Cardiff University- School of Engineering

Modelling the embodied energy of the UK housing stock for shallow refurbishment

by

Eman Mohamed El-alwani

Bachelor of Architectural Engineering (B.Eng.)

A dissertation submitted to Cardiff University in partial fulfilment of the requirements for the degree of Master of Philosophy in Sustainable Engineering.

(May 2016)

.

I dedicate this work to the spirit of my father,

Mohamed Ali El-alwani

Acknowledgment

It is a great opportunity to thank my both supervisors; Dr. Monjur Mourshed and Dr. Thomas Beach for their help and support to make this thesis possible.

I would also offer my gratitude to all of those supported me at any respect during the completion of the project, my family and friends.

Abbreviations

CHM	Cambridge Housing Model
EE	Embodied Energy
OPE	Operational Energy
EPC	Energy performance Certificate
DECC	Department of Energy Climate Change
BRE	Building Research Environment
SAP	Standard Assessment Procedure
CERT	Carbon Emissions Reduction Target
ECO	Energy Company Obligation
CESP	Community Energy Saving program
RCEP	Royal Commission Environment Project
SEEH	Swedish Energy Efficient Homes
FEES	Fabric Energy Efficiency Standard
WG	Weather Generator
HEEP	Household Energy End-use Project
MMC	Modern Methods of Construction
HEFE	Housing Energy Fact File
ECUK	Energy Consumption in the UK
ICE	Inventory of Carbon and Energy
DHWS	Domestic Hot Water System
EHS	English Housing Survey

Table of Contents

List of figures

List of tables

List of equations

Abstract

Energy conservation and carbon emissions reduction are ways of mitigating the damage caused to the environment as a result of greenhouse gas emissions. All activities that consume energy also produce carbon dioxide (CO_2), which, in turn, contributes to greenhouse gas emissions. Energy use in buildings accounts for 40-50% of the UK's CO_2 emissions, and the residential sector contributes more than half of these emissions.

The Climate Change Act (2008) has committed to reducing the UK's current carbon dioxide emissions by 80% by 2050. The Act is considered the primary mechanism for achieving the desired cut in emissions and it requires local authorities to draw up plans to improve their domestic energy efficiency by 30% over the next 10-15 years. The Department of the Environment, Transport, and Regions (DETR) has estimated that a 30% reduction in domestic energy consumption is possible through energy conservation and efficiency without effecting services standards. Considering that new builds represent just 1% of the overall housing stock, action must be taken to renovate existing dwellings in order to improve their energy efficiency.

These renovations, however, must be considered in the light of embodied energy that will be consumed in their undertaking. In this case, embodied energy comprises all the energy inputs that are needed to manufacture the material elements of the building that are being renovated. Great care must be taken to ensure that embodied energy consumed is considered when planning renovations to existing housing stock.

This thesis will document how the required reduction in the greenhouse gas emissions from the UK housing stock can be achieved and to outline ways of reducing the impact of domestic emissions on the environment, considering at all times, the embodied energy that is required to do so. Secondly, it aims to provide efficient homes with lower energy bills and to convince householders to implement appropriate retrofit solutions to improve the energy efficiency of their dwellings.

To achieve this, the Cambridge Housing Model 2010 was used as a direct source of housing data in order to create an embodied energy model that allow a direct comparison of the embodied energy and the operational energy gains and various refurbishment strategies.

This model was used to test various de-carbonisation scenarios that build towards achieving the targeted reduction in CO_2 emissions. This entailed the identification of the optimal insulation of each

building element, refurbishing the building fabric, insstalling double-glazing and installing more efficient building systems.

Outputs from these scenarios were compared with regard to energy consumption (both embodied and operational), cost and CO_2 emissions, to predict the most efficient and cost-effective scenario for the entire UK housing stock.

The results of this study show that embodied energy is a vital factor because the lower the embodied energy of the insulation, the greater the energy conservation and the shorter the payback periods for any renovation.

This study also has found that mineral wool was the most efficient cavity wall insulation, whereas the optimal insulants for warm- and cold-pitched roofs were expanded polystyrene (EPS) and cellular glass, respectively. Cellular glass was the only applicable insulation for internal and external walls and sheep wool was far more efficient for floor insulation.

The analysis conducted confirmed the findings outlined in the literature review that suggested embodied energy is a significant contributor to energy efficiency. Further results have also shown that retrofitting a dwelling's fabric and building services systems can considerably improve energy performance and help to achieve the energy efficiency standards that have been set by the UK government.

Finally, this research has proven that retrofitting, as opposed to rebuilding, is the most practical and feasible solution to achieving the desired emissions reductions by 2050.

Chapter 1
Introduction

The UK government has committed to achieving an 80% reduction in carbon dioxide emissions by 2050. In order to achieve this, the reduction of emissions from domestic properties is essential. The research documented in this thesis aims to outline ways of reducing the impact of domestic emissions on the environment and encourage the use of available technologies in new build houses to lower their environmental impact.

Shallow refurbishment includes all the basic measures that support energy efficiency at minimum costs with no focus on new technologies and renewable energy sources. Basically, this strategy represents the available refurbishments in the UK, and in most of the cases applies installation of double glazed windows, replacement of boilers and insulating walls, roofs and floors where applicable(Martjanova, 2015).

Deep refurbishment measure applies new technologies and uses renewable energy sources. This strategy should influence not only energy efficiency of the building, but also add the new architectural value of the refurbishment by introducing new volumes or elements to the building. Energy efficiency by this strategy could reach more than 60%(Martjanova, 2015).

1.1 Background

While there are various ways to define embodied energy based on the discussion of the study, one of the most appropriate definitions has been put forward by (Crowther, 1999), who writes that embodied energy is:

The total energy needed in the building creation, including the direct energy used in the assembly and construction process, and the indirect energy that is required to manufacture the materials and components of the building. This indirect energy includes all energy required from the raw material extraction, through processing, manufacturing, construction and transportation.

Embodied energy comprises all the energy inputs that are needed to manufacture the material elements of building, such as flooring, glazing, roofing, fittings and fixtures. Embodied energy can be defined as the total energy utilised in the extraction of natural resources, processing them, producing building materials, and constructing a building. This may also include the energy used in transportation at each stage. Renovation, maintenance and demolition are also considered within the embodied energy calculation during the lifecycle of a building (Williams et al., 2000).

Factors such geographical location, technology, and the machinery involved in the manufacturing process, along with the construction's type, play a significant role in determining the embodied energy of the material (Williams et al., 2000; Crowther, 1999). Increasing a building's energy efficiency in order to reduce its operational energy usage has become a prime concern worldwide (DECC, 2012). However, operational energy is only one aspect of the total energy consumption. Embodied energy is usually neglected when calculating the total energy consumption of dwellings (Alcorn and Wood, 1998). However, recent research (DECC, 2012; ECUK, 2015) has indicated the importance of embodied energy as it accounts for approximately 20% of the total dwelling energy consumption. "The energy embodied in new construction and renovation each year accounts for about 10% of the United Kingdom's energy consumption"(Sustainable Homes, 1999). Therefore, in order to analyse the total energy usage and make improvements to it, it is important to consider the significance of the embodied energy in the extraction, processing, manufacturing and delivery of building materials to the construction site (Climate Change Act, 2008).

The British Government is under pressure to provide more housing while also encouraging a reduction in carbon emissions (DECC, 2012, UK green building council, 2015). A major source of the UK's current emissions emanates from the housing sector (The UK Fact File, 2013). Figure 1.1 shows the total energy consumed in the UK by sector. The energy use of residential buildings accounts for a third of the UK's total energy consumption and more energy is utilised in dwellings in the UK than in transportation and industry. This means that the housing sector presents a major opportunity to cut energy use and CO_2 emissions (The UK Fact File, 2013).

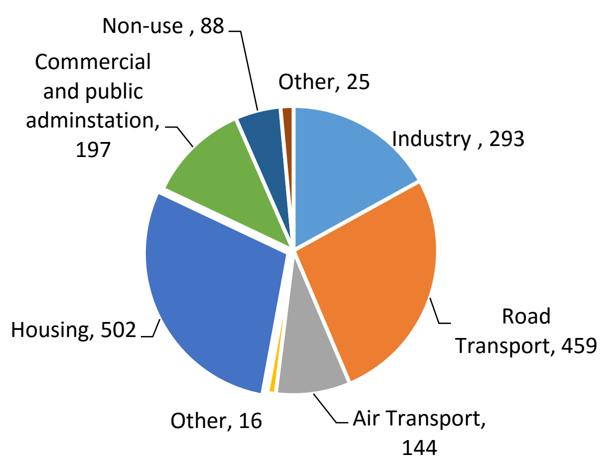


Figure 1.1: Total energy consumption by sector in TWh.
Source*:* The UK Fact File (2013)

Numerous factors affect the energy demands of a household. These include location, construction type, and occupant behaviour and the impact of these factors have changed over time (ECUK, 2015). It is known that the environmental performance of new housing stock has the potential to improve (Zachariadis, 2007). In 2014, the UK's total overall primary energy consumption was 193.4 million tonnes of oil equivalent. This was a reduction of 6.6% from the energy consumption in 2013, and a reduction of 7% from the usage in 2012. This year-on-year decrease is recorded as the third highest since before 1970 (ECUK, 2015).

This dramatic reduction in energy consumption has been attributed to the minimisation of the energy embodied in the housing sector by the use of passive house techniques, low-energy materials, more efficient building systems, increases in building fabric insulation and improved building regulations (Zachariadis, 2007). In addition, refurbishment of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions and plays a major role in addressing the UK's long-term emissions target (Climate Change Act, 2008).

1.2 Problem description

The United Kingdom's housing stock has been recorded as the least energy efficient stock in Europe, and it accounts for approximately a quarter of the UK's annual carbon emissions (Climate Change Act, 2008). Recently, this has given focus to both the government and the private sector in determining strategies to reduce CO_2 emissions from the UK's domestic housing stock (UK Green Building Council, 2015)

The government has committed to an 80% reduction in CO_2 emissions by 2050 (Climate Change Act, 2008). Energy use in buildings accounts for 40-50% of the UK's emissions, and the residential sector contributes more than half of these. Thus, the existing housing stock has a key part to play in achieving these reductions (DECC, 2012, Humar et al., 2011).

A complete renovation of the UK building fabric is therefore necessary (Climate Change Act, 2008). This renovation include windows, external doors, ground floors and roofs. Thirteen percent of the UK's CO_2 emission comes from the energy we use in homes for space heating and hot water. However, to achieve the stated reduction, a 29% cut in carbon emissions is required by 2022 in the residential sector alone (DECC, 2012, Humar et al., 2011, Roberts, 2008).

1.3 Research hypothesis

The hypothesis analysed in this thesis is:

""Modelling the embodied energy of the UK's housing stock can identify the most significant group of dwellings by age, location or type to target, in order to achieve the required reduction in the UK's gas emissions. Subsequently, it identifies the most efficient strategy for improving the energy usage of these buildings; either refurbishment or rebuilding".

1.4 Research questions

The research presented in this thesis addresses a number of issues that are central to substantiating the above hypothesis:

1. What is the most efficient strategy for improving the energy usage of, and reducing greenhouse gases emissions for, existing domestic properties in the UK: rebuilding or refurbishing of the dwelling?
2. Can refurbishing existing properties enable them to reach current new build standards?
3. Does the operational energy gain of refurbishments offset the embodied energy of the refurbishments?
4. What dwelling characteristics have the largest impact on the refurbishment payback periods?
5. What building element makes the biggest improvement in terms of energy conservation when refurbishing?
6. Are there any considerable differences in the energy performance of existing dwellings of the same type but in different locations?
7. Which is the more efficient and affordable when comparing the costs and energy conservation of the applied renovation scenarios?

