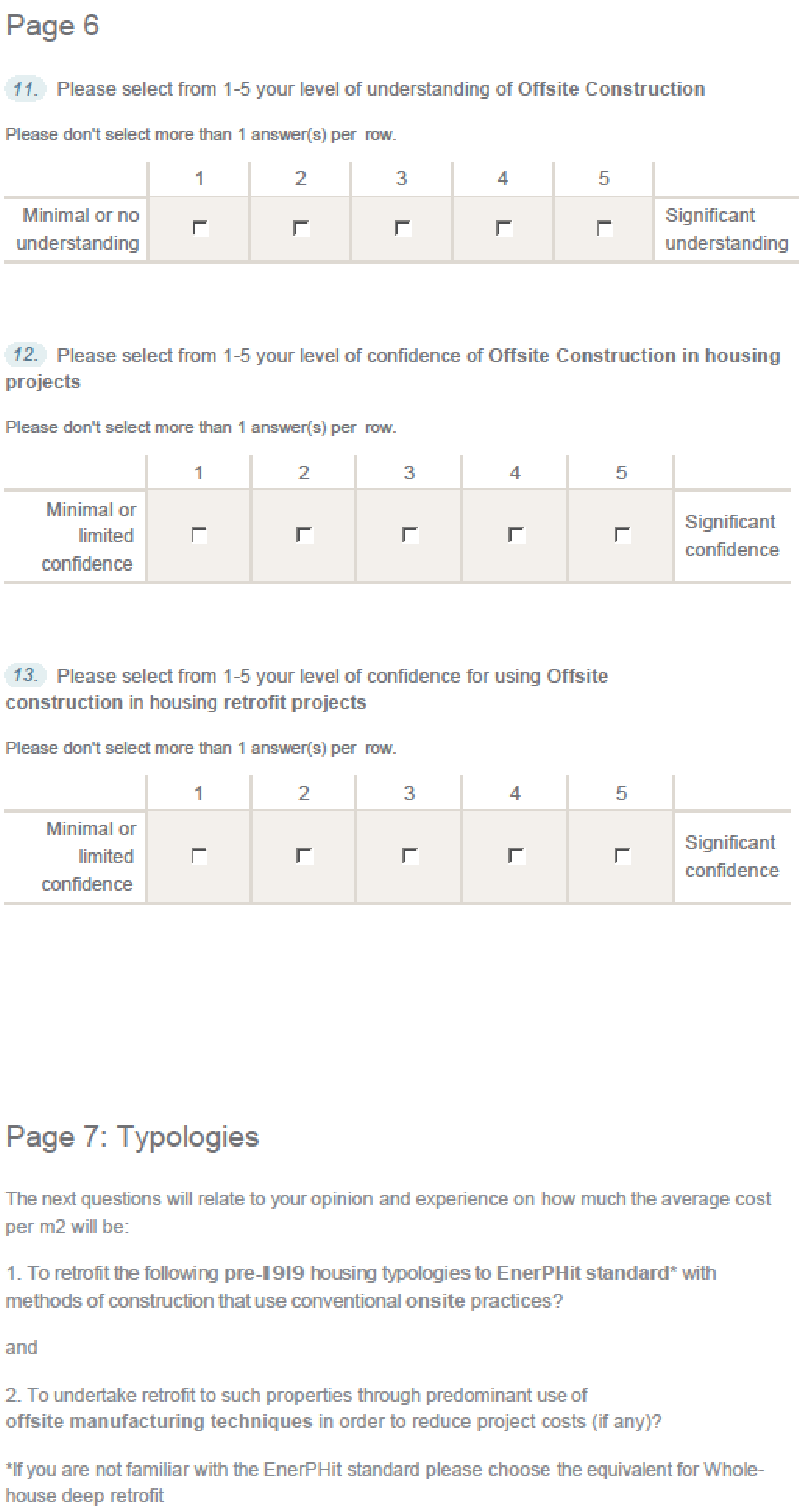
9. Do you believe a **Passive House or EnerPHit** certified building guarantees the quality of construction?

○ YES
○ NO

9.a. *Optional: Please provide a few words for your opinion

10. Please state your opinion on the following statement: "There is sufficient knowledge & experience across the UK's construction industry to deliver the **EnerPHit** standard on UK's existing housing stock."

○ • Strongly agree
○ • Agree
○ • Not sure
○ • Disagree
○ • Strongly disagree



Page 6

11. Please select from 1-5 your level of understanding of **Offsite Construction**

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or no understanding	☐	☐	☐	☐	☐	Significant understanding

12. Please select from 1-5 your level of confidence of **Offsite Construction in housing projects**

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or limited confidence	☐	☐	☐	☐	☐	Significant confidence

13. Please select from 1-5 your level of confidence for using **Offsite construction** in housing **retrofit projects**

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	
Minimal or limited confidence	☐	☐	☐	☐	☐	Significant confidence

Page 7: Typologies

The next questions will relate to your opinion and experience on how much the average cost per m2 will be:

1. To retrofit the following **pre-1919** housing typologies to **EnerPHit standard*** with methods of construction that use conventional **onsite** practices?

and

2. To undertake retrofit to such properties through predominant use of **offsite manufacturing techniques** in order to reduce project costs (if any)?

*If you are not familiar with the EnerPHit standard please choose the equivalent for Whole-house deep retrofit

14. Onsite retrofit cost per m^2

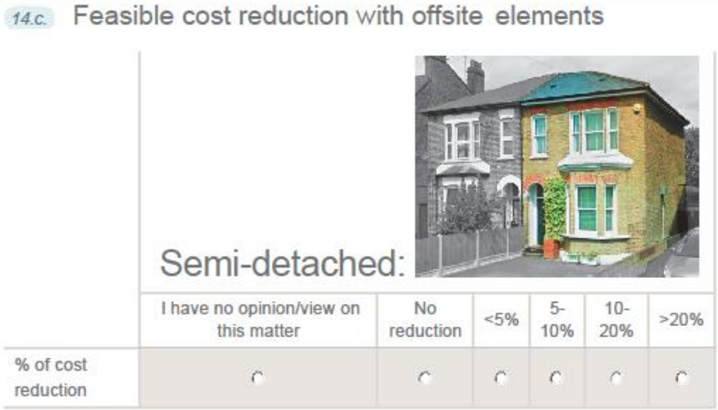
	I have no opinion/view on this matter	<£200	£200 - £400	£400 - £600	£600 - £800	>£800
Average cost per m2	○	○	○	○	○	○

14.a. Feasible cost reduction using offsite construction techniques

	I have no opinion/view on this matter	No reduction	<5%	5-10%	10-20%	>20%
% of cost reduction	○	○	○	○	○	○

14.b. Onsite retrofit cost per m2

	I have no opinion/view on this matter	<£200	£200 - £400	£400 - £600	£600-£800	> £800
Average cost per m2	○	○	○	○	○	○



14.c. Feasible cost reduction with offsite elements

	I have no opinion/view on this matter	No reduction	<5%	5-10%	10-20%	>20%
% of cost reduction	○	○	○	○	○	○

14.d. Onsite retrofit cost per m2:

End terrace:

	I have no opinion/view on this matter	<£200	£200 - £400	£400 - £600	£600- £800	> £800
Average cost per m2	○	○	○	○	○	○

14.e. Feasible cost reduction with offsite elements

End terrace:

	I have no opinion/view on this matter	No reduction	<5%	5-10%	10-20%	>20%
% of cost reduction	○	○	○	○	○	○

14.f. Onsite retrofit cost per m2

Terrace with Bay window & Back extension:

	I have no opinion/view on this matter	<£200	£200 - £400	£400 - £600	£600- £800	> £800
Average cost per m2	○	○	○	○	○	○

14.g. Feasible cost reduction with offsite elements

Terrace with Bay window & Back extension:

	I have no opinion/view on this matter	No reduction	<5%	5-10%	10-20%	>20%
% of cost reduction	○	○	○	○	○	○

14.h. Onsite retrofit cost per m2

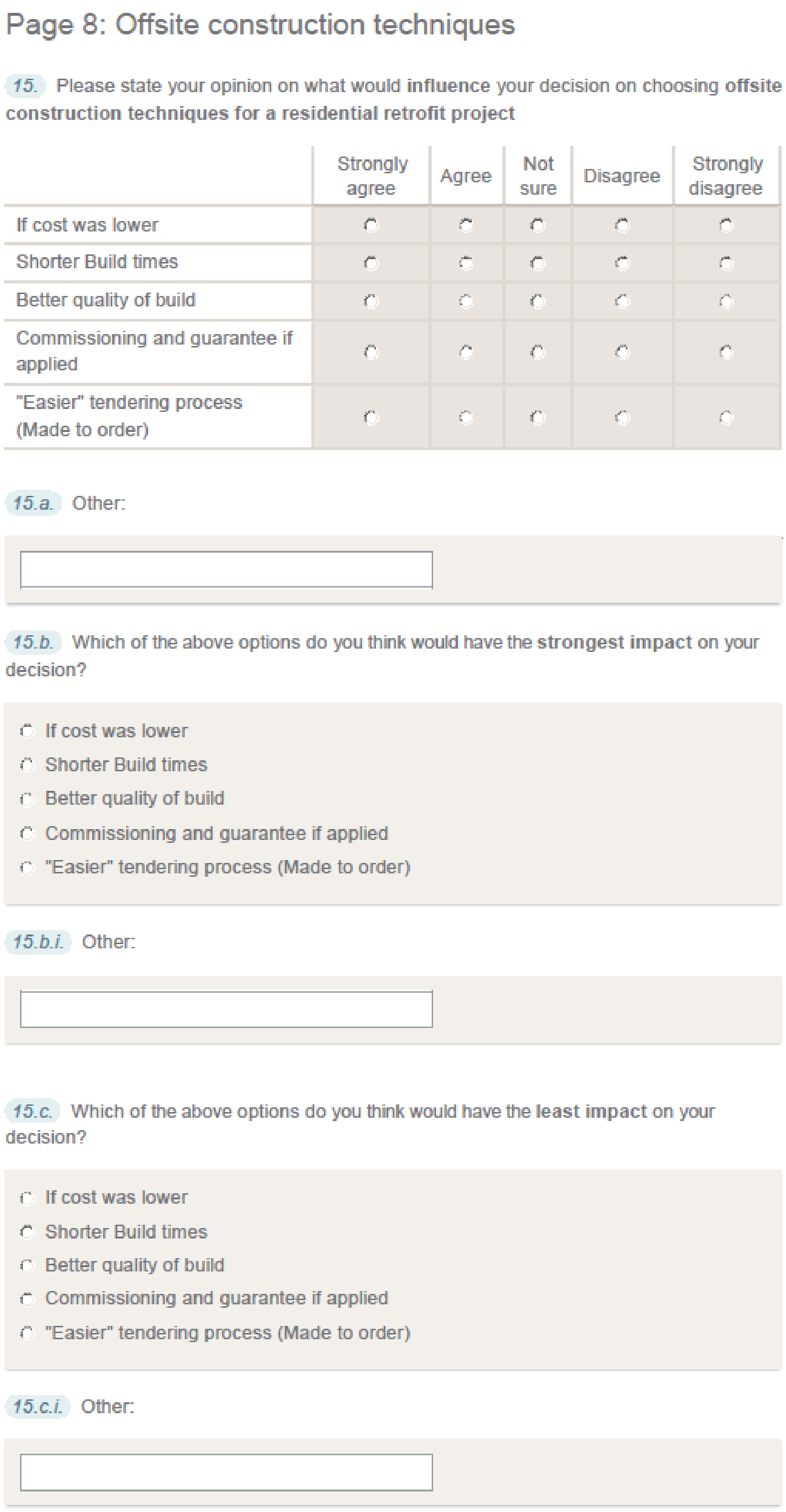
Terrace Flat Front & Back

	I have no opinion/view on this matter	<£200	£200 - £400	£400 - £600	£600-£800	> £800
Average cost per m2	○	○	○	○	○	○

14.i. Feasible cost reduction with offsite elements

Terrace Flat Front & Back

	I have no opinion/view on this matter	No reduction	<5%	5-10%	10-20%	>20%
% of cost reduction	○	○	○	○	○	○



Page 8: Offsite construction techniques

15. Please state your opinion on what would **influence** your decision on choosing **offsite construction techniques for a residential retrofit project**

	Strongly agree	Agree	Not sure	Disagree	Strongly disagree
If cost was lower	○	○	○	○	○
Shorter Build times	○	○	○	○	○
Better quality of build	○	○	○	○	○
Commissioning and guarantee if applied	○	○	○	○	○
"Easier" tendering process (Made to order)	○	○	○	○	○

15.a. Other:

15.b. Which of the above options do you think would have the **strongest impact** on your decision?

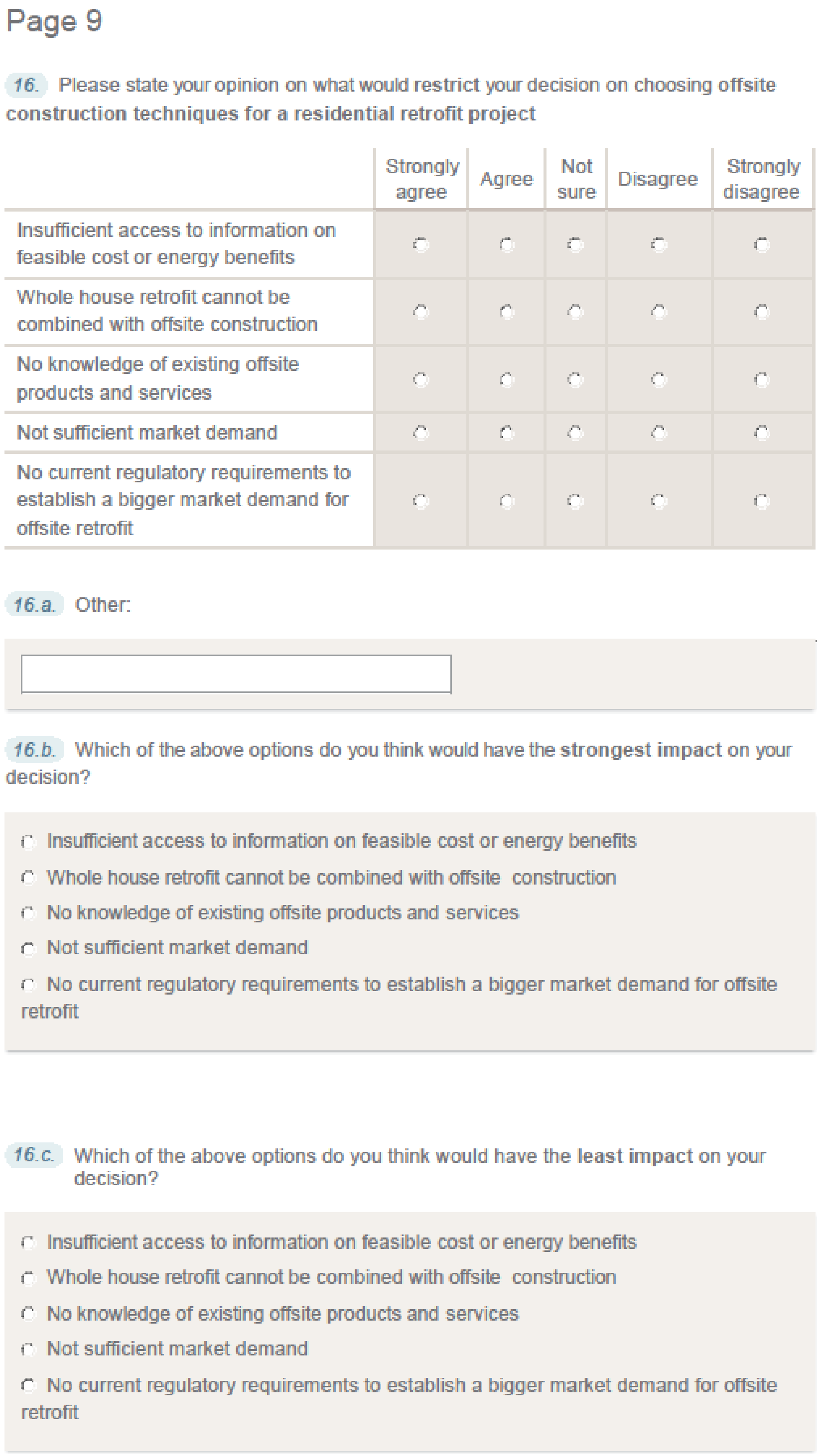
- ○ If cost was lower
- ○ Shorter Build times
- ○ Better quality of build
- ○ Commissioning and guarantee if applied
- ○ "Easier" tendering process (Made to order)

15.b.i. Other:

15.c. Which of the above options do you think would have the **least impact** on your decision?

- ○ If cost was lower
- ○ Shorter Build times
- ○ Better quality of build
- ○ Commissioning and guarantee if applied
- ○ "Easier" tendering process (Made to order)

15.c.i. Other:



Page 9

16. Please state your opinion on what would **restrict** your decision on choosing **offsite construction techniques for a residential retrofit project**

	Strongly agree	Agree	Not sure	Disagree	Strongly disagree
Insufficient access to information on feasible cost or energy benefits	○	○	○	○	○
Whole house retrofit cannot be combined with offsite construction	○	○	○	○	○
No knowledge of existing offsite products and services	○	○	○	○	○
Not sufficient market demand	○	○	○	○	○
No current regulatory requirements to establish a bigger market demand for offsite retrofit	○	○	○	○	○

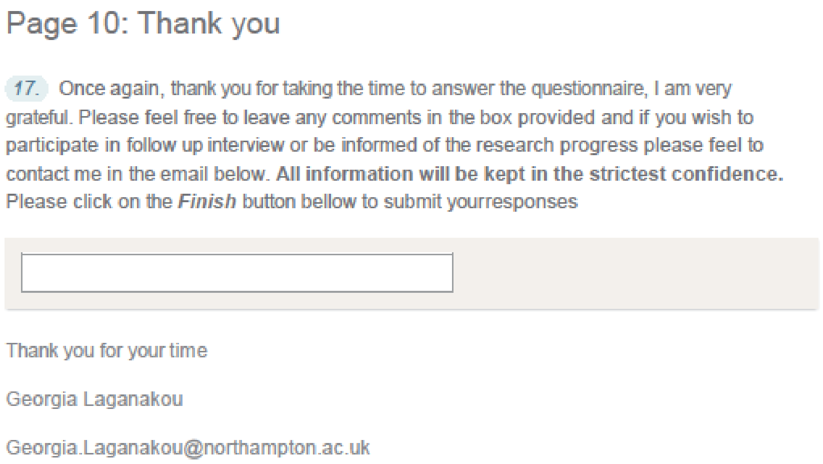
16.a. Other:

16.b. Which of the above options do you think would have the **strongest impact** on your decision?

- ○ Insufficient access to information on feasible cost or energy benefits
- ○ Whole house retrofit cannot be combined with offsite construction
- ○ No knowledge of existing offsite products and services
- ○ Not sufficient market demand
- ○ No current regulatory requirements to establish a bigger market demand for offsite retrofit

16.c. Which of the above options do you think would have the **least impact** on your decision?

- ○ Insufficient access to information on feasible cost or energy benefits
- ○ Whole house retrofit cannot be combined with offsite construction
- ○ No knowledge of existing offsite products and services
- ○ Not sufficient market demand
- ○ No current regulatory requirements to establish a bigger market demand for offsite retrofit



Page 10: Thank you

17. Once again, thank you for taking the time to answer the questionnaire, I am very grateful. Please feel free to leave any comments in the box provided and if you wish to participate in follow up interview or be informed of the research progress please feel to contact me in the email below. **All information will be kept in the strictest confidence.** Please click on the ***Finish*** button bellow to submit yourresponses

Thank you for your time

Georgia Laganakou

Georgia.Laganakou@northampton.ac.uk

Appendix D– Percentage differences between Onsite and Offsite ROI

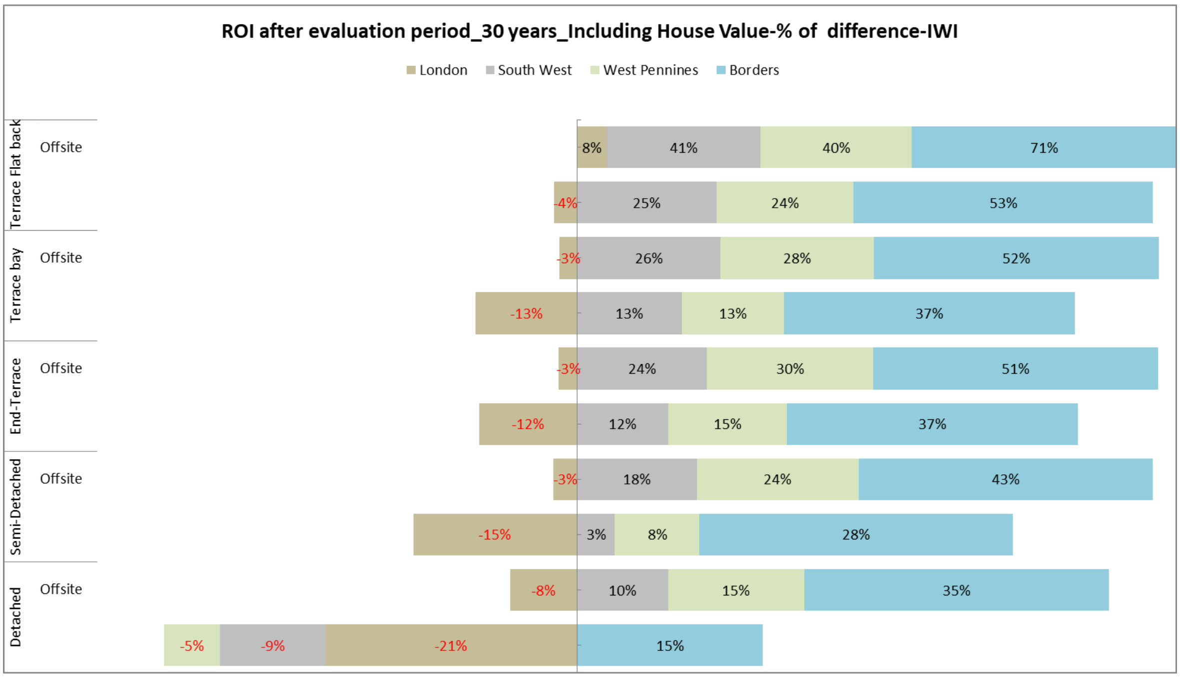


Figure D.1 *Return On Investment that includes* ***House Value****. Percentage difference of Offsite measure using Internal Wall Insulation*

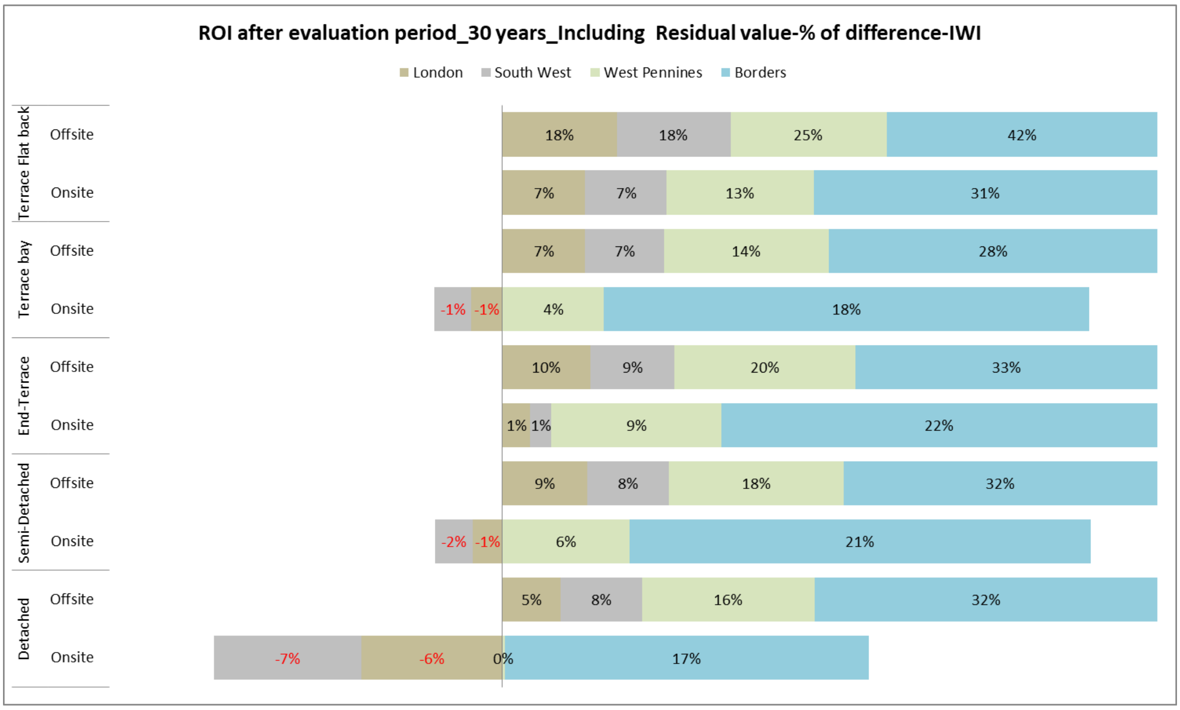


Figure D.2 *Return On Investment that includes* ***Residual Value****. Percentage difference of Offsite measure using Internal Wall Insulation*