1.5 Contribution to knowledge

Contribution 1: An understanding of how to refurbish the existing UK housing stock to be more energy efficient in order to meet the objectives stated in the Climate Change Act 2008 and to achieve a reduction in the UK's greenhouse gas emissions.

Contribution 2: In relation to buildings, the embodied energy is the energy required for the production, maintenance and demolition of a building where the operational energy can be defined as the energy consumed through the use of the building, which includes heating, appliances, lighting, and other systems.

Contribution 3: The majority of the related work in this field has focused on analysing small-scale models of a single building, or pairs of buildings, in a specific location in order to provide greater details, ease comparisons and reduce modelling errors. Small-scale models are useful for assessing the embodied energy and increasing the understanding of a specific area of study, but they never illustrate a complete picture of the whole stock. Therefore, this study was carried out on a national scale to explore the possibility of modelling the entire housing stock because of the variations in age and type within the UK housing profile.

Contribution 4: The study focused on a wider measure to control the embodied energy of housing stock and analysed some of the possible renovation scenarios that support the reduction of energy consumption in the residential sector. The research concentrates on proposing the best possible retrofit scenario for the existing stock to make it more energy efficient. Exploring various refurbishment measures by applying different renovation scenarios to the stock has enabled an investigation into the impact of each improvement individually and in combination with another refurbishment measure.

Contribution 5: An understanding of which retrofitting measures remain effective under the widest of climate change uncertainty. This contribution is important because there is a considerable uncertainty regarding how the projected changes in the UK's climate might develop over the next 50 years. Consequently, decisions are often based on the current thermal demand of the built environment. Thus, before applying any retrofitting measures, it is important to identify the ones that remain effective under the widest range of climate uncertainty.

Contribution 6: Each building is constructed from a combination of processed materials, and each of these materials contributes to the building's total emissions.

Contribution 7: Building refurbishment is the most practical and feasible solution to reduce the impact of domestic emissions on the environment over time and to save buildings from being demolished unnecessarily.

1.6 Overview of the study

The overall thesis organisation is presented in Figure 1.2. **Chapter 2** gives a brief introduction to embodied energy and the existing studies on the residential sector in the UK and Europe and summarises the findings of these studies. **Chapter 3** focuses on the field of insulation types and the refurbishment techniques that are currently available. The proposed renovation scenarios, the development of the embodied energy model and the research methodology are defined in **Chapter 4**. The results and analyses of determining the optimal insulation material for each building element and outlining the most efficient scenario is discussed in **Chapter 5**. **Chapter 6** states the conclusion of this report, outlines the study limitations and suggests some possible further work that could be done to improve this thesis.

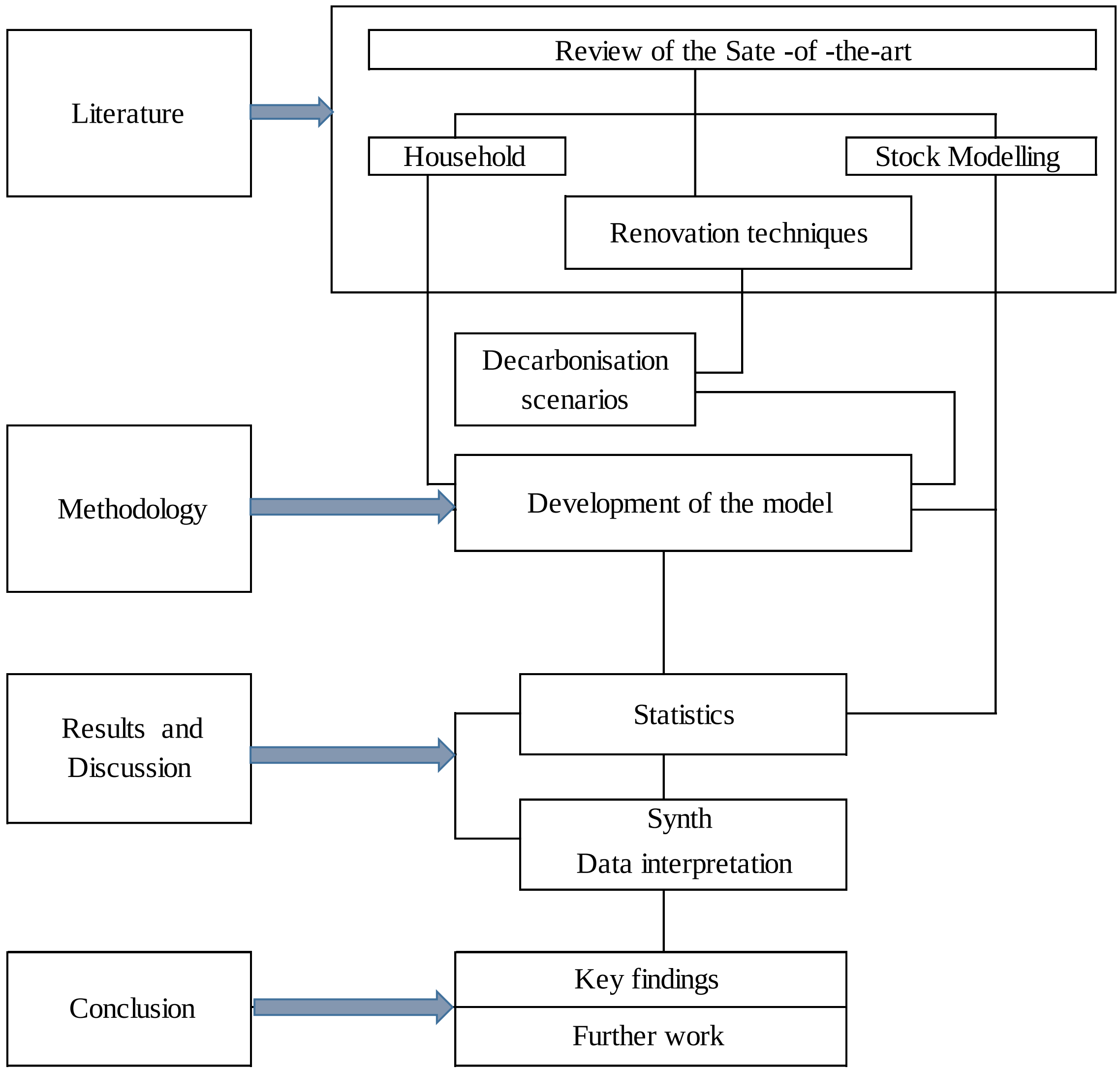


Figure 1.2: Study outline.

Chapter 2
Literature review

There has been a trend towards saving energy and cutting carbon emissions. Thus, a significant reduction in the building's operational energy by less dependency on natural resources and selecting better energy efficient alternatives is evident everywhere in the world (Osmani and O'Reilly, 2009). Embodied energy accounts for 20% of a dwelling's total consumption; therefore, decreasing embodied energy can significantly reduce the overall environmental impact of the building (Crowther, 1999, Dixit et al., 2010). Sections 2 and 2.2 will discuss the meaning and the importance of embodied energy in order to gain a deeper understanding of the concepts and the impact of embodied energy on the built environment.

2.1 Embodied energy

The embodied energy of a dwelling can be defined as the total energy needed for extracting the building materials, processing, manufacturing and delivering them to the construction site (Crowther, 1999). In general, it refers to *"the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to acquisition of the natural resources and the share of energy used in making equipment and in other supporting function i.e. direct energy plus indirect energy"* (Treloar, 2009).

However, there are various ways of defining embodied energy based on how the energy is consumed and according to the study's set boundaries. One these definitions, for example, relies on the way that energy is consumed and divides it into three main areas (Yohanis and Norton, 2002):

- **Initial energy**: the non-renewable energy that is utilised in the raw materials production process, manufacturing and transportation to the site. It has two main components: ***(a) Direct energy***, the energy used to transport the building products to the site, and then to construct the building; and ***(b) Indirect energy,*** the energy required to acquire, process and manufacture the building materials, including any transportation of these activities.
- **Recurring energy**: the energy needed to refurbish and maintain the building at any stage of its lifetime.
- **Demolition energy:** the energy required for a building's disposal at the end of its life (Yohanis and Norton, 2002).

Regarding the system boundaries, another definition of embodied energy was set out (Densley Tingley and Davison, 2012). Embodied energy can be defined by four phases, as shown in

Figure 2.1 namely: cradle-to-gate, cradle-to-site, cradle-to-grave and cradle-to-cradle. These boundaries determine the flexibility and rigidity of the system on the study’s goal and scope (Densley Tingley and Davison, 2012). Each boundary phase is explained as follows:

- **Cradle-to-Gate** describes the energy required to produce the finished product but no further considerations.
- **Cradle-to-Site** defines the embodied energy as the energy required to extract the raw materials, process and assemble them into usable products then transport them to a site.
- **Cradle-to-Grave** defines embodied energy as the consumed energy throughout a building's life. This method is useful for considering a building or a project holistically, although it is admittedly much more complicated to estimate.
- **Cradle-to-Cradle** is similar to cradle-to-grave but assumes that an existing building’s element has a final energy rate at the end of its first life, and the waste produced by the construction process can be treated as a raw material for any future re-production (Densley Tingley and Davison, 2012).

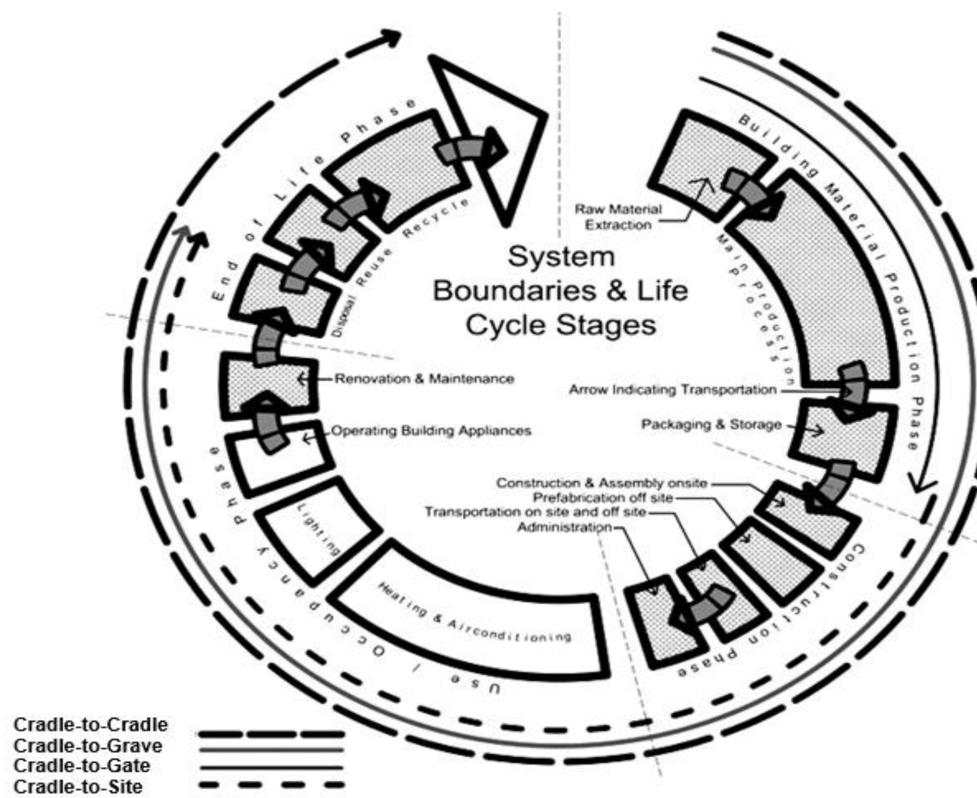


Figure 2.1: The common methods of assessing embodied energy.

Source: (Densley Tingley and Davison, 2012).

2.2 The importance of embodied energy

Due to the high proportion of operating energy in a building's total life cycle energy consumption, operating energy is often the sole focus when designing a building and the potential to limit operating energy has attracted recent attention (Alcorn and Wood, 1998).

However, the embodied energy that is required for material production and building construction has grown significantly (Ma et al., 2012). Recent research shows that the off-site production of construction elements accounts for three-quarters of the total energy embedded in buildings throughout their lifetimes (Barker et al., 2012). Thus, there is an authentic demand to calibrate the performance of buildings regarding both embodied and operating energy to reduce emissions. Each building is constructed from a combination of processed materials, and each of these materials contributes to the building's total emissions. The current emphasis has shifted to include the embodied energy of the construction materials due to the creation of more energy efficient equipment and appliances, along with more advanced and efficient insulation materials (Alcorn and Wood, 1998, Crowther, 1999, Dixit et al., 2010). Thus, embodied energy acts as an important component in the life cycle impact of a building. Furthermore, it is an important factor that needs to be considered when assessing the life cycle impact of a building as it relates directly to the sustainability of the built environment (Hernandez and Kenny, 2010, Sartori and Hestnes, 2007).

2.3 The UK's residential energy demand

To ensure a realistic understanding of the residential market demand, a house's energy demands can be divided into two main areas, namely: thermal demand and electrical demand. Both include different building services, such as space heating, hot water, electrical appliances, lighting and cooking. In addition, some factors contribute an amount of energy that affects the total energy consumption of a house. Figure 2.2 outlines these factors.

The influence of these factors has changed energy consumption patterns over time. Consequently, understanding the current energy efficiency ratings and the UK's dwelling profiles is essential to recommend the appropriate services and identify any further trends that may require consideration in the future.

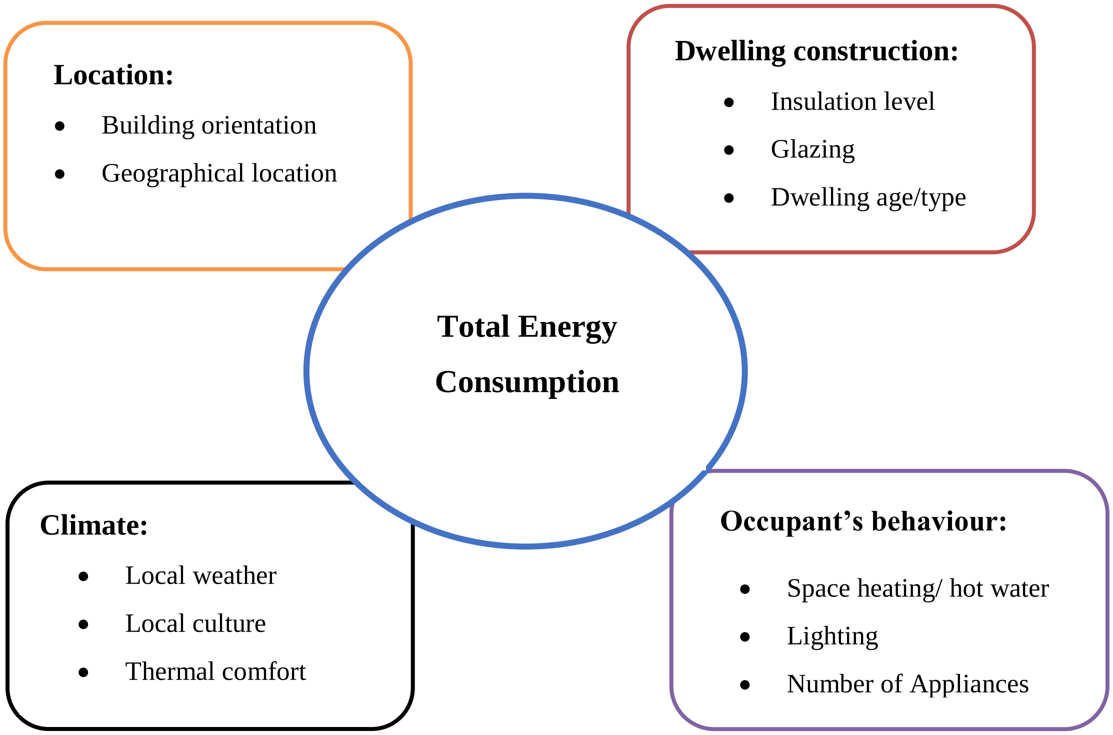


Figure 2.2: Contributing factors to the total energy consumption of a building.

2.3.1 The UK's dwelling profile

Understanding a residence's profile is important so that services can be appropriately provided and possible future trends identified. The status of existing buildings in the UK shows that thermal efficiency of both houses and public building is very low (Roberts, 2008). Reducing energy use is essential to address the challenges presented by existing buildings since the UK housing stock is currently being replaced at a low-efficiency rate of about 1% per year (Roberts, 2008).

Buildings built in the nineteenth and twentieth centuries were made with solid walls and single glazing and the primary source of heating in this period was coal. Since the 1930s, building standards have improved. Cavity walls were introduced as a way of preventing the penetration of damp into buildings and were used between two separate layers of brick. High-rise buildings up ten storeys were constructed using masonry walls and concrete floors up until the 1950s; since then, concrete framed buildings have followed. Blocks of 30 storeys and more began to appear in the 1960s, using pre-cast concrete at first, which was then replaced with site concrete in the 1970s. Steel frames and concrete floors were adopted in the 1990s (Roberts, 2008). Figure 2.3 shows the age distribution of the UK housing stock from 1900 to 20007.

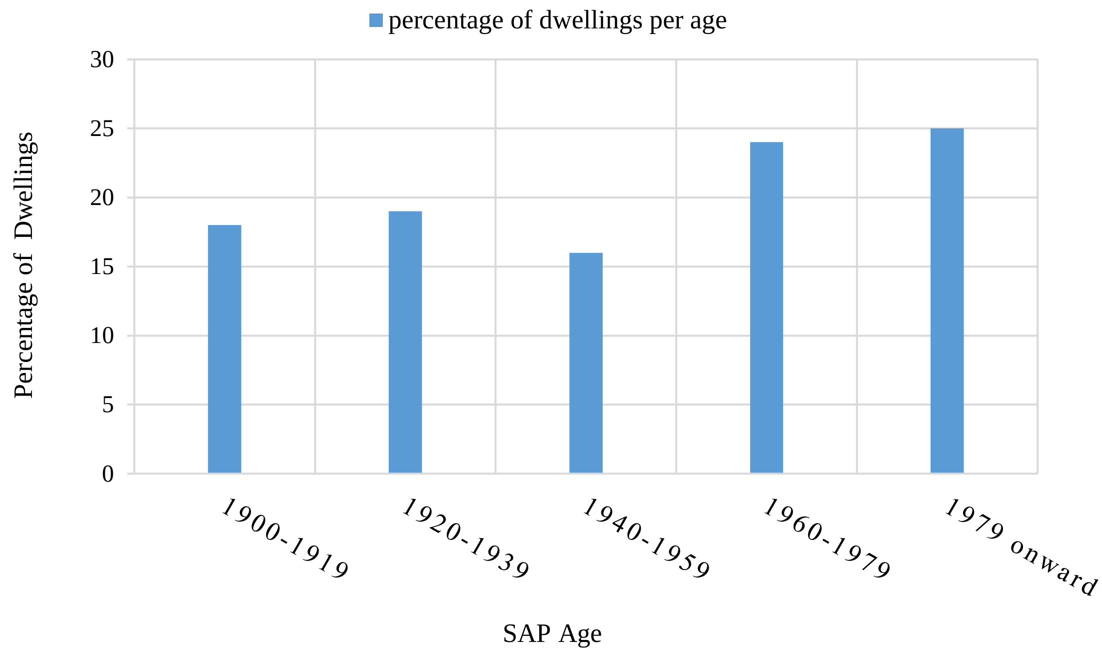


Figure 2.3: Age distribution of the UK housing stock (1900-2007)

Source: (Roberts, 2008).

2.3.2 Energy efficiency rating

The UK government established an approved methodology for rating the energy performance of dwellings in 2005, which is called the standard assessment procedure (SAP). The SAP rating is based on energy costs and is expressed on a scale of 1–100; the higher the number, the lower the operating cost. The assessment considers a range of features, including construction materials, thermal insulation, heating, hot water, ventilation, and lighting, but assumes standard use by typical occupants (Roberts, 2008).

Over 40% of properties built before 1919 have an SAP rating of less than 41. Two-thirds of all properties have SAP values of 41–70, whereas 60% of properties built in 1990 have SAP ratings greater than 70. Hard-to-treat has the lowest SAP rating because these homes were built either with solid walls, no gas supply, no loft space or they were constructed in high-rise blocks (Roberts, 2008).

Building regulations and SAP directly affect the energy base load of a dwelling. In order to improve the energy efficiency standards of new and existing dwellings, the government predicted that the next revision of the building regulations would mean that new homes would be carbon neutral by 2020 (Gaterell and McEvoy, 2005). However, the Energy Efficiency Commitment (EEC) that was designed to increase the uptake of energy efficiency measures in households was extended to improve the consumption of resources and reduce long-term damage to existing dwellings (Gaterell and McEvoy, 2005).

In 2010, the government of England and Wales introduced new building regulations that raised the energy efficiency standards for new buildings. To follow the regulations, new buildings should meet a minimum energy performance target (Pan and Garmston, 2012).

The Energy Performance Certificate (EPC) was later introduced, which is similar to the energy labels provided on household appliances and indicates a dwelling's energy efficiency. The certificate classifies energy efficiency from A to G (as in Figure 2.4) (Watson, 2010). The higher the rating, the more efficient the dwelling; (A) is very efficient and (G) is the least efficient. This type of classification is known as an asset rating. The asset rating reflects the age and condition of the building (Communities and Government, 2008). The EPC includes recommendations to help owners or occupiers to improve the energy efficiency of their homes, such as cost-effective improvements and further improvements that achieve higher standards but are not necessarily cost-effective. For each recommendation, the anticipated cost, average cost savings, and the performance rating change after improvement are given (Communities and Government, 2008, Pan and Garmston, 2012).

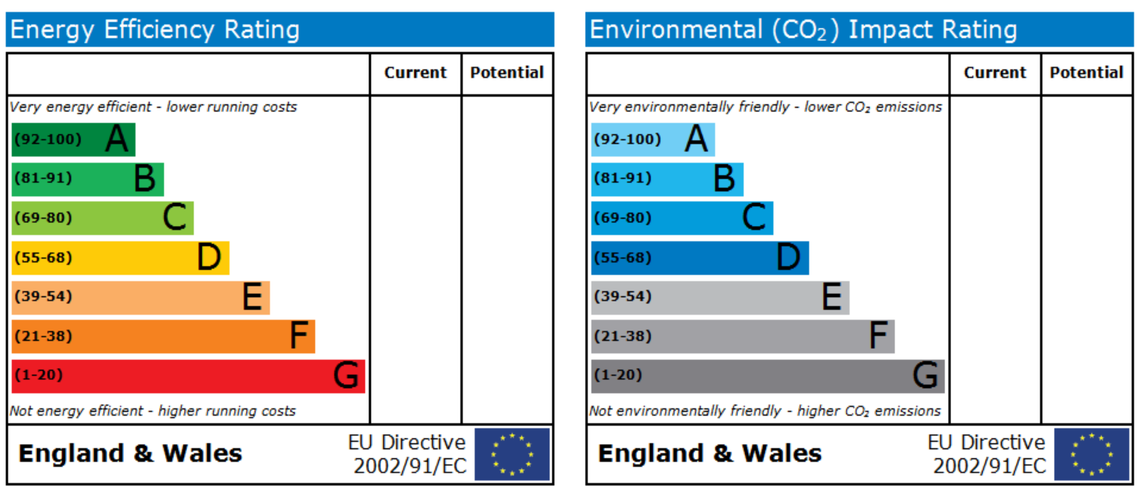


Figure 2.4: EPC rating of England and Wales.
Source: (Communities and Government, 2008).