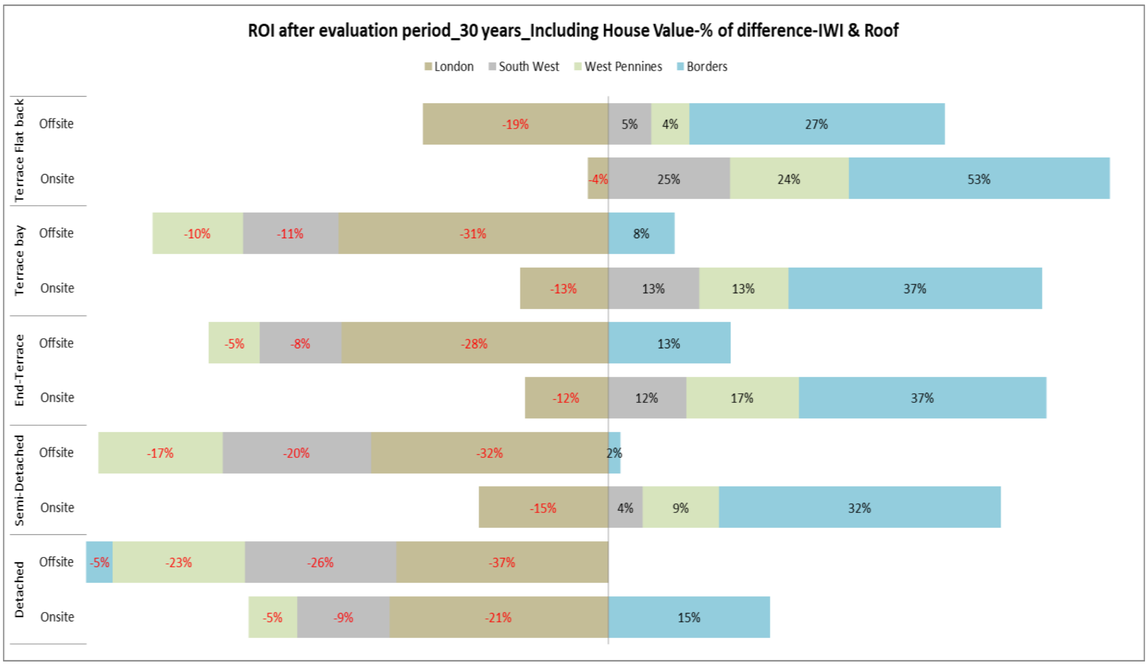


Figure D.3 *Return On Investment that includes* ***House Value****. Percentage difference of Offsite measure using Internal Wall Insulation and Roof*

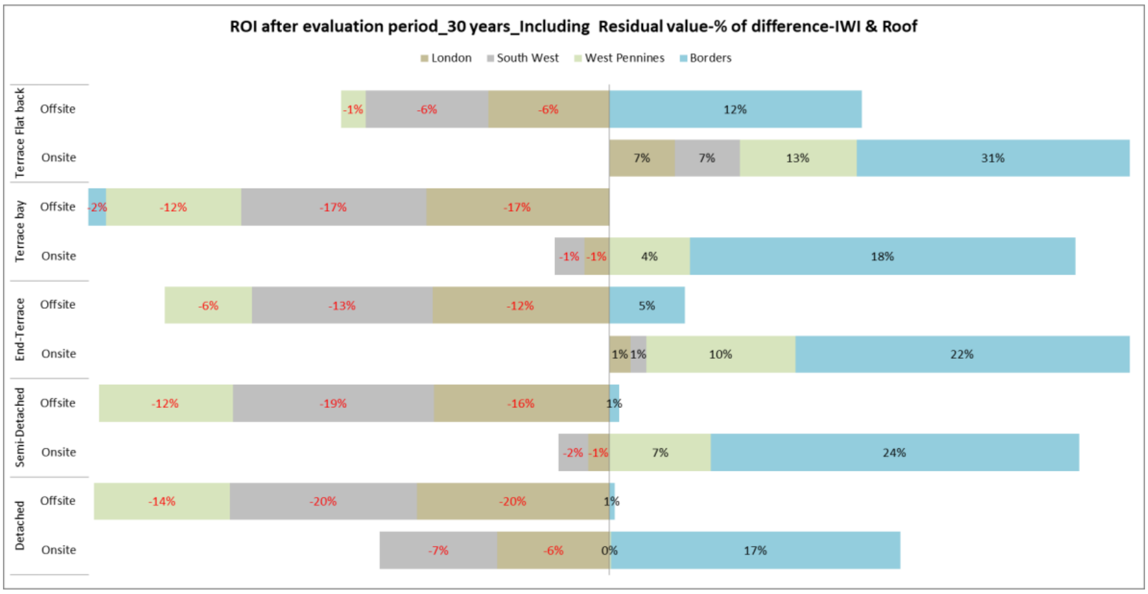


Figure D.4 *Return On Investment that includes* ***Residual Value****. Percentage difference of Offsite measure using Internal Wall Insulation and Roof*

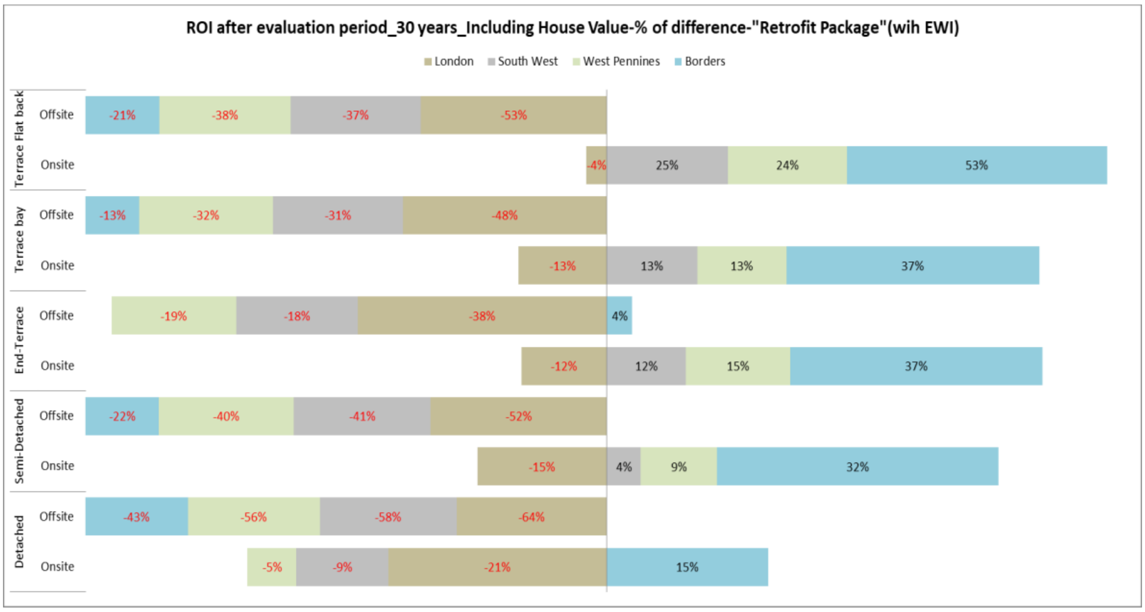


Figure D.5 *Return On Investment that includes **House Value**. Percentage difference of Offsite measure using "Retrofit Package"*

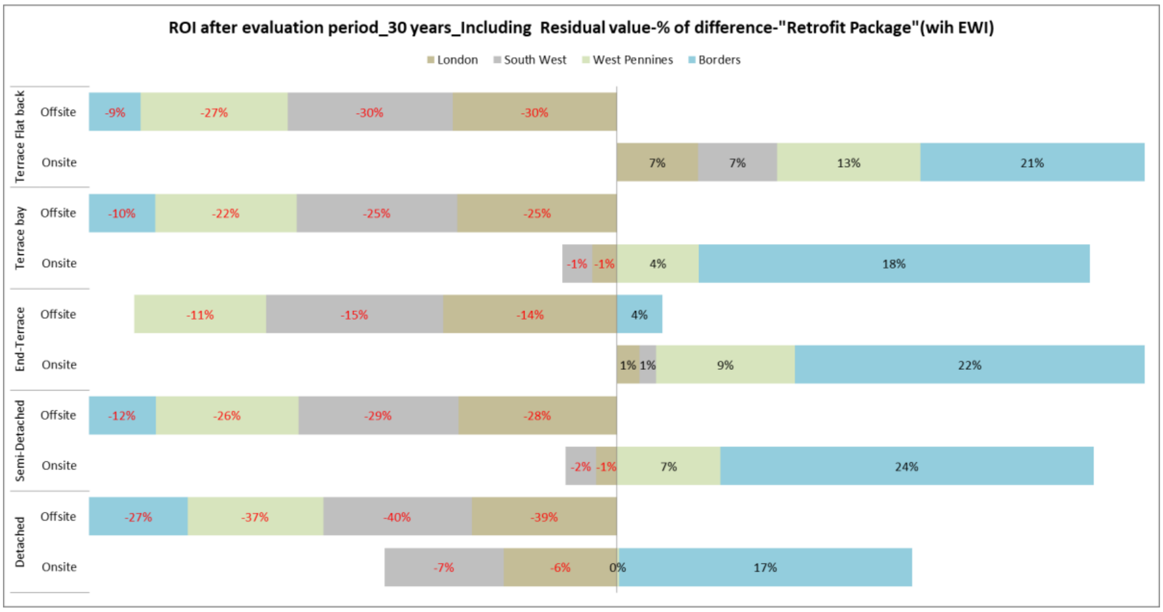
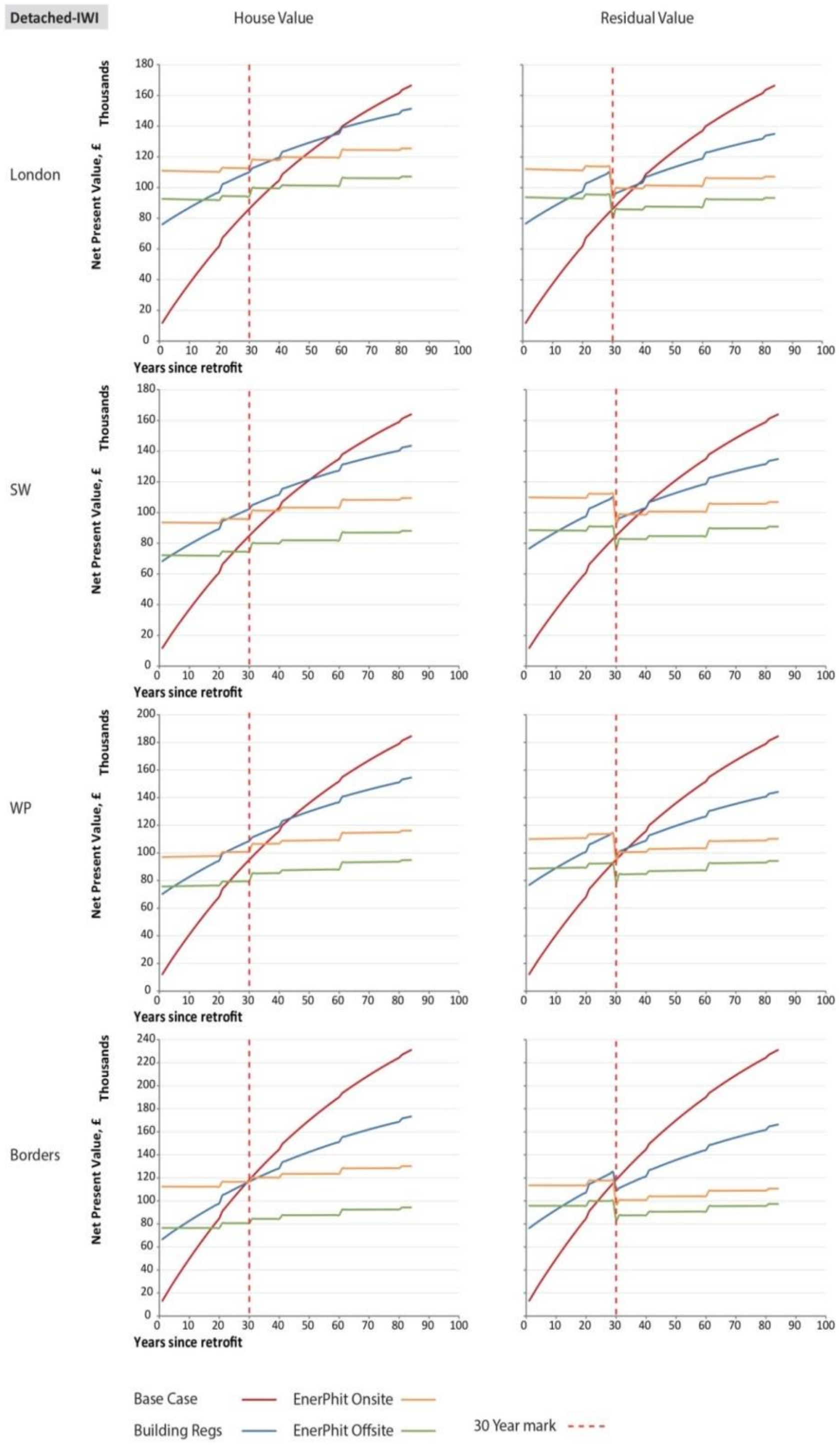