2.4 Energy policy context

As energy policies change depending on the way of lifestyles, some of the EU's and the UK's government policies have highlighted the importance of upgrading energy policies frequently and emphasised the role of the built environment in achieving policy-based targets (Gaterell and McEvoy, 2005).

2.4.1 The EU's energy policy

Nearly 150 million units of the EU member states' residential sectors were built before 1972, when the adoption of thermal insulation measures was very mixed. This is reflected in the significant variation in the member states' residential energy consumption records, but only some of which is attributable to differing climatic conditions. The planned EU directive on the energy performance of buildings aims to achieve savings in the built environment through improving energy efficiency, as it accounts for more than a quarter of EU's total energy consumption (Gaterell and McEvoy, 2005). This directive includes residential buildings and focuses specifically on the building envelope; it also covers heating, air-conditioning and ventilation, but it does not include non-installed equipment like domestic appliances (Gaterell and McEvoy, 2005). The directive suggests that improving the thermal insulation standards of existing buildings would not only help realise a significant proportion of the available savings but would also be a cost-effective option in many cases (Gaterell and McEvoy, 2005). The EU produced a report entitled "Towards a European Strategy for Energy Supply" which listed the following factors to highlight the importance of reducing energy consumption in Europe:

- The increasing reliance of the EU on external energy supplies is creating a very challenging problem and is estimated to increase by 20% by 2030 if current trends continue.
- The EU's persistent increase in greenhouse gas emissions is problematic when it comes to responding to climate change and meeting targets.
- The EU's opportunity to influence international energy supply conditions is limited due to the continual rise in local gas emissions. Moreover, raising awareness of energy consumption and promoting energy savings is the only way to achieve the stated agreement (Gaterell and McEvoy, 2005).

2.4.2 The UK's energy policy

The UK government designed the UK energy policy goals and published them in the Energy White Paper (2003) to help to develop a low-carbon economy, by applying environmental sustainability to reliable and competitive energy markets (Gaterell and McEvoy, 2005). The government highlighted the need to:

- Reduce greenhouse gas emissions from anthropogenic activity to help limit any potential changes in the global climate;
- Update the existing UK energy infrastructure, which will be a response to the need for efficient import of power generation.

Regarding these challenges, the energy policy has set some goals to:

- Maintain the reliability of energy supplies through establishing appropriate energy infrastructure and regulatory systems in the UK, and helping to promote liberalised energy markets in the EU.
- Promote competitive markets in the UK and beyond which are intended to raise the sustainable rate of economic growth.

Nearly 30% of the reductions are required to meet the interim target in 2020 and are mainly meant to be made available via improving energy efficiency in the household. Thus, improving domestic energy efficiency, reducing carbon dioxide emissions and providing affordable heat can be a way of achieving the previously stated goals (Gaterell and McEvoy, 2005).

2.5 Climate change

Evidence of global climate change is growing rapidly (Energy White Paper, 2003). The UK has projected that climate change has a considerable impact on the thermal performance of the residence sector and influences the effectiveness of the measures designed to improve thermal performance (Gaterell and McEvoy, 2005). However, if emissions continue on their present trajectory, global average temperatures are likely to rise from 4°C to 6°C, and such an increase may have catastrophic consequences (Energy White Paper, 2003). Higher temperatures will have an impact on the thermal performance of the built environment, as in some cases higher insulation levels are required to reduce the risk of overheating and minimise the cost-effectiveness of other retrofitting measures (Gaterell and McEvoy, 2005). In addition, the performance of some measures designed to improve the thermal characteristics of buildings is likely to be sensitive to the precise nature of climate change in the UK.

However, there is considerable uncertainty regarding how the projected changes in the UK's climate might develop over the next 50 years. Consequently, decisions are based on the current thermal demand of the built environment. Thus, before applying any retrofitting measures, it is important to identify the ones that remain effective under the widest range of climate uncertainty (Gaterell and McEvoy, 2005).

2.5.1 The UK and the international response to climate change

An 80% reduction in carbon dioxide emissions is required in the UK's residential sector, according to the green deal that was outlined by the UK's government in 2003 (Boardman et al., 2005). Such a large decrease is essential in light of the significant influence of climate change. The green deal was designed to improve the energy efficiency and cut the carbon emissions of the UK's residential sector with no upfront costs to householders. This deal works with the new energy company obligation (ECO), which replaces the old community energy saving programme (CESP) and the carbon emissions reduction target (CERT).

The energy company obligation has offered extra support to hard-to-treat dwellings. The assistance is also provided to low-income residents and vulnerable households in need of support (Car et al., 2013). A realistic upgrade of existing houses will result in an average space heating demand of 6,800 (kWh/year) as more than 60% of dwellings that will exist in 2050 are already in existence (Boardman et al., 2005). To reach the stated target, 100% of the existing building must have cavity wall insulation, loft insulation, and high-performance windows. A demolition strategy for 14% of the current stock is also suggested in the deal as these dwellings had the worst energy performance (Boardman et al., 2005).

The Royal Commission on Environmental Pollution (RCEP) has suggested the UK's target of 80% reduction by 2050. It has also raised awareness about the problem that faces the whole universe in the way that all the world countries would be contributing to a global cut in carbon emissions. An example of the UK's contributions towards climate change action is adopting the United Nations Framework Convention in 1992 and the Kyoto Protocol in 2005. The UK recorded a reduction of 12.5% in greenhouse gases in 2010, which is approximately 8% of the European Union's collective target. A number of EU countries, including the UK, have supported the Kyoto target to address the suggested goals as summarised in Table 2.1 (Boardman et al., 2005).

Table 2.1: Examples of long-term climate change targets of European countries.
Source: (Boardman et al., 2005).

Country	Achieved targets	Future plans
France	Stabilise CO_2 concentrations at 450 ppm or less.	Limit per capita emissions to 0.5 tonnes carbon (t° C) by 2050.
Germany	The surface temperature rose to 20°C or less compared with pre-industrial levels, and by 0.2° C or less per decade.	Reduce the energy related to CO_2 emissions by 45-60% by 2050.
Sweden	Limited CO_2 concentrations to below 450 ppm. Stabilise atmospheric concentrations of all GHGs at 550 ppm, with concentrations at 500 ppm or less.	40% reduction by 2020 if EU commits to a 35% reduction over that period. Reduction in the CO_2 emissions and other greenhouse gases from 2.3 t° C to below 1.2 t° C by 2050 and further reductions thereafter.
UK	Stabilise CO_2 concentrations at 550 ppm or less.	Reduce national CO_2 emissions by 60% compared to 1997 levels by 2050.

In December 2015, a climate change conference was held in Paris to set out new global actions to reduce CO_2 emissions; 195 countries have adopted the suggested plans, including the UK (Labat et al., 2015). The governments agreed on a long-term goal of CO_2 reduction since this will significantly lower the risks of climate change and global warming. The agreement set out the required actions to achieve the planned reduction, and it will open again in New York at 2016 for signatures. Followed by its limited contribution to the Kyoto Agreement, the EU is now leading the international support (Pullen, 2011b) for a global climate act (Labat et al., 2015).

2.6 Housing stock modelling

There is a significant number of studies that outlined the need for modelling a building's embodied energy, and most of them concur on the substantial influence of embodied energy on the emissions created by the built environment (Palmer et al., 2011, Monahan and Powell, 2011a, Waterfield, 2006). The majority of researchers have focused on analysing small-scale models of a single or a pair of buildings in a specific location to ease comparison. Small-scale models are useful for the development of an embodied energy model and for increasing an understanding of a specific area of study. Moreover, the percentage of modelling errors can be reduced and easily tracked.

A study of Swedish energy-efficient homes (SEEH) showed that across 50 years of a building's life, its embodied energy accounted for almost 45% of the total energy consumed during that period. Thus, over the recorded time, nearly half of the household energy consumption and carbon emissions were composed by the indirect energy that was used in the construction process. However, choosing building materials with low embodied energy and considering future retrofit measures can make a considerable difference in the amount of building emissions. Therefore, the embodied energy of a building should be modelled and calculated throughout all of the construction phases (Palmer et al., 2011).

A Canadian case study was conducted in a three-storey building that was constructed using three different structural systems: wood, steel, and concrete, in order to enable comparison of the operational energies of each. The results indicated that over a recorded time, the recurring embodied energy exceeds the initial embodied energy and that no recurring energy occurred due to the structural system, which means that the variation of the embodied energy of the three different systems occurs only at the initial stages of the construction. Additionally, when the structures were erected at time zero, the embodied energy formed less than 15% of the total energy consumption. Further results showed that 50 years into a building's lifetime, the recurring embodied energy of its finishes, envelope and services are responsible for three-quarters of the embodied energy of the whole building. Therefore, reducing the energy of these three elements can be the first step towards achieving a total reduction in the entire building (Black et al., 2010, Roberts, 2008).

Pierquet and Bowyer investigated a study in which both the operational and embodied energies of construction were modelled (Crawford et al., 2011). The study assessed the life-cycle energy implications of various wall systems in different dwellings and used a software called HOT 2000 to quantify the annual operational energy required for a single season. The results showed that the opportunities for improving the thermal performance of the retrofitted elements were reasonably high, but there was a significant rise in the initial embodied energy (Crawford et al., 2011). Thus, lowering the operational energy through refurbishing could directly affect the building's thermal performance and perhaps increase its total emissions (Crawford et al., 2011).

Although the three listed studies (Crawford et al., 2011) used small-scale modelling, they all outlined the substantial effect of the embodied energy on the total energy consumption of a dwelling. However, each clarified the importance of modelling and assessing this energy throughout all of the construction processes, starting with the extraction of the natural materials, and processing, manufacturing, and transporting them to the construction site and during constructing the building.

Publication by (Monahan and Powell, 2011a) was carried in a greater scale to improve the accuracy level of the obtained results of modelling the entire stock. Fourteen newly constructed dwellings that support most of the best practice technologies were investigated in this study. Four different approaches were adopted to reduce their energy and carbon emissions, namely through ground source heat pumps, active solar power (thermal and photovoltaic), mechanical ventilation and solar gain and conventional high-efficiency gas boilers. Two analyses were carried out on the provided results; the first one was to investigate the energy consumption of the dwelling for a full year and quantify the resulting emissions. The second considered the embodied carbon emissions over the last 20 years of the dwelling's life, and made a final analysis to enable a deeper understanding of the consequences. Patterns identified in the four approaches were compared across three criteria: energy, CO_2 emissions and cost (total annual fuel expenditure) (Monahan and Powell, 2011b).

The results estimated that only five cases met the expected levels of reduction. However, when the outputs of the four energy typologies were compared, it was shown that over 20 years, heat pumps have the highest annual energy demands, highest CO_2 emissions, and greatest annual operating costs. However, homes with active solar technologies provided the most beneficial way of saving energy across all three evaluation criteria (Monahan and Powell, 2011b).

In comparison to the three research projects described above, this study was carried out on a larger scale to explore the possibility of modelling the UK's entire stock since it is estimated that only a small number of the investigated cases have addressed the embodied energy of the entire housing stock.

Installing or increasing thermal insulation levels is an essential need for energy conservation in the built environment, and official reports have emphasised the need for adequate insulation in both existing and new building to limit the rate of heat loss from buildings (Nash, 1955).

The Building Research Station demonstrated that improving thermal insulation could result in a reduction of fuel consumption when an experiment was carried out on a group of houses in Hertfordshire. The houses were similar in design and orientation but had different standards of thermal insulation; the heating systems were similar and were run to provide the same level of heat service in each house. The comparison of fuel consumption showed that under these conditions, less fuel was used in the well-insulated houses than in the poorly insulated ones (Nash, 1955).

The combination of inappropriate design and unstable local climate conditions can put the dwelling sector at a serious risk of the overheating. However, low-energy housing standards implemented in several developed countries represent international best practice for the minimum performance outcomes for new dwellings (Zachariadis, 2007).

The British Government has announced an ambitious target for all new houses to meet net zero carbon dioxide emissions from 2016. It is committed to increasing housing and supports the use of modern methods of construction (MMC) as a possible solution to the overheating risk (Rodrigues et al., 2013). A well-insulated steel frame dwelling was designed to test the MMC solutions and other innovative technologies to achieve zero carbon without compromising the occupant's comfort. To investigate the dwelling's potential for overheating in the current climate and in future scenarios, a computer model was used. The results show that despite the addition of the innovative technologies, a house that is comfortable now will still carry a risk of overheating in the future (Rodrigues et al., 2013).

To investigate whether zero carbon dwellings provide a high standard of thermal comfort or face overheating risks, Cardiff University has set a scenario of modelling using probabilistic data derived from the UKCP09 weather generator (WG) coinciding with dynamic simulation and global sensitivity analysis techniques. To assess the performance of typical zero carbon dwellings, a number of dwellings were compared to identical fabric energy efficiency standard dwellings over a recorded time. The emphasis of the study was to understand the impact of climate change in overheating risks for zero carbon dwellings, and to define the design factors that have the highest impact on the thermal performance of dwellings. The results showed that optimization of a small number of design inputs, including glazing ratios and external shading devices, play a significant role in minimising future overheating risks (McLeod et al., 2013).

To explore the risk of overheating, a similar study was carried out using New Zealand's energy and temperature data taken from 400 randomly selected samples. The data was collected through the household energy end-use project (HEEP) to explore the drivers of indoor heating power. The initial analysis of the study was based on comparing living room temperatures. The results showed that newer houses (post-1978) have the warmest living rooms, which was counted as an advantage in winter, but was potentially uncomfortable in the summer season. Further analysis proved that heating type and dwelling age are the main drivers of indoor temperature, followed by house design, construction, the local climate and the ventilation type (French et al., 2007). Nevertheless, there is an argument to be made as to whether to renovate or rebuild existing buildings as their embodied energy and carbon emissions have no relevance today. However, the use of strong and long-lasting refurbishing techniques can improve the existing dwelling's thermal performance in the long term; in some cases, the existing dwelling can reach the efficiency standards of new builds.

As it is currently unclear whether demolition or refurbishment is the best way to reduce the greenhouse gases that human emit to the atmosphere, a case study has discussed three pieces of evidence to clarify which is the most efficient approach (Roberts, 2008, Power, 2008).

First, the Environmental Change Institute at Oxford University has determined that approximately three million demolitions are needed by 2050 to eliminate greenhouse gases. Moreover, a particular reduction target will be required to housing stock if the energy use exceeds the limits (Roberts, 2008, Power, 2008). The demolition figures provided by the institute are based on sophisticated modelling with tiny, but useful, modifications that made a significant difference in the numbers. The assessment did not consider the embodied carbon costs, but it counted the factors that have some effects on the environment, such as land use and infrastructure, to clarify the scale of the challenge and the relative value of demolition or refurbishment (Roberts, 2008, Power, 2008). Second, the Sustainable Development Commission argued for the essential need to upgrade 70% of all homes that will still exist in 2050. The maximum feasible number of demolitions by 2050 is two million existing units; figures suggest that 10% of the current stock has to be demolished (Roberts, 2008, Power, 2008).

Third, the German federal housing ministry has announced an ambitious reduction program that aims to improve the thermal performance of all pre-1984 homes in Germany by 2020. The number of houses to be demolished estimated to be 30 million units. The program was based on evidence from several CO_2 reduction programs carried out since1996 and the feasibility of upgrading the units. An 80% reduction in energy consumption of the German housing stock has been achieved, making the performance of the renovated homes at least as good as Germany's current new build standards.

Chapter 3
Literature review: Retrofitting techniques

In order to develop the decarbonisation scenarios that support the reduction of energy consumption and carbon emissions in the housing sector, this chapter will review the possible renovation techniques and summarise the most cost-effective available retrofitting measures for the old stock.

3.1 Refurbishment of the existing stock

The opportunity to improve energy efficiency varies widely depending on the housing type, construction and the nature of the required repair work. Protecting the architectural heritage is a primary benefit of refurbishment, since improving the thermal efficiency of buildings is economically, socially and environmentally advantageous (Ma et al., 2012).

Retrofitting the existing buildings offers significant opportunities for reducing global emissions, and it has been considered to be one of the main approaches toward achieving low-cost sustainability in the built environment since, in many cases, a building's refurbishment costs less than demolition or reconstruction – even for high levels of retrofit operations (Zachariadis, 2007). However, the literature reveals that nearly 75% of the current stock will still exist in 2050, thus, a greater focus on retrofitting the existing stock is required since it will have more potential to make deeper cuts in CO_2 emissions (Power, 2008).

3.2 Refurbishment techniques

There are two main methods of improving the energy efficiency of existing dwellings: upgrading the dwelling's heating system and enhancing the insulation of the building fabric (Construction Products Association, 2010).

3.2.1 Building envelope insulation

One of the main methods of improving a dwelling's energy performance is by improving its insulation. Retrofitting the building fabric is vital in achieving the required reduction in the energy demands of the residential sector (Xing et al., 2011).

Retrofitting a dwelling through improving the building fabric insulation can be achieved by either increasing the thickness of the existing insulation or by installing the minimum required thickness in the case of cavity walls (Pullen, 2011b).

Insulation comes in many types and forms, and can be easily applied to all building elements such walls, roofs and floors. All insulation types work in the same way, i.e., they trap air, reduce radiative heat loss and provide resistance to moisture. This explains why insulation measures are carried out before boilers or heating systems are replaced (Al-Hassan, 2009, Pullen, 2011a).

Before installing or repairing the insulation in a typical house, it is essential to know the average heat loss through each element in order to predict the influence of the improvements after refurbishment. The Energy Saving Trust institution has estimated the average heat loss for each building element, as shown in Figure 3.1. Roofs have been recorded to have the highest heat loss, followed by walls and floors. Ten percent of heat loss is attributed to draught proofing, whereas up to 15% of heat lost may escape through windows and doors (BRE, 2005).

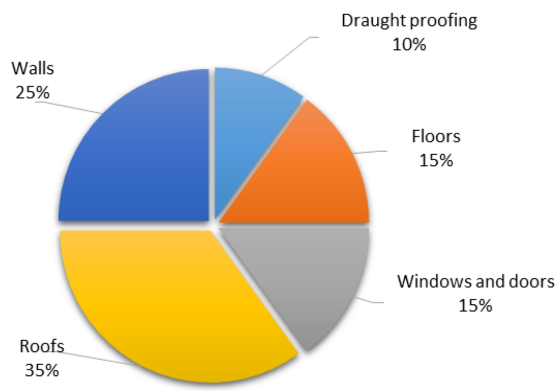


Figure 3.1: Heat losses through building fabric.
Source: (BRE, 2005).

3.2.1.1 Walls

Wall insulation has attracted interest in recent years, not only for its role in the environmental impact of excessive energy consumption but also because of the high cost of energy (Hordeski, 2004). Two methods of insulating walls have been observed to be the best, namely, cavity wall insulation and solid wall insulation. This includes internal and external wall insulation, as shown in Figure 3.2.

Cavity wall insulation (CWI) prevents heat loss in winter and heat gain in summer, and reduces the energy consumption of space heating (i.e., it lowers fuel bills). The insulation, in this case, is injected into the cavity between the inner and outer layer of brick, which acts as the external wall of the property, as in Figure 3.2.

Different insulating materials are available for this type of wall insulation, but the common materials used for cavity wall insulation are mineral wool, rock wool and expanded polystyrene

Table 3.1 and Table 3.2 show the properties of the insulation materials that are used for different purposes to create the renovation scenarios in this study. All of these materials resist water penetration and do not transmit water across or below the cavities (Pullen, 2011a, Burton, 2001).

Solid walls can be insulated in two ways: internally or externally as illustrated in Figure 3.2. Each of the options increase space comforts, reduce the running costs and the associated environmental impact but are always combined with other major repair work (Kay, 1993, DECC, 2012). The advantage of external insulation is that there is no internal space loss, minimum disruption, and less condensation risk. However, in some cases, external insulation cannot be applied to protect the historical facade; in such cases, internal, or cavity wall, insulation is replaced, where applicable (Kay, 1993, Xing et al., 2011).

The estimated cost and annual energy and carbon dioxide savings for wall insulation according to different types of dwellings are shown in Table 3.3.

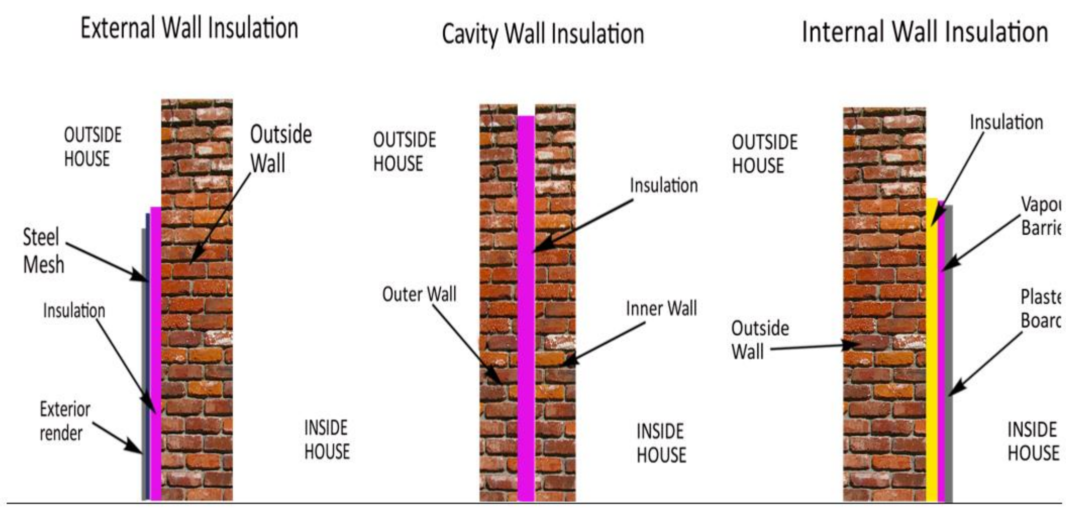


Figure 3.2: Wall insulation techniques.
Source: (Hordeski, 2004).

Table 3.1: Insulation material properties.

Source: (Energy Saving Trust)

Material	Density	Embodied Energy	Embodied Carbon	Boundary	Thermal Conductivity	R-Value
	(kg/m^3)	(MJ/kg)	($kgCO_2/K$)	(-)	(W/m·K)	($W/m^2·K$)
Rock Wool	30	16.8	1.12	C -G[1]	0.039	0.461
Mineral Wool	25	16.6	1.28	C - g	0.034	0.735
EPS	12	88.6	3.29	C - g	0.039	0.641
Fibre Cellulose	40	0.94	-	C - g	0.04	0.625
Fibre Cellulose	40	3.3	-	C - g	0.04	0.625
Sheep Wool	22	2.45	-	-	0.039	0.641

Table 3.2: The applied insulation for each building element.

Building element		Insulation material
Roof	Cold-pitched Warm-pitched	Rock wool, mineral wool and cellulose fibre EPS, rigid polystyrene and cellular glass
Wall	Cavity wall Solid wall	EPS, mineral wool and rock wool EPS, rock wool and cellular glass.
Floor	Underfloor board	Sheep wool

3.2.1.2 Roofs

Loft insulation is a type of roof insulation and one of the most common thermal improvements to the building fabric. It is cheap, not disruptive and takes no more than few hours for installation (Construction Products Association, 2010). Insulating over joists provides a lightweight storage solution when insulation is fixed to joists (Construction Products Association, 2010).