Figure D.6 *Return On Investment that includes **Residual Value**. Percentage difference of Offsite measure using "Retrofit Package"*

Appendix E – NVP per typology



London including House Value payback time (years)
Offsite: 37
Onsite: 47
Residual Offsite:30
Onsite :40

South West including House Value payback time (years)
Offsite: 26
Onsite: 39
Residual Offsite:30
Onsite: 39

West Pennines including House Value payback time (years)
Offsite: 22
Onsite: 35
Residual Offsite:29
Onsite: 33

Borders including House Value payback time (years)
Offsite: 18
Onsite: 29
Residual Offsite:25
Onsite:30

Figure E.1 *Net Present Value with Internal Wall Insulation-Detached*

The Building Regulations scenario is only below the 30 year mark in the Borders region (including House Value).

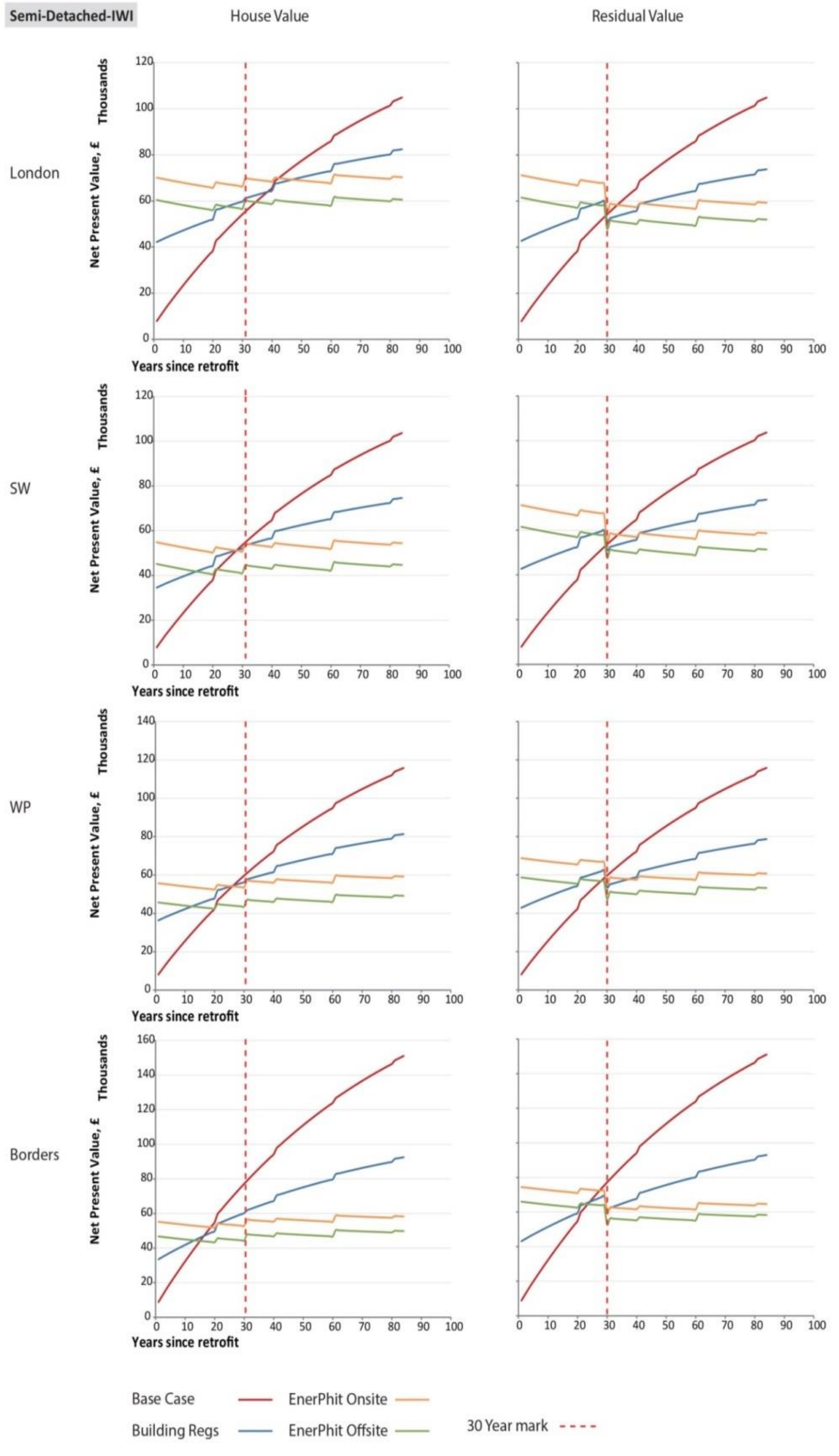


***Figure E.2** Net Present Value with Internal Wall Insulation-Semi-Detached*

London including House Value payback time (years)
Offsite: 32
Onsite: 42
Residual Offsite:30
Onsite :32

South West including House Value payback time (years)
Offsite: 22
Onsite: 28
Residual Offsite:30
Onsite: 32

West Pennines including House Value payback time (years)
Offsite: 20
Onsite: 27
Residual Offsite: 28
Onsite: 30

Borders including House Value payback time (years)
Offsite: 15
Onsite: 18
Residual Offsite: 22
Onsite: 28

The Building Regulations scenario is below the 30 year mark in all regions with the exception of London (including House Value).

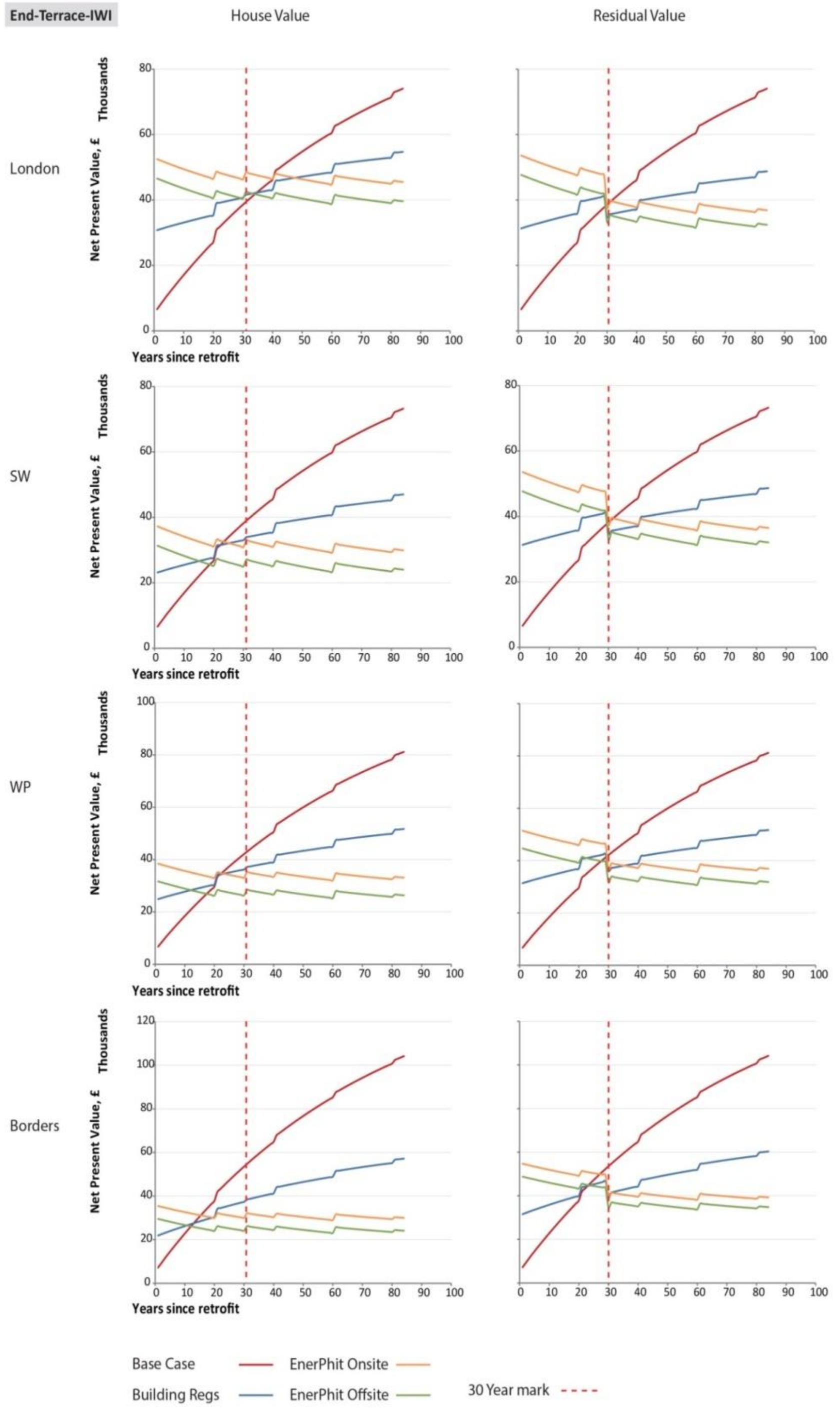


Figure E.3 *Net Present Value with Internal Wall Insulation-End-Terrace*

London including House Value payback time (years)
Offsite: 32
Onsite: 42
Residual Offsite:30
Onsite :30

South West including House Value payback time (years)
Offsite: 18
Onsite: 22
Residual Offsite:30
Onsite: 30

West Pennines including House Value payback time (years)
Offsite: 17
Onsite: 22
Residual Offsite: 28
Onsite: 30

Borders including House Value payback time (years)
Offsite: 12
Onsite: 16
Residual Offsite: 22
Onsite: 27

The Building Regulations scenario is below the 30 year mark in all regions with the exception of London (including House Value).