Mainly, there are two different ways of insulating a roof. First, the warm-pitched roof, as in Figure 3.2, it makes the entire structure of the building warm in an attempt to avoid any cold bridging. In this case, the insulation is located above, or above and between, timber rafters (Reddy and Jagadish, 2003). The second technique of roof insulation is the cold-pitched, as in Figure 3.3, where the

[1] C- G is Cradle to Grave and C-g, is Cradle to Gate.

insulation is placed either between and under the rafters, or at ceiling joist level (Reddy and Jagadish, 2003). The estimated cost and annual energy and carbon dioxide savings of the loft insulation of different types of dwellings are shown in Figure 3.3.

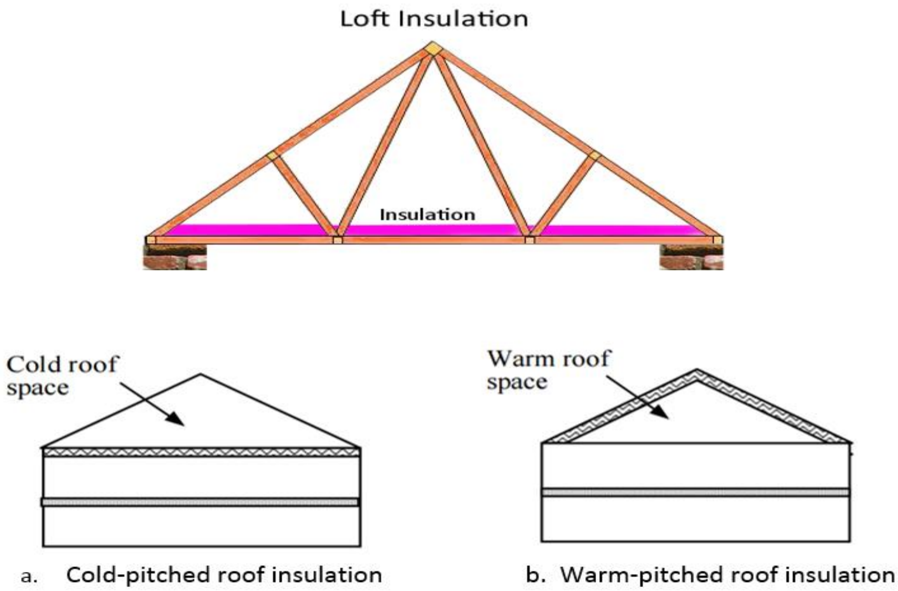


Figure 3.3: Pitched roof types.

Source: (Hordeski, 2004).

3.2.1.3 Floors

About 10-15% of total building heat losses are through the flooring area, thus more consideration should be given to floor insulation. Floor insulation can improve internal conditions and eliminate thermal bridging at the floor to wall junctions, thereby reducing heat loss. There are four ways to insulate floors, namely, insulating under floorboards, solid floor and skirting (Mallick, 1996). The method used in this study is insulating under the floorboards with sheep wool, as listed in Table 3.2.

3.2.1.4 Double-glazed windows

To make the building's fabric more energy efficient, all elements should be considered as one unit. Thus, the 15% of heat lost through the windows and doors, as in Figure 3.1, should be seriously considered. Improving the glazing of dwelling windows and doors can minimise heat loss, improve dwelling warmth and quietness and reduce energy bills (BRE, 2009).

The estimated costs, annual energy, and carbon dioxide savings of installing double-glazing on different types of dwellings are shown in Table 3.4.

3.2.2 Systems upgrade

The energy efficiency of a dwelling can be obtained in its systems by catering to the three main components of the building system: heating, ventilation, and lighting. Heating is by far the largest energy requirement of a dwelling. Thus, to make an energy-efficient building, appropriate heating systems should be installed.

Energy-efficient heating systems consider the correct size and efficiency of the boiler, can be controlled through thermostats so that the heat is used only when and where it is required, and the reliability and easy maintenance of the system. Some other operational factors, such the climate, size, age and style of house, insulation levels, air tightness, the amount of solar energy gained and lost through windows and heat given off of lights and other appliances can help in the determination of the amount of heating required for a dwelling (BRE, 2009). The estimated cost of installing a new boiler with different efficiency ratings are shown in Table 3.5.

There are many types of heating systems, and their efficiencies vary on the heating load of a dwelling. The systems are such as the solar thermal collectors and the heat pumps, which are both using a renewable source of energy.

There are two types of the heat pumps namely; the air and the ground heat pumps i.e. depend on the energy source. Since the ones that using air sources are very easy to install and need less space than the ground source heat pumps, they are considered the better retrofit option as they combine heat and power in another way to reduce gas emissions and use the heat produced during the generation of electricity, which improves the efficiency of the system by 30% (Xing et al., 2011).

Biomass is another energy-efficient method of space heating as it reduces the carbon lifecycle and greenhouse emissions by combusting fossil fuels and it also diversifies the energy supply at a reasonable cost (Xing et al., 2011).

Table 3.3: Estimated cost and annual savings of fabric insulation.

Source: Energy Saving Trust (2016)

Item	Refurbishment	Detached	Semi-Detached	Mid-Terrace	Bungalow	Flat
Fuel saving (£/year)	Cavity wall	275	160	105	110	90
	Solid wall	455	260	175	740	145
	Roof	240	140	135	195	135
	Floor	70-90	40-55	30-40	65-80	25-40
Carbon ($kg/CO_2/year$)	Cavity wall	1100	650	430	450	360
	Solid wall	1900	1100	720	740	610
	Roof	1000	590	560	820	700
	Floor	310-370	180-220	120-160	270-330	90-120
Insulation cost (£)	Cavity wall	720	475	370	430	330
	Solid wall	External (£5,000 to £18,)		Internal (£3,000 to £14,000)		
	Roof	395	300	285	375	270
	Floor	Up to 200				
Payback time (Years)	Cavity wall	4 or more				
	Solid wall	10 or longer				
	Roof	Up to 5				
	Floor	Up to 2				

Table 3.4: Estimated cost of installing double-glazed windows.

Source: Energy Saving Trust (2016)

Energy Rating	Detached	Semi-Detached	Mid-Terrace	Bungalow	Flat
A-rated	£120 - £160	£85 - £110	£65 - £90	£55 - £75	£40 - £60
B-rated	£110 - £145	£75 - £100	£60 - £80	£50 - £70	£40 - £55
C-rated	£110 - £135	£75 - £95	£60 - £75	£50 - £65	£40 - £50

Table 3.5: Estimated figures based on installing a new condensing boiler.

Source: Energy Saving Trust (2016)

Old boiler rating	Detached	Semi- Detached	Bungalow	Mid-Terrace	Flat
G (< 70%)	£570	£340	£290	£280	£145
F (70–74%)	£430	£255	£215	£210	£105
E (74–78%)	£360	£215	£180	£175	£90
D (78–82%)	£300	£300	£175	£145	£70

Chapter 4
Methodology

This chapter will discuss the research methodology, model development and review the decarbonisation scenarios that support the reduction of energy consumption and carbon emissions in the UK residential sector.

4.1 Data source

Housing stock models were developed to evaluate the current energy consumption and CO_2 emissions associated with the UK's existing dwellings and to predict the impact of applying various retrofit measures and renewable technologies on reducing the energy demand and corresponding CO_2 emissions (He et al., 2014).

Most building physics models are built on the basis of the factors that influence the energy demand of a dwelling. Examples of the considered factors are: total floor area, window area, fabric construction, insulation properties, air tightness, heating technology and the efficiency of the heating system. These models compute heat flows in buildings based on the heat transfer through the building fabric, heat transfer through air infiltration and ventilation, and internal heat gains from occupants and their use of household appliances (BRE, 2009, He et al., 2014).

There are various data sources for modelling the UK housing stock and Table 4.1 discusses the key aspects of some of the available sources. Most of the previous work developing UK housing stock models is based on steady-state calculations using a version of the Building Research Establishment's Domestic Energy Model (BREDEM). BREDEM is based on a series of steady-state heat transfer equations and empirical relationships that are used to estimate the annual or monthly energy consumption of an individual dwelling.

For comparison purposes, the Cambridge Housing Model (CHM) has been chosen as a suitable steady-state housing stock model. The primary source of input data for CHM is the 2009 English Housing Survey (EHS), which comprises data on 16,670 dwellings. The dataset is representative of the entire English housing stock, where each case represents a number of dwellings. The extrapolated values are also given in the dataset. The wider representation in the dataset enables us to model a high-resolution housing stock.

The CHM reads in the EHS cases for every dwelling and carries out the building physics calculations to determine energy consumption and associated CO_2 emissions, by use and by fuel type, for each representative residence and the entire English stock. Multiplying the energy consumed and CO_2 emissions by the associated number of dwellings and adding all the cases gives the total values for England. The approximate GB and UK energy uses and CO_2 emissions totals were calculated using appropriate England-to-GB and GB-to-UK scaling factors based on the number of dwellings in the three locations (CHM, 2010).

The input data of the Cambridge Housing Model (2010) were used to develop the embodied energy model of this study, where relevant housing data were utilised (as discussed in the following sections) to allow a direct comparison of the embodied energy and the operational energy gains.

Table 4.1: Various sources of the UK housing stock modelling.

Source: (Author's own) created from BRE (2009) and He et al. (2014).

Source	Modelling features
The national household model **(NHM)** is a domestic energy policy modelling for Great Britain (GB), built by the Centre of Sustainable Energy (**CSE)** and commissioned by the Department of Energy and Climate Change **(DECC)**.	- Represents the physical characteristics of the GB housing stock and householders. The Welsh housing stock model was created from the English Housing Survey using a reweighting process. - Allows scenario modelling for a single dwelling by investigating the energy demand and other associated factors, including fuel bills and SAP, also suggests installation of energy efficiency measures, where applicable. - Provides an estimation of the household energy demand by using the 'energy calculator' that includes all the codes and algorithms needed. - Creates policy scenarios and explores the potential impacts on domestic energy demands over time.
Energy Saving Trust is a source of housing data and analysis and energy modelling services for GB's housing sector.	- Runs a number of supporting schemes for GB housing stock, such as Renewable Heat Incentive **(RHI)**, Feed-in Tariffs **(FITs**) and **ECO** Energy Company Obligation. - Provides housing data and energy modelling services for every GB address. - Identifies the potential for retrofit – energy saving measures. - Helps to target energy saving activity and meet the **ECO** obligation. - The data relies on the EHS. - Assists businesses in creating credible business plans and in informing the decisions for key investments.

The Building Research Establishment **(BRE)** housing stock modelling service **(HSMS)** provides the national authorities' estimation for the key housing and energy variables at the dwelling level.	- Developed the first set of housing stock models in August 2003 for the whole of Great Britain. - 20 years of experience in national housing surveys, such as **EHS**, **LIW** and **NIHS[2].** - Provides a basis for designing a sample house condition survey and determines the households that need assistance in improving housing conditions. - Holds a large part of the responsibility for EHS data since it started in 1967. - Acquired new stock models in 2011 that allow a combination of developments in dwelling and authority levels. - The latest stock models give an estimation of the carbon emissions in England's residential sector. - The key indicators of the BRE in housing stock models in a dwelling level are the energy efficiency variable, EPC and the Basic Green Deal.
Cambridge Housing Model (CHM) is a source of housing data that was used in this study. It was developed by the Cambridge Architectural Research for Department of Energy and Climate Change **(DECC).**	- The model uses EHS 2009 data, coupled with a SAP-based energy calculator. - Estimates energy consumption and CO_2 emissions for all homes, broken down by total use. - The dataset is representative of the entire English housing stock, where each case represents a number of dwellings. - Used to underpin the 2012 Housing Energy Fact File and Energy Consumption in the UK. - Aimed to inform householders of housing policy decisions.