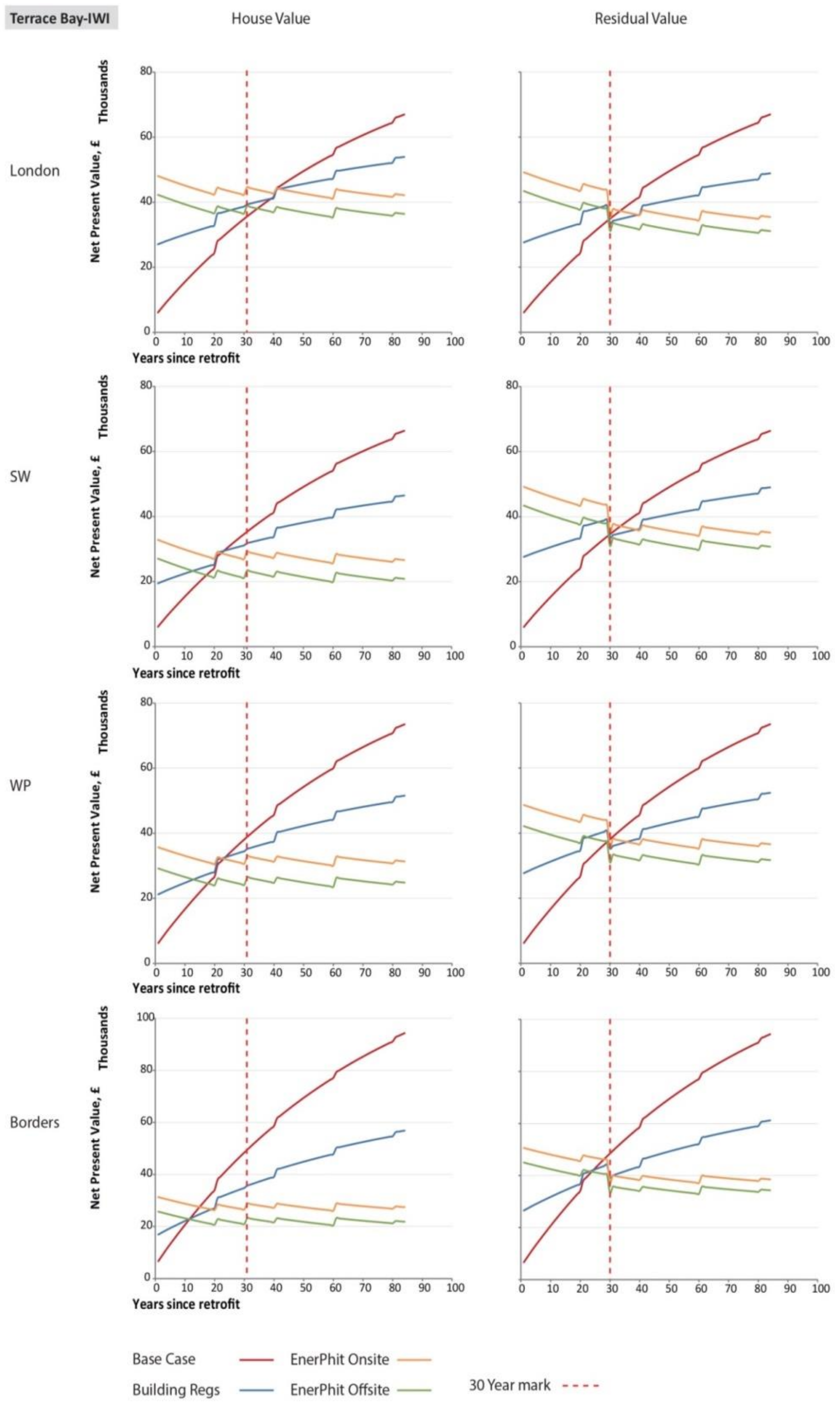


Figure E.4 *Net Present Value with Internal Wall Insulation- Terrace Bay*

London including House Value payback time (years)
Offsite: 32
Onsite: 42
Residual Offsite:30
Onsite : 32

South West including House Value payback time (years)
Offsite:16
Onsite: 22
Residual Offsite:30
Onsite: 32

West Pennines including House Value payback time (years)
Offsite: 19
Onsite: 23
Residual Offsite: 30
Onsite: 31

Borders including House Value payback time (years)
Offsite: 11
Onsite: 15
Residual Offsite: 24
Onsite: 29

The Building Regulations scenario is below the 30 year mark in all regions with the exception of London (including House Value).

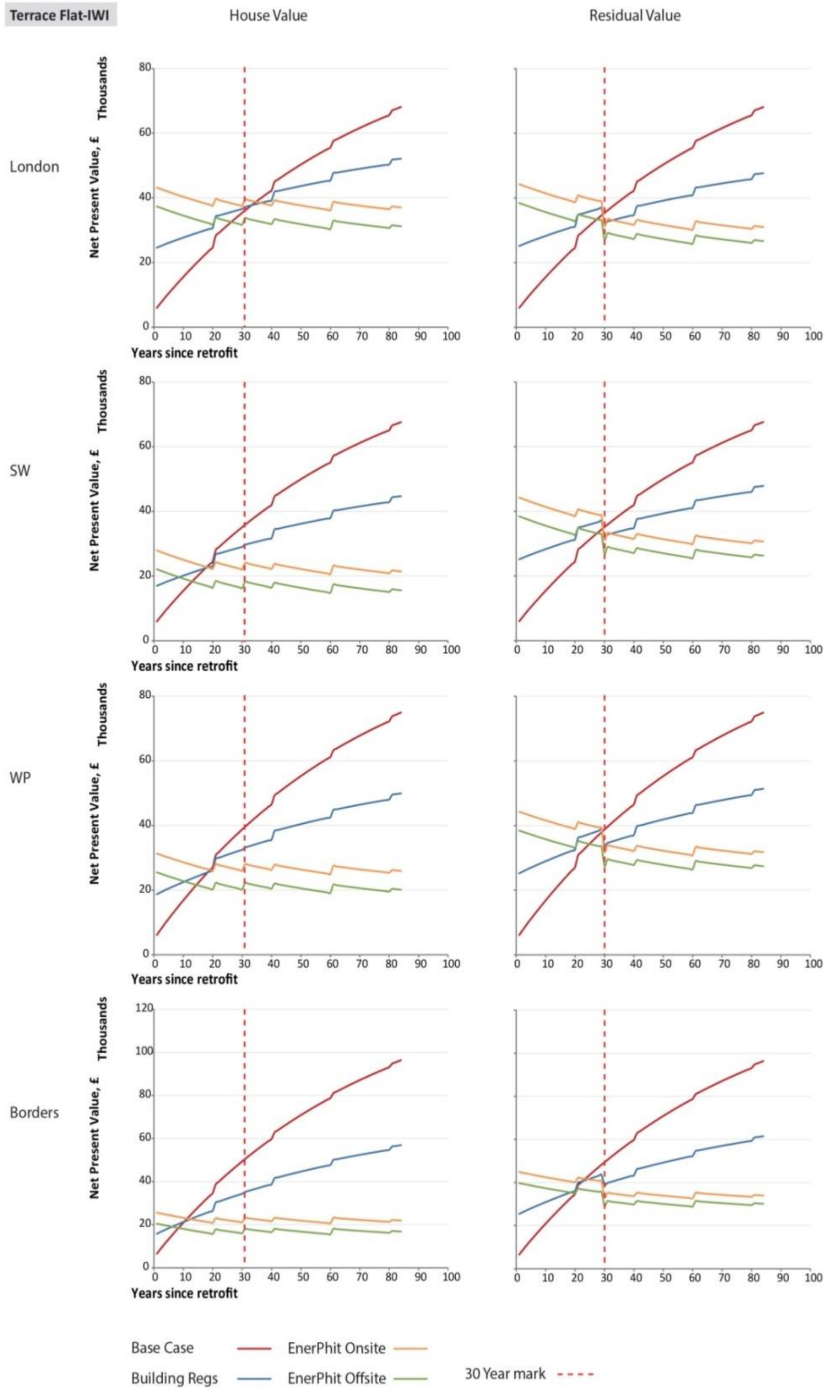


***Figure E.5** Net Present Value with Internal Wall Insulation-Terrace-Flat*

The Building Regulations scenario when House Value is included is below the 30 year mark in all regions with the exception of London and in Borders when the Residual Value is taken into account.

London including House Value payback time (years)
Offsite: 28
Onsite: 33
Residual Offsite:29
Onsite: 30

South West including House Value payback time (years)
Offsite: 12
Onsite: 18
Residual Offsite: 29
Onsite: 30

West Pennines including House Value payback time (years)
Offsite: 13
Onsite: 17
Residual Offsite: 25
Onsite: 30

Borders including House Value payback time (years)
Offsite: 8
Onsite: 11
Residual Offsite: 20
Onsite: 22

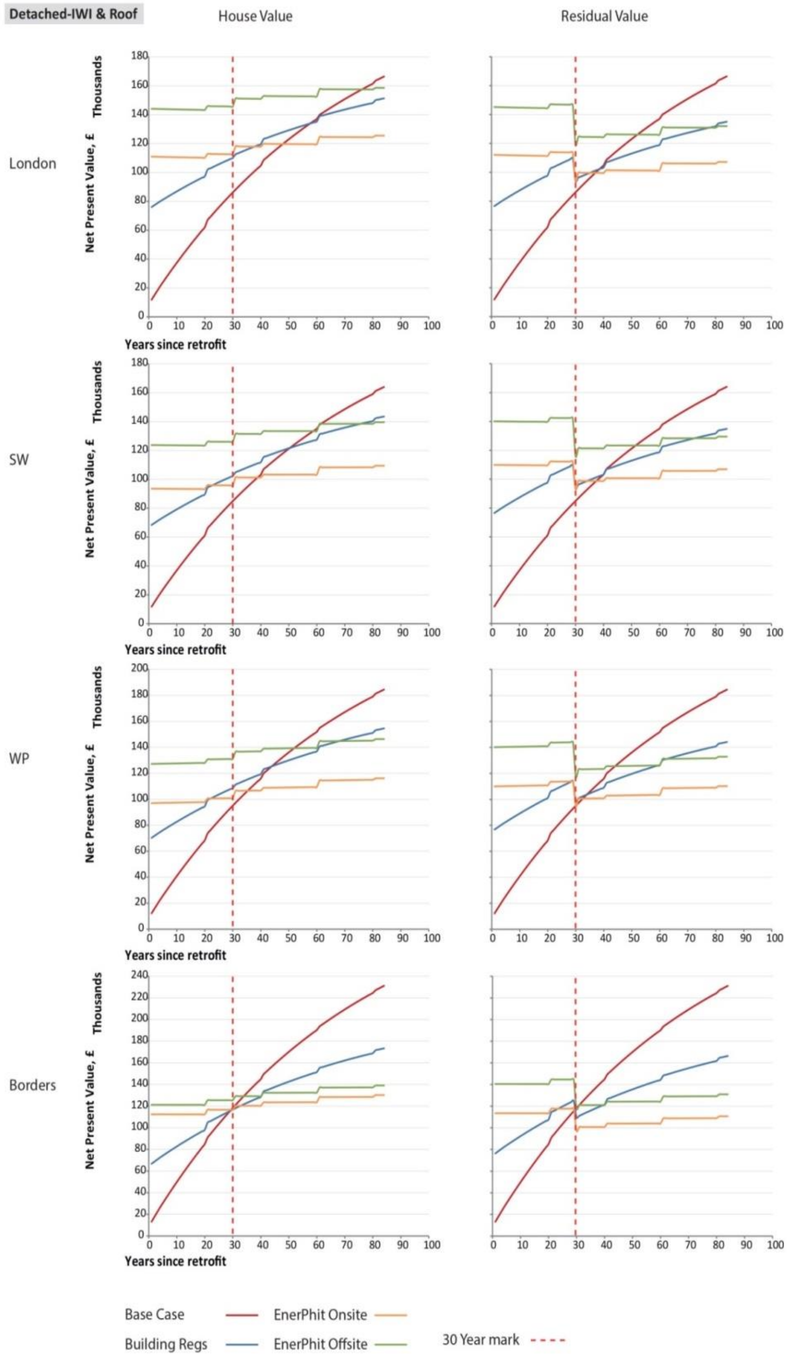


***Figure E.6** Net Present Value with Internal Wall Insulation and Roof –Detached*

London including House Value payback time (years)

Offsite: 75

Onsite: 47

Residual Offsite: 51

Onsite :40

South West including House Value payback time (years)

Offsite: 58

Onsite: 39

Residual Offsite: 51

Onsite: 39

West Pennines including House Value payback time (years)

Offsite: 51

Onsite: 35

Residual Offsite:42

Onsite: 33

Borders including House Value payback time (years)

Offsite: 34

Onsite: 29

Residual Offsite:30

Onsite:30

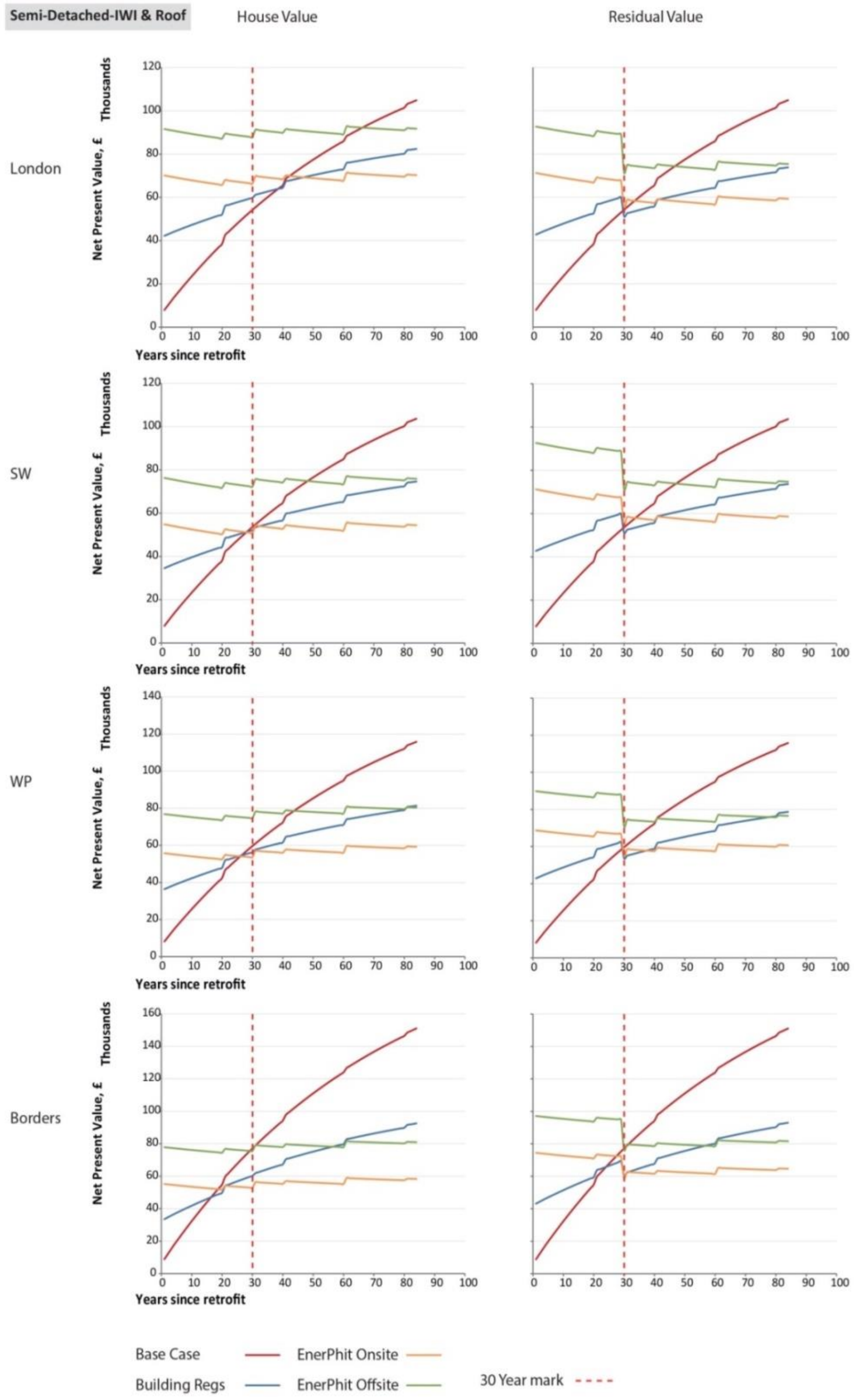


***Figure E.7** Net Present Value with Internal Wall Insulation and Roof –Semi-Detached*

London including House Value payback time (years)

Offsite: 65

Onsite: 42

Residual Offsite:47

Onsite :30

South West including House Value payback time (years)

Offsite: 48

Onsite: 28

Residual Offsite:47

Onsite: 32

West Pennines including House Value payback time (years)

Offsite: 43

Onsite: 27

Residual Offsite: 40

Onsite: 30

Borders including House Value payback time (years)

Offsite: 29

Onsite: 18

Residual Offsite: 30

Onsite: 28

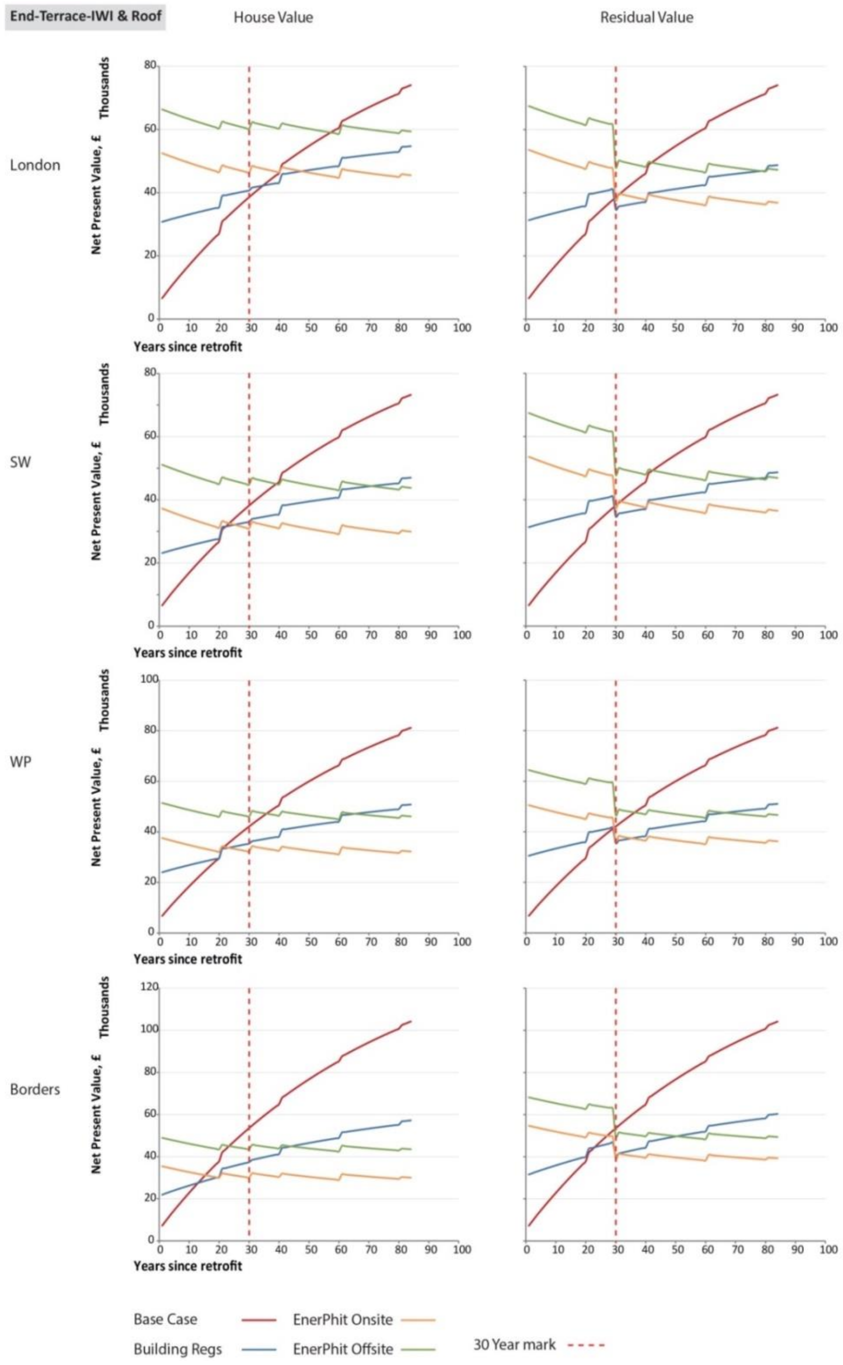


***Figure E.8** Net Present Value with Internal Wall Insulation and Roof –End Terrace*

London including House Value payback time (years)

Offsite: 58

Onsite: 42

Residual Offsite:41

Onsite :30

South West including House Value payback time (years)

Offsite: 38

Onsite: 22

Residual Offsite:41

Onsite: 30

West Pennines including House Value payback time (years)

Offsite: 35

Onsite: 22

Residual Offsite: 30

Onsite: 30

Borders including House Value payback time (years)

Offsite: 23

Onsite: 16

Residual Offsite: 30

Onsite: 27

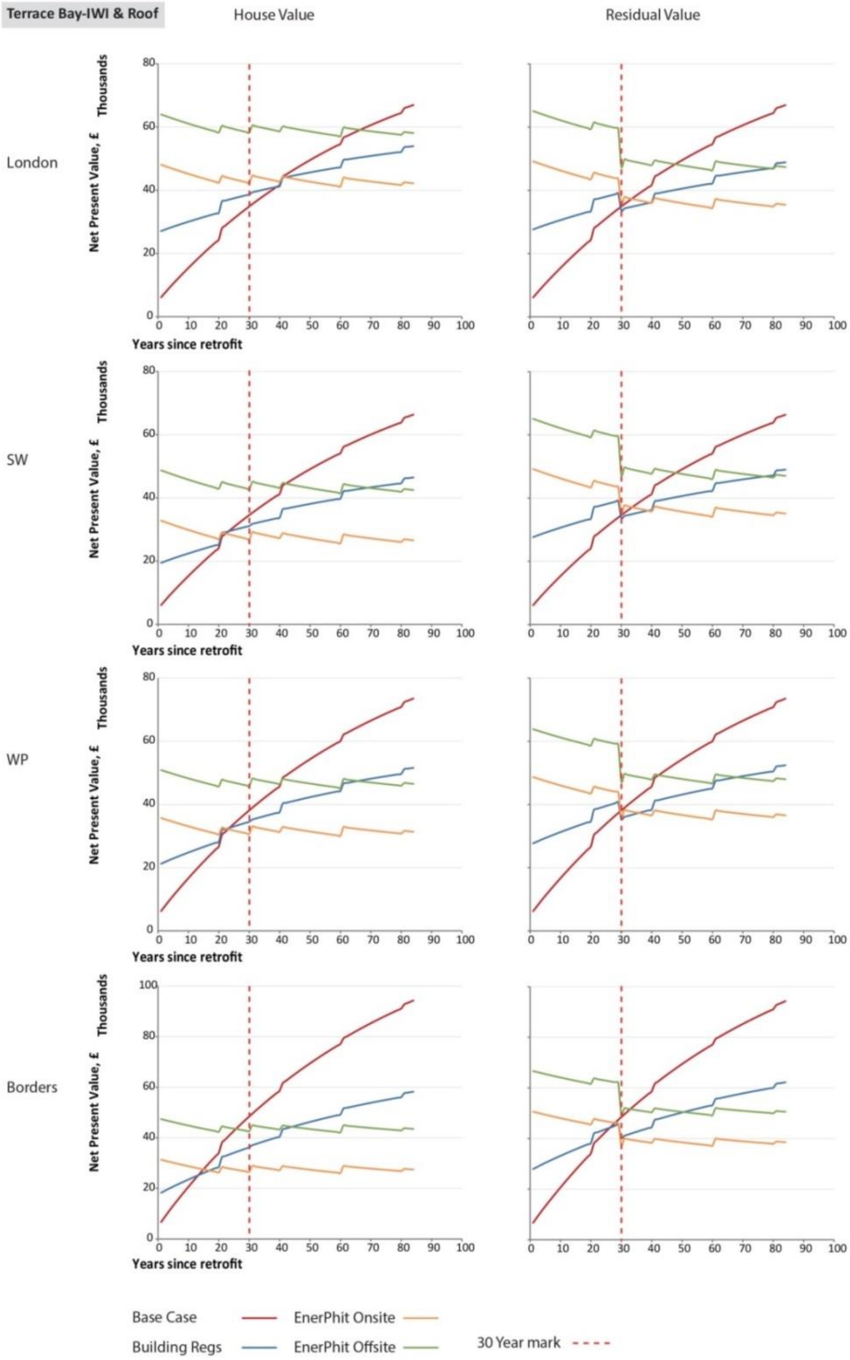


Figure E.9 *Net Present Value with Internal Wall Insulation and Roof- Terrace-Bay*

London including House Value payback time (years)

Offsite: 65

Onsite: 42

Residual Offsite:48

Onsite : 32

South West including House Value payback time (years)

Offsite:41

Onsite: 22

Residual Offsite: 48

Onsite: 32

West Pennines including House Value payback time (years)

Offsite: 40

Onsite: 23

Residual Offsite: 42

Onsite: 31

Borders including House Value payback time (years)