The housing stock models were also used as an alternative to the housing condition surveys. The extent of the use of housing stock models by local authorities for decision-making varies; however, some innovative examples are as follows (BRE, 2009):

- **Sandwell Metropolitan Borough Council** (**MBC**) combined the vulnerable households in non-decent homes model with other local data sources to apply a package of assistance strategies on individual vulnerable households.
- **Gateshead MBC** integrated the housing stock model with other sources, such as new build and clearance data, to update its housing stock.

[2] English Housing Survey (EHS), Living in Wales Survey (LIW) and The Northern Ireland House Condition Survey (NIHCS)

4.2 Research approach

The approaches for modelling embodied energy were reviewed and presented in Figure 4.1. In addition, current practices for insulating dwellings were also explored to gather the data required to build the embodied energy model used in this research. Once the common methods of calculating the embodied energy were reviewed, the model was then developed using the input-output analysis method, as illustrated in Modelling was for all types, ages, and locations of dwellings and the outcomes expressed in terms of energy consumption, CO_2 emissions, and normalised costs.

The embodied energy is modelled and assessed to set the energy efficiencies for all refurbishments to help to achieve the UK's target for CO2 emissions reductions. The models were created in Microsoft Excel to: (a) ensure transparency so that the reader can investigate the assumptions made; and (b) compare outputs of this research with those of the CHM. Comparing the operational energy gains and the embodied energy values of different insulation materials provides a comprehensive assessment for choosing the most efficient insulation material for the right element.

The reason for constructing a model based on 16,670 cases from EHS data is the variation within the UK housing stock with respect to age, type, and the potential and challenges inherent in renovating dwellings. Therefore, exploring an individual building of a certain age, type and location will not provide a comprehensive picture to inform the development of policies or identify optimum refurbishment strategies. Moreover, retrofit measures applied in one dwelling may not be suitable for use in another. Thus, involving the entire stock as one aggregated whole was the best option to achieve the objectives of this study.

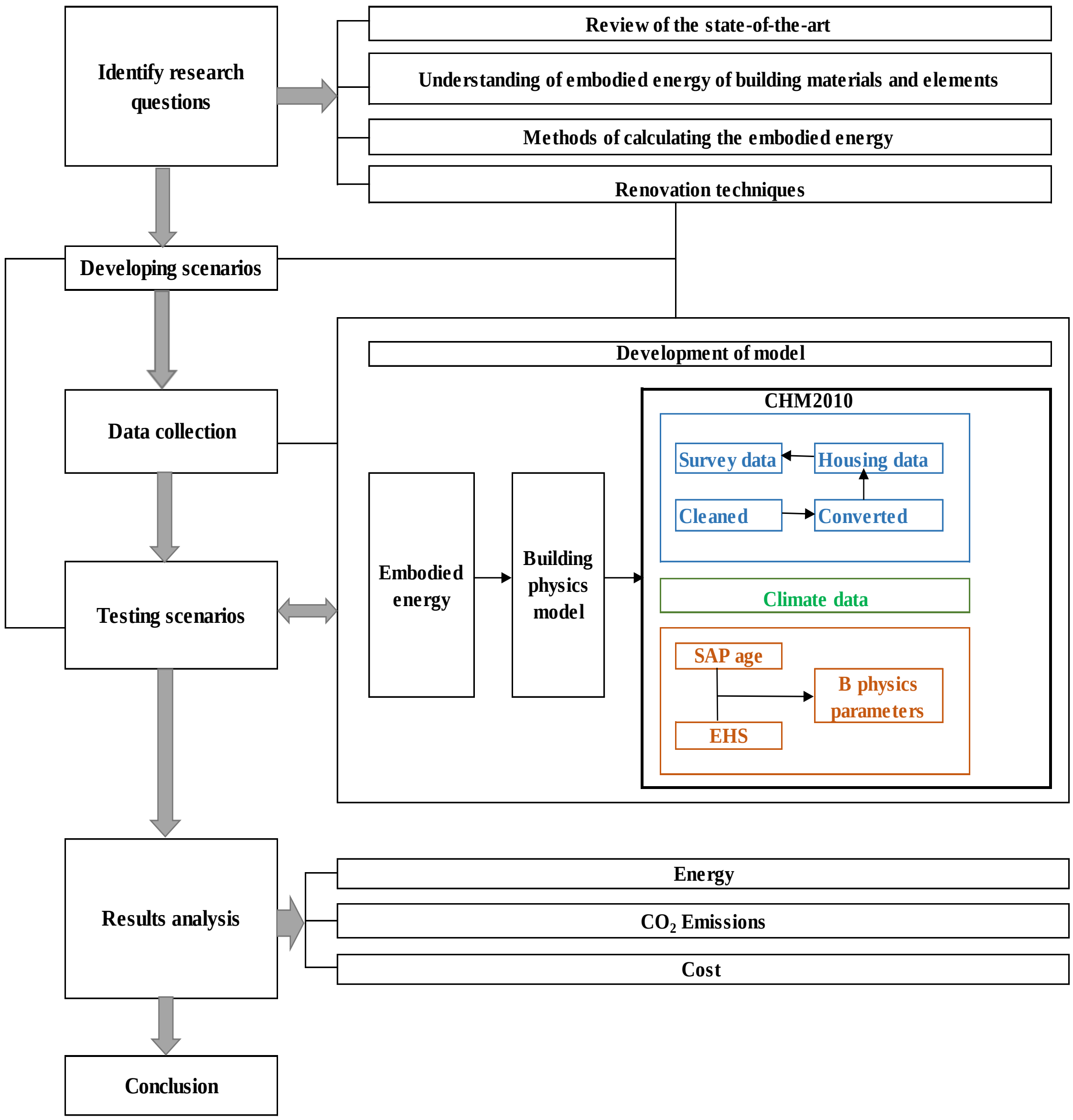


Figure 4.1: Flow chart of research methodology.

4.3 Developing decarbonisation scenarios

Having reviewed the potential renovation strategies, a set of decarbonisation scenarios was developed and tested on the developed model in this research. The chosen scenarios were built on the findings from the review of the state-of-the-art and rationalised against contemporary policy objectives. Each scenario consists of different renovation measures, which are summarised in Table 4.2. The reasons for adopting these scenarios are:

- **Ease of installation.** Relates to how easy it is to install a particular refurbishment option without disrupting the day-to-day operation of a building, as well as whether changes need to be made to the external structure and internal layout. For example, standard insulation measures, e.g., cavity wall insulation can be easily installed on walls without affecting the operation of the building or internal living space.
- **Cost, availability and lifespan**. Cost is one of the primary considerations, both for the end user and policy makers. Capital costs (material and labour) are mostly considered in this research, as the difference in maintenance cost may be minimal between an existing and refurbished element. In some cases, e.g., for new boilers, there is likely to be a reduction in maintenance costs.[3]
- **Effectiveness.** Insulating the building fabric is a critical component of improving the energy performance of a dwelling. Roofs and floors are responsible for a significant percentage of the space heat losses through the building envelope. The percentages of heat that escapes through walls and roofs are 25% and 35%, respectively. Floors account for 10-15% of total house heat loss. According to the Building Research Establishment (BRE, 2009), properly chosen and installed thermal insulation can improve internal conditions and eliminate thermal bridging at the floor to wall junctions, thus reducing heat loss further. Double-glazed windows and wall insulation represent the greatest potential for annual cost reduction in the UK. On the other hand, installing an appropriate heating system is essential for maximising energy efficiency. About 61% of the energy used in a dwelling is for space heating; therefore, choosing the right size and efficiency of a boiler is vital to minimise the demand for heating.

The adopted scenarios are described in the following sub-sections and summarised in Table 4.2.

4.3.1 Scenario 1 – Baseline (BaS)

No modifications were made in this scenario. The original model is left as-is so that the effects of the other scenarios can be compared to it.

4.3.2 Scenario 2 – Refurbished fabric

This scenario is aimed at finding the optimum insulation and double-glazing parameters.

- **Scenario 2.1 – Optimal insulation for each dwelling element**. This scenario aims to identify the optimal insulation type for the dwelling elements: cavity walls, external and internal walls,

[3] The maintenance cost varies significantly between products from different manufactures and are sometimes location-specific (e.g., rural vs. urban).

floors and warm- and cold-pitched roofs. Construction materials for houses[4] were modified to include the selected types of insulation as in Table3.2By calculating the embodied energy, operational gains and payback periods of the insulation, the optimal insulant of each element could be found. The **BaS** scenario plus the optimal insulation of each element can then be used to form the optimal insulation model.

- **Scenarios 2.2 and 2.3 – Optimal double-glazing.** To find the optimal double-glazing level, a set of two models is constructed: the first model is a combination of the **BaS** model and the double-glazing refurbishment added to all applicable dwellings, which is called S2.2, and the second model, S2.3, is the double-glazing improvement added to the optimal insulation model S2.1.

4.3.3 Scenario 3 – The efficient heating system

Using the model of sub-scenario 2.3, namely the optimal insulation with double-glazing, another renovation model was developed with an additional upgrade on the heating systems, called S3.1. This was then compared to the new model, S3.2, which constructed from S2.1 the optimal insulation model plus the heating system upgrade. Further comparison is considered to investigate the optimal heating system scenario, where the changes to the heating systems were added once to the BaS model, and named S3.3, and once more to the baseline with double-glazing refurbishment model S3.4.

Table 4.2: Renovation scenario features.

Renovation Types		**Scenarios**							
		S1	**S2.1**	**S2.2**	**S2.3**	**S3.1**	**S3.2**	**S3.3**	**S3.4**
Fabric refurbishment	Insulation	-	✓	-	✓	✓	✓	-	-
	Double-glazing	-	-	✓	✓	✓	-	-	✓
Heating system upgrade	Pipework insulation	-	-	-	-	✓	✓	✓	✓
	Hot water tank jacket	-	-	-	-	✓	✓	✓	✓
	Draught proofing	-	-	-	-	✓	✓	✓	✓
	Boiler replacement	-	-	-	-	✓	✓	✓	✓

4.4 Testing scenarios

Before applying any refurbishments to the dwellings, the stock was checked to determine the percentage of applicability for each renovation.

[4] Only houses without insulation were targeted for full cavity wall insulation. The modification for houses with insulation involved upgrading the insulation thickness up to 0.025 m.

Table 4.3 shows the number and proportion of cases that were included in the calculation for each refurbishment strategy. The developed scenarios were then entered individually into the model and outputs compared regarding energy and cost, and discussed generally in Chapter 5.

Table 4.3: Housing data applicability to renovation.

Refurbishment	Number included	Number excluded	Percentage included	Percentage excluded	Total
Cavity wall	6493	1017	38.95	61.50	100
External/internal wall	16658	12	99.93	0.07	100
Cold-pitched roof	12654	4016	75.91	24.09	100
Warm-pitched roof	1489	15186	8.90	91.10	100
Floor	5701	10969	34.20	65.80	100

4.5 Model development

This section will outline the two main concepts of the integrated model of this research; the operational energy of the Cambridge Housing Model will be described first, and the embodied energy model will follow.

4.5.1 Operational energy model (CHM10)

The Cambridge Housing Model (CHM) is a British domestic energy model. The model is used to generate estimates of energy consumption and associated factors for DECC and energy consumption in the UK (ECUK) domestic data tables, replacing the building research establishment housing model for energy studies (BREHOMES) (CHM, 2010 , CHM User Guide 2010). The primary source of input data for the CHM is the English Housing Survey 2009 (EHS). This data comes in various forms, and the data was prepared before it could be used (CHM, 2010).