Offsite: 25

Onsite: 15

Residual Offsite: 33

Onsite: 29

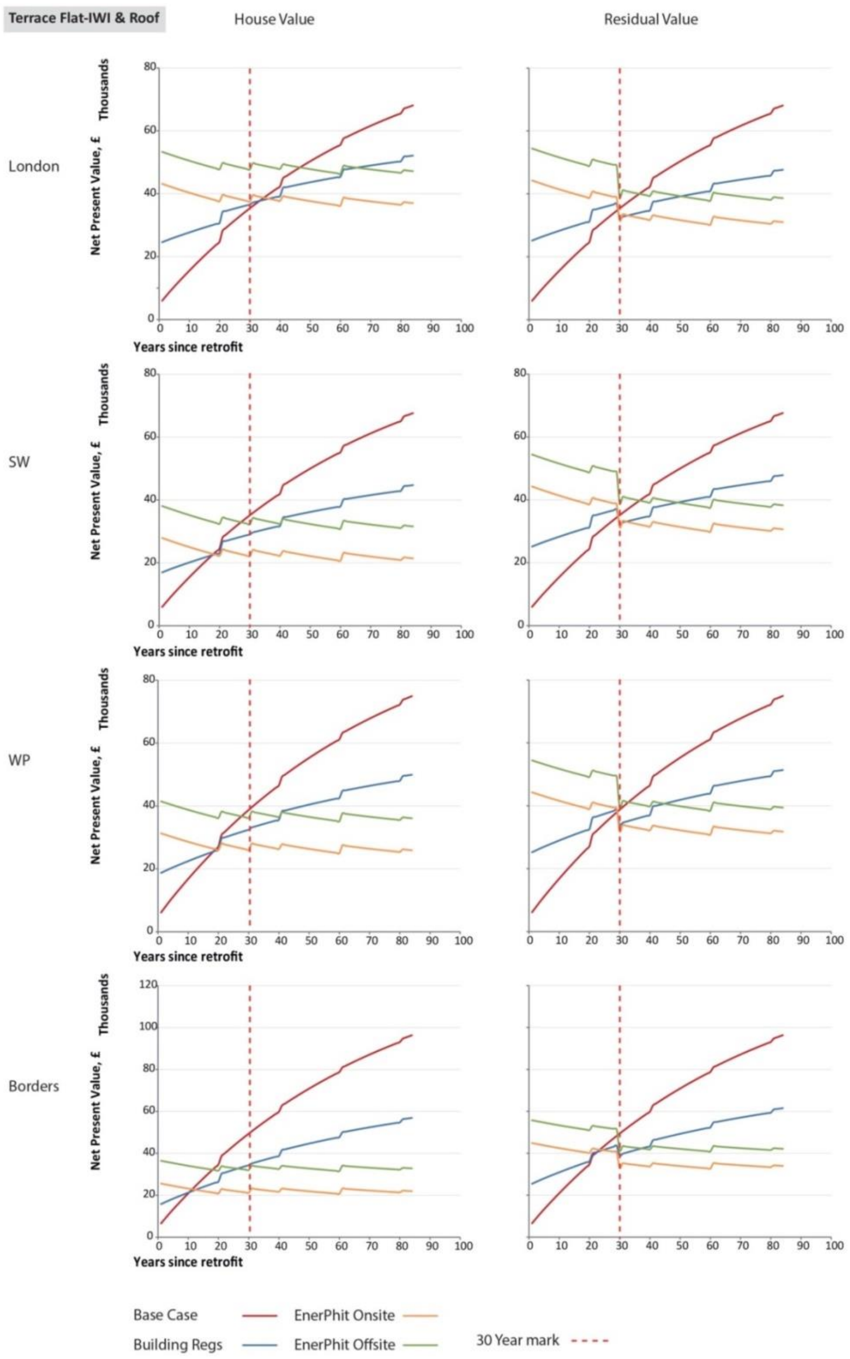


Figure E.10 *Net Present Value with Internal Wall Insulation and Roof –Terrace Flat*

London including House Value payback time (years)
Offsite: 47
Onsite: 33
Residual Offsite:36
Onsite: 30

South West including House Value payback time (years)
Offsite: 28
Onsite: 18
Residual Offsite:35
Onsite: 30

West Pennines including House Value payback time (years)
Offsite: 27
Onsite: 17
Residual Offsite: 32
Onsite: 30

Borders including House Value payback time (years)
Offsite: 18
Onsite: 11
Residual Offsite: 29
Onsite: 22

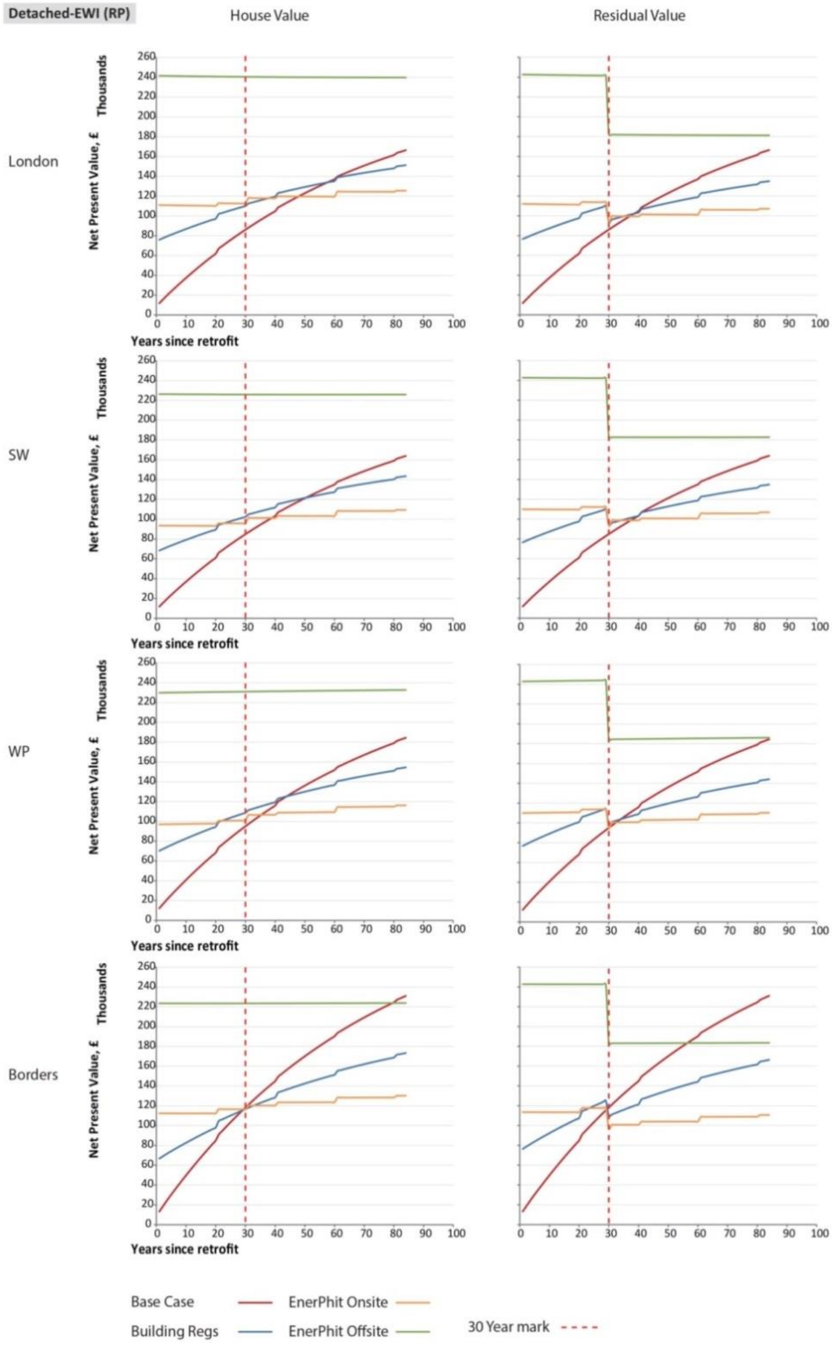


Figure E.11 *Net Present Value with "Retrofit Package"- Detached*

London including House Value payback time (years)
Offsite: >100
Onsite: 47
Residual Offsite: >100
Onsite :40

South West including House Value payback time (years)
Offsite: >100
Onsite: 39
Residual Offsite: >100
Onsite: 39

West Pennines including House Value payback time (years)
Offsite: >100
Onsite: 35
Residual Offsite:85
Onsite: 33

Borders including House Value payback time (years)
Offsite: 79
Onsite: 29
Residual Offsite:58
Onsite:30

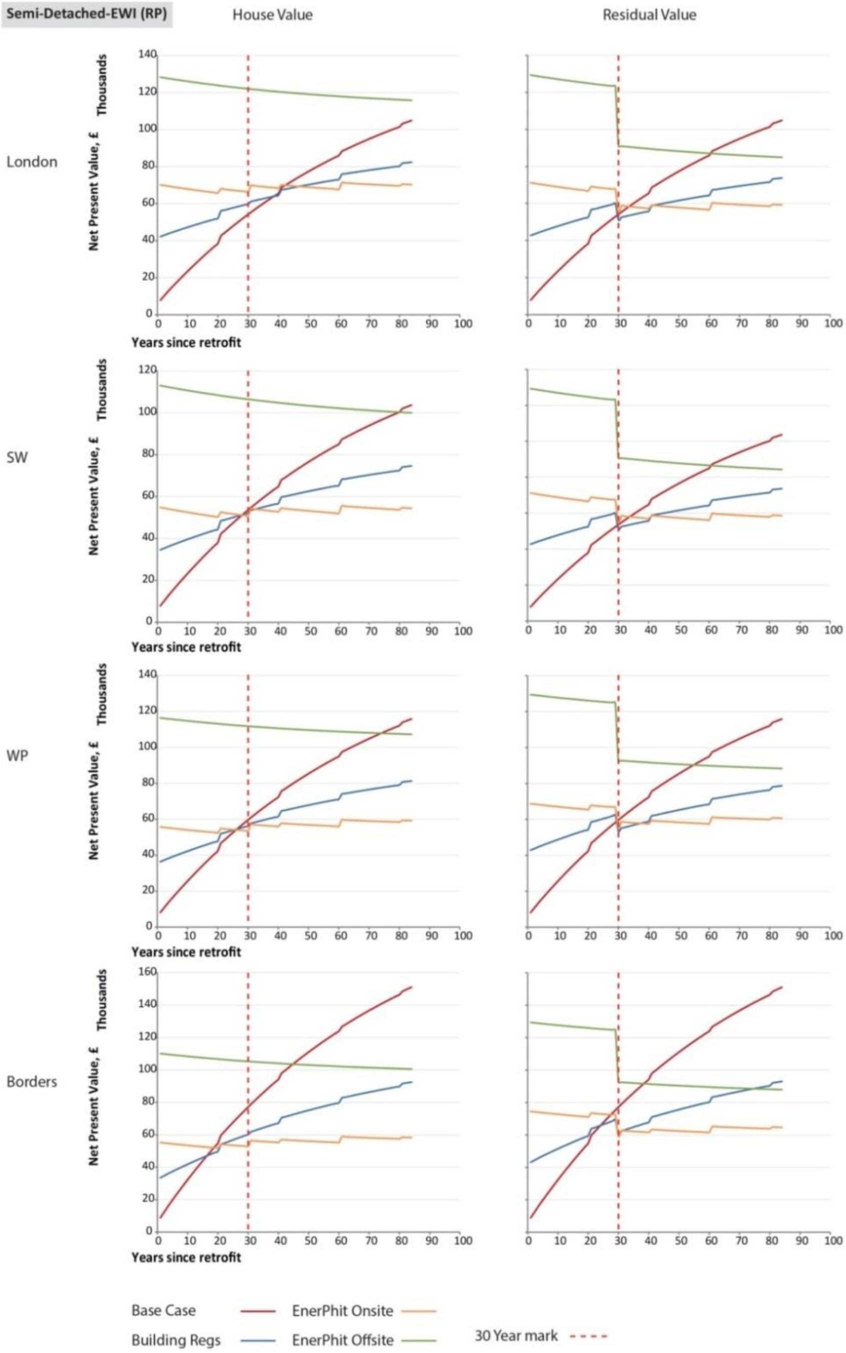


Figure E.12 *Net Present Value with "Retrofit Package"-Semi-Detached*

London including House Value payback time (years)
Offsite: >100
Onsite: 42
Residual Offsite: 60
Onsite :30

South West including House Value payback time (years)
Offsite: 79
Onsite: 28
Residual Offsite:60
Onsite: 32

West Pennines including House Value payback time (years)
Offsite: 73
Onsite: 27
Residual Offsite: 55
Onsite: 30

Borders including House Value payback time (years)
Offsite: 45
Onsite: 18
Residual Offsite: 38
Onsite: 28

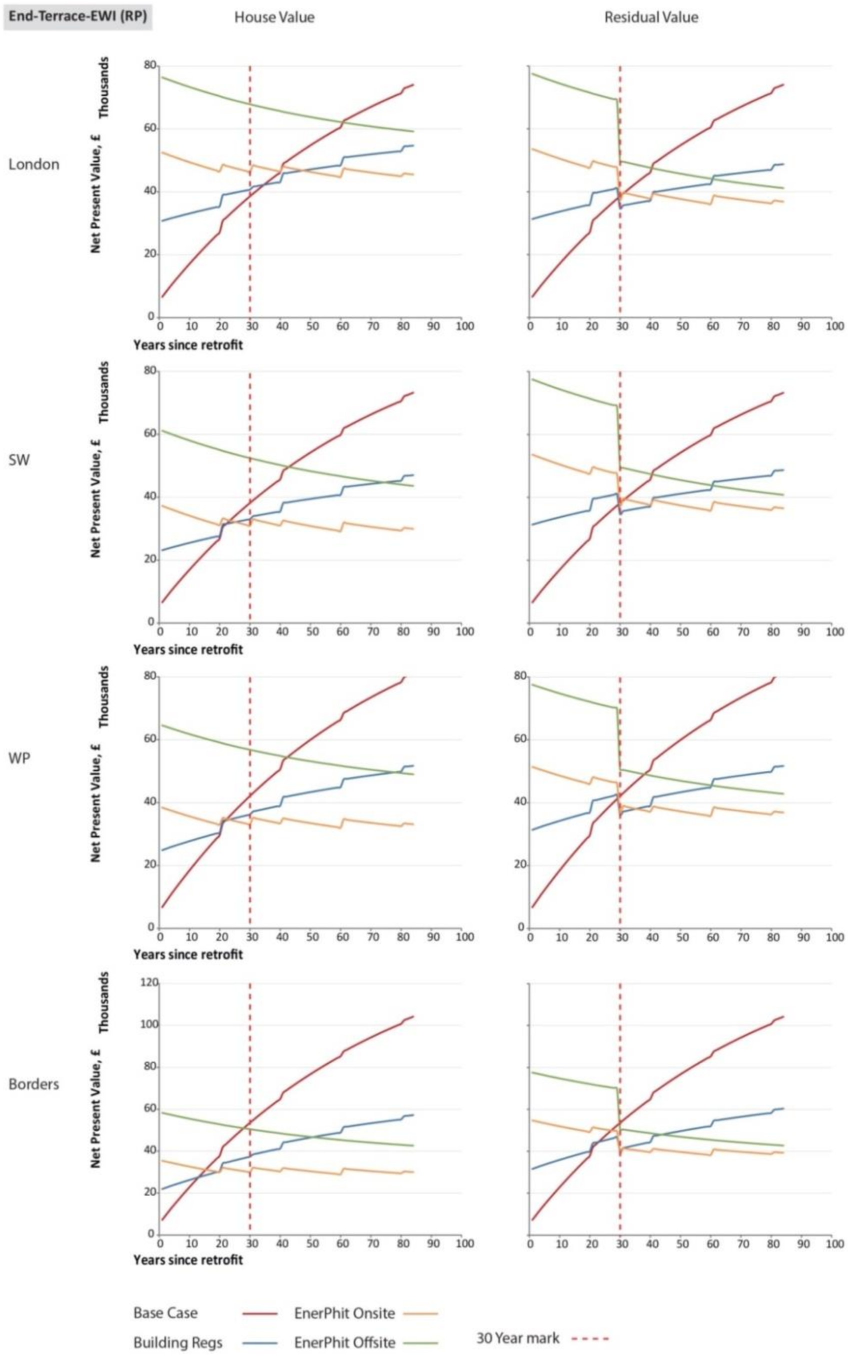


Figure E.13 *Net Present Value with "Retrofit Package"-End-Terrace*

London including House Value payback time (years)

Offsite: 60

Onsite: 42

Residual Offsite:40

Onsite :30

South West including House Value payback time (years)

Offsite: 43

Onsite: 22

Residual Offsite:40

Onsite: 30

West Pennines including House Value payback time (years)

Offsite: 42

Onsite: 22

Residual Offsite: 39

Onsite: 30

Borders including House Value payback time (years)

Offsite: 29

Onsite: 16

Residual Offsite: 30

Onsite: 27

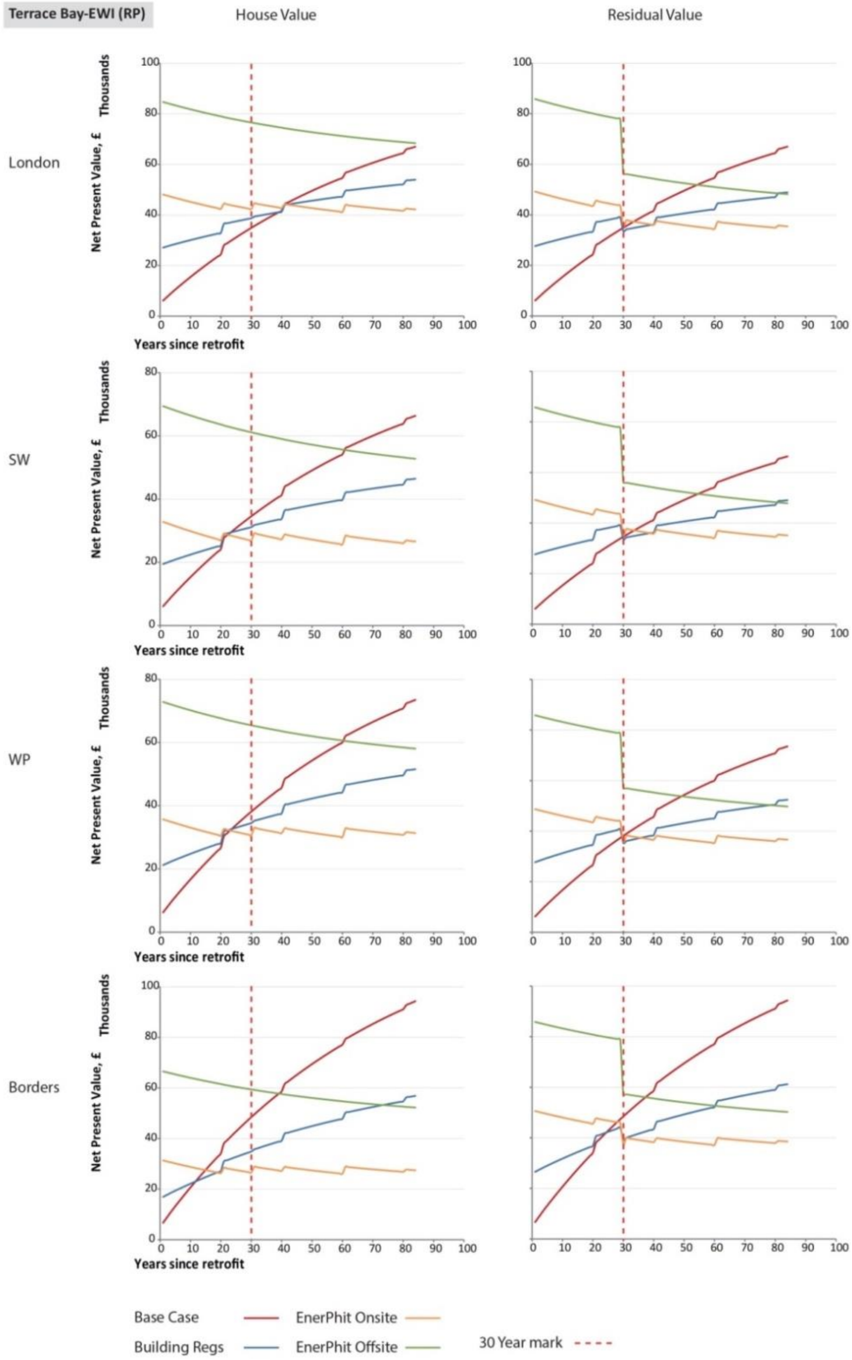


Figure E.14 *Net Present Value with "Retrofit Package"-Terrace-Bay*

London including House Value payback time (years)

Offsite: 95

Onsite: 42

Residual Offsite:53

Onsite :30

South West including House Value payback time (years)

Offsite: 60

Onsite: 22

Residual Offsite: 55

Onsite: 30

West Pennines including House Value payback time (years)

Offsite: 60

Onsite: 22

Residual Offsite:50

Onsite: 30

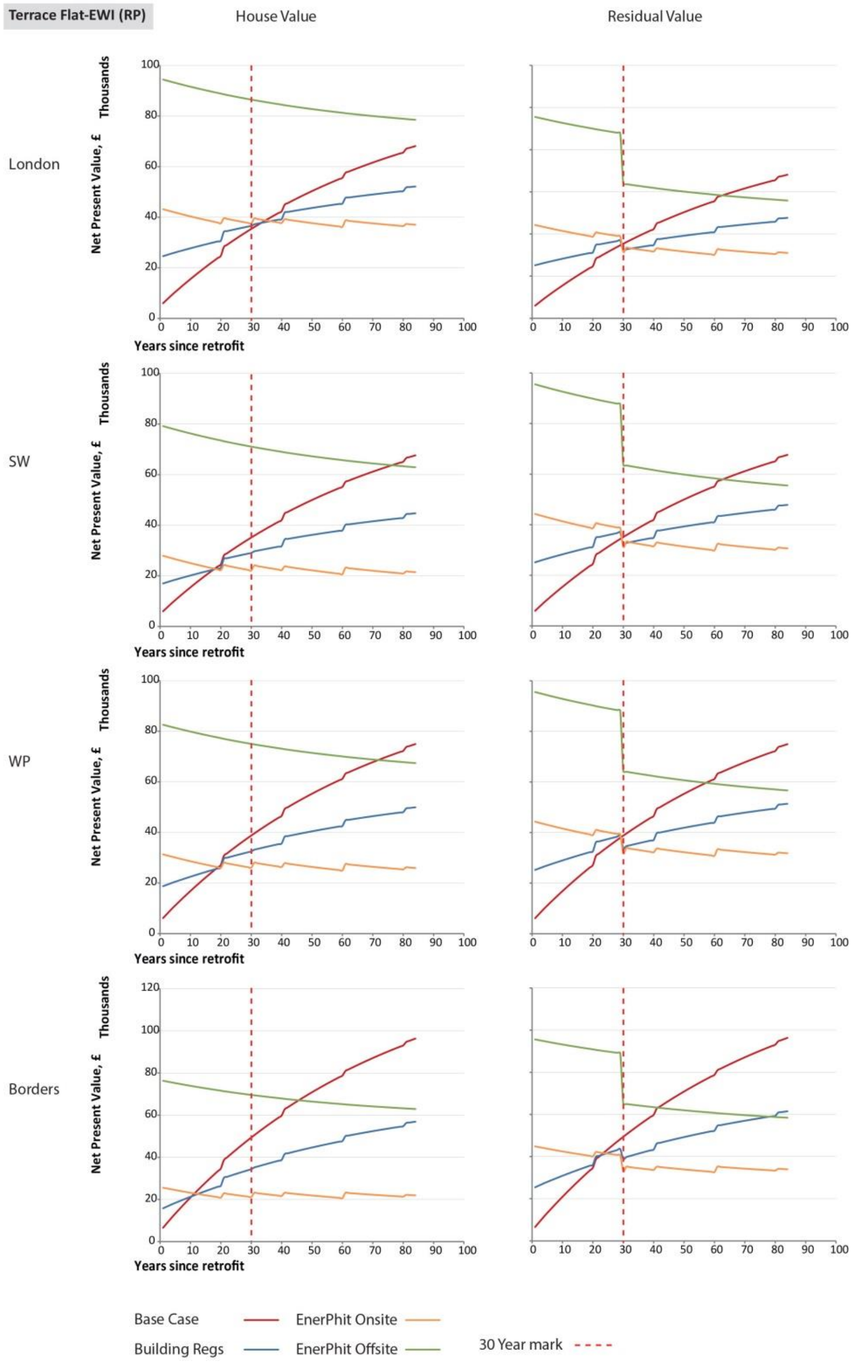
Borders including House Value payback time (years)

Offsite: 39

Onsite: 16

Residual Offsite: 38

Onsite: 27



London including House Value payback time (years)

Offsite: >90

Onsite: 33

Residual Offsite:62

Onsite: 30

South West including House Value payback time (years)

Offsite: 78

Onsite: 18

Residual Offsite: 62

Onsite: 30

West Pennines including House Value payback time (years)

Offsite: 72

Onsite: 17

Residual Offsite: 58

Onsite: 30

Borders including House Value payback time (years)

Offsite: 45

Onsite: 11

Residual Offsite: 41

Onsite: 22

Figure E.15 *Net Present Value with “Retrofit Package“-Terrace-Flat*