The principle components of the CHM are climate data, housing data, building physics calculations derived from the standard assessment procedure (SAP) plus associated SAP data, and the model outputs. The SAP building physics data comprises information such as SAP parameters used in SAP calculations, like the thermal bridge parameter, and U-values. The CHM was built in Microsoft Excel, with calculations principally performed directly within the worksheets to make it accessible and transparent to third parties (Car et al., 2013).

4.5.1.1 Data structure

The input data are given in the first worksheet of the model and named the housing data. This data included a single top row for each case, with columns representing descriptive data for that case, such as the dwelling ID, numbers of units, type, and age band of (1-10), occupant data, dimensions and areas of the dwellings, information on the space heating and hot water systems, levels and availability of insulation and available glazing type (CHM, 2010).

Input climate data, plus climate calculations provided in the second worksheet, are followed by the main calculation sheet and all the assumptions made therein. All model outputs are contained within the operational gains worksheet. The primary outputs are energy consumption by use and by fuel type and the associated CO_2 emissions by use and by fuel type, for each of the cases (CHM, 2010 , CHM User Guide 2010).

4.5.1.2 Calculating energy use and emissions

The calculations of the model are primarily based on the SAP 2009 where references to all SAP calculations are shown in the CHM worksheets. The majority of model calculations are undertaken in the building physics model and some other calculations were made in the climate data and physics parameters (CHM, 2010 , CHM User Guide 2010).

As the focus of SAP is calculating energy, use comprises space and water heating, fixed lighting, ventilation and pumps, the determination of energy consumption and associated CO_2 emissions for the electrical appliances and cooking that are not stated in SAP 2009, but were additionally considered in the Cambridge model (CHM, 2010 , CHM User Guide 2010).

The electrical appliances calculations were added as a part of SAP in 2009, referred to as the internal gains calculations. For the cooking calculation, the model provided two options: has hob and electric oven or electric cooker, and assumed the use of gas for cooking, primary heating, and domestic hot water production (DHW); otherwise, the term electric cooker is applied.

Finally, the total values of energy use and CO_2 emissions of all the services were multiplied by the associated weighting of England and summed across all of the cases (CHM, 2010 , CHM User Guide 2010).

4.5.2 Embodied energy model

To create the embodied energy model, the correct U-value calculation tables were identified to ensure that the correct data is changed. The utilised values were then substituted, and the model run for each refurbishment using different insulation materials and different scenarios. The outcomes were in exactly the same form as the operating model, but the values of the total energy, energy consumption and carbon emissions were different from before due to the impact of the refurbishments. These were either lowered or increased, depending on the type of refurbishment.

The procedure modelling the insulation's embodied energy has gone through a number of stages, as presented in Figure 4.2. Each stage will be briefly discussed in the following sections.

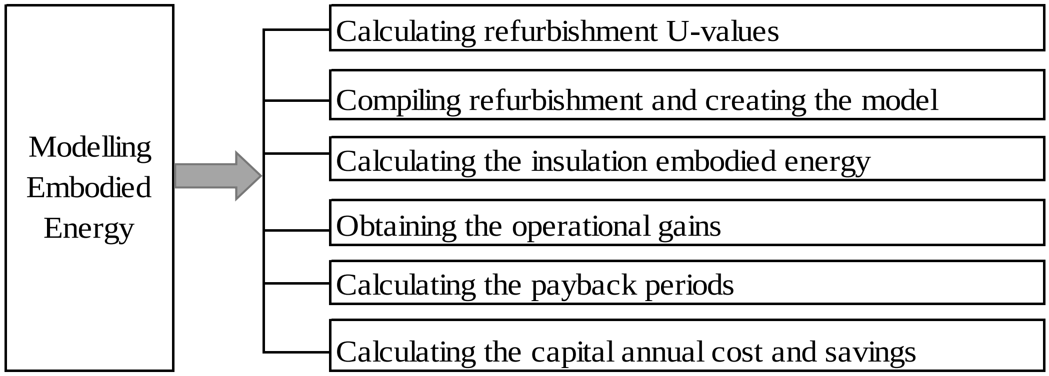


Figure 4.2: Flowchart of the embodied energy model.

4.5.2.1 Calculating the refurbished U-values

The refurbished U-values of the building elements were calculated for the model using equations (**4.1**) and (**4.2**):

$$U = {}^{1}\!/_{\sum R} \qquad \textbf{4.1)}$$

$$U = {}^{1}\!/_{\left(\frac{1}{U_0} + R_u\right)} \qquad \textbf{4.2)}$$

where, U is the "thermal conductivity" of the materials resultant U-value of element (W·m^{-2}/K), U_0 is the thermal conductivity of the element between heated and unheated spaces unheated space adjacent to the element. R_u is the effective thermal resistance of unheated space (W/m^2·K) and can be derived from equations (4.3) and (4.4)

$$R = {}^{1}\!/_{U} \qquad \textbf{4.3)}$$

$$R = {}^{x}/_{(\mathrm{k} \cdot \mathrm{A})} \qquad \mathbf{4.4)}$$

where, x = wall thickness (m), k = thermal conductivity of the material (W/m^2·K) and A = total area of the heat exchanger (m^2)

$$U_{w,e} = \left[{}^{1}/_{(1 + U_W)} + 0.04\right] \qquad \mathbf{4.5)}$$

where,U_w, e is the window U-value measured without curtains and (0.04) is the R-value of the air gap (W/m^2·K).

4.5.2.2 Compiling the refurbishment and creating the model

Renovations included elements that represent a significant percentage of the total heat loss in a dwelling, such as walls, roofs, floors, and windows, respectively. Double-glazing windows and heating systems upgrades were also considered. Wall refurbishments considered cavity, external, and internal walls. Roof renovations included cold- and warm-pitched roofs, whereas floor refurbishments considered insulating the ground floors under the floorboards. Flat roof refurbishment was excluded, as the percentage of buildings with flat roofs was very small.

The correct U-value tables in the Cambridge Housing Model were identified to ensure that the correct data are changed. The modified tables are as the following:

- For the cavity wall refurbishments, the U- values associated with wall construction type 9 in SAP Table S6 are used.
- For internal and external wall renovations, the wall thicknesses in SAP Table S3 increased by 0.025m. The U-values in SAP Table S3 are also used.
- For cold-pitched roof refurbishments, the U-values in columns 1 and 2 in SAP Table S9 and the first column in S10.
- For warm-pitched roof renovations, the U-values in columns 1 and 2 in SAP tables S9 and the second column in S10.
- For floor repairs, the U-values in columns 1 and 2 in SAP Tables S11 and S12.

4.5.2.3 Calculating embodied energy

The embodied energy and embodied carbon values for each applicable case have been computed using Table 3.1 with the housing data sheet in each model. To calculate the embodied energy and embodied carbon of the applied insulation, the volume and mass of the insulation were determined.

The CHM10 assumed the air gap of the unfilled cavity walls was 250 mm thick. Thus, the same thickness was adopted for each refurbishment of all other insulated elements to enable comparisons between all of the building elements. Equation (4.6) was used to calculate the insulation volume, where the external wall area and roof area were multiplied by the 0.025 m thickness for all wall and roof refurbishments. The external wall areas and the roof areas were already given in the housing data sheet. Multiplying the volumes by the insulation density has delivered the mass of insulation in equation (4.7). Embodied energy and embodied carbon were then recorded in (MJ/kg) and ($kgCO_2$/kg), respectively. Thus, multiplying the embodied energy and embodied carbon by the mass of the insulation provided the energy and kilograms of CO_2 of the refurbishments in.

$$V = t \times A \qquad \textbf{4.6)}$$

where, V is the insulation volume (m^3), t is the thickness (m) and A is the area (m^2)

$$m = V \times d \qquad \textbf{4.7)}$$

where, m is the mass in (kg), d is the density of the insulation material (kg/m^3)

$$EE = Ins_{EE} \times m \qquad \textbf{4.8)}$$

where, EE is the total embodied energy (MJ), Ins_{EE} is the insulation material embodied energy (MJ/kg).

4.5.2.4 Obtaining operational energy gains

The operational energy gains obtained by calculating the differences between the refurbished output data and the original output data, i.e., the variance of the energy consumed and carbon emitted by all the dwelling services in (kWh/yr.).

4.5.2.5 Calculating payback periods

Two types of payback periods have been computed from the model. Firstly, the energy payback periods, which derived from the embodied energy of insulation, and secondly, the operational energy gains in (kWh). The operational energy output from the CHM produced all of the energy data per year. Thus, dividing the embodied energy and carbon values by the obtained operational gain values produced the payback period in years. The other payback periods were calculated in terms of money, where the annual cost of total energy consumption was found in (£/yr.). The number of payback years was then obtained using equation (4.9).

$$P = \frac{C_R}{P_E \times E_A} \qquad \textbf{4.9)}$$

where P is payback period (yr), C_R is refurbishment cost (£), P_E is price of energy (£) and E_A is annual energy consumption (kWh).

4.5.2.6 Calculating the capital, annual cost and savings

The total values of energy use (kWh/yr.) and CO_2 emissions (kg/CO_2) of all the services were computed by summing across all of the cases. Multiplying the energy consumption of each service (kWh/yr.) by the fuel price (£/kWh) has determined the annual cost of energy and CO_2 emissions.

The annual savings of energy and other emissions were calculated using the differences between the original annual cost (kWh/yr.) and the post- refurbishment cost. The capital cost (£) was determined by multiplying the number of payback years by the annual cost.

Chapter 5
Results and discussion

This chapter will discuss and analyse the results of the three renovation scenarios that were built in Chapter 4. Investigation into the optimal scenario presented by each renovation will also be outlined in this chapter.

5.1 Determining the optimal insulant for each of the building elements

When choosing an insulation material, it is important to consider key environmental issues such as the hazardous materials used in manufacturing process that might cause pollution to the air, land and water and the embodied energy of the material. The embodied energy of the material is primarily necessary because as the operational use of the material in the dwelling is lowered through the additional of insulation, the embodied energy within the material becomes more prominent (Roberts, 2008, Council, 2015, Black et al., 2010).

To investigate the optimal insulation for each of the building elements, different insulants were compared. The insulation's embodied energy and operational energy gains were compared to understand their influence on the payback period and to outline their importance in assessing the proper type of insulation material for the right element. The mean values of the embodied energy, operational gains and payback periods were plotted per dwelling type to ease the comparison.

From the models, it is apparent that the lower the embodied energy values, the better the insulant as the insulation is mainly added to reduce the total energy consumed in the dwelling.

By comparing the embodied energy of each insulant, the insulant that produces less embodied energy is the one that should be chosen. The reason for this is because the lower the embodied energy, the less energy that needs to be conserved. Higher operational energy gains are optimal because the greater the operational energy gains, the faster the embodied energy is accounted for by energy savings.

Through plotting the operational energy gains of each insulant, the insulant that produces the greatest operational energy gains can be determined.

Lower paybacks are optimal because they are delivered either from lower embodied energy values or higher operational energy gains, or both together. Lower payback periods, therefore, indicate a shorter time period in which the energy savings account for the embodied energy and an overall greater energy efficiency.

5.1.1 Cavity walls

Mineral wool, rock wool, and EPS are the three insulants that are applied to cavity walls, as in Table 3.2. Figure 5.1 shows that mineral wool has the lowest embodied energy when compared to rock wool and EPS. From Table 3.2, mineral wool is shown to have a lower density and embodied energy when compared to rock wool, so it was also expected that mineral wool would have lower embodied energy values as well. Comparing mineral wool to EPS, mineral wool has higher density, but less embodied energy than EPS; therefore, mineral wool has the lowest embodied energy among the three. Thus, from an embodied energy perspective, mineral wool is the optimal insulant for cavity walls.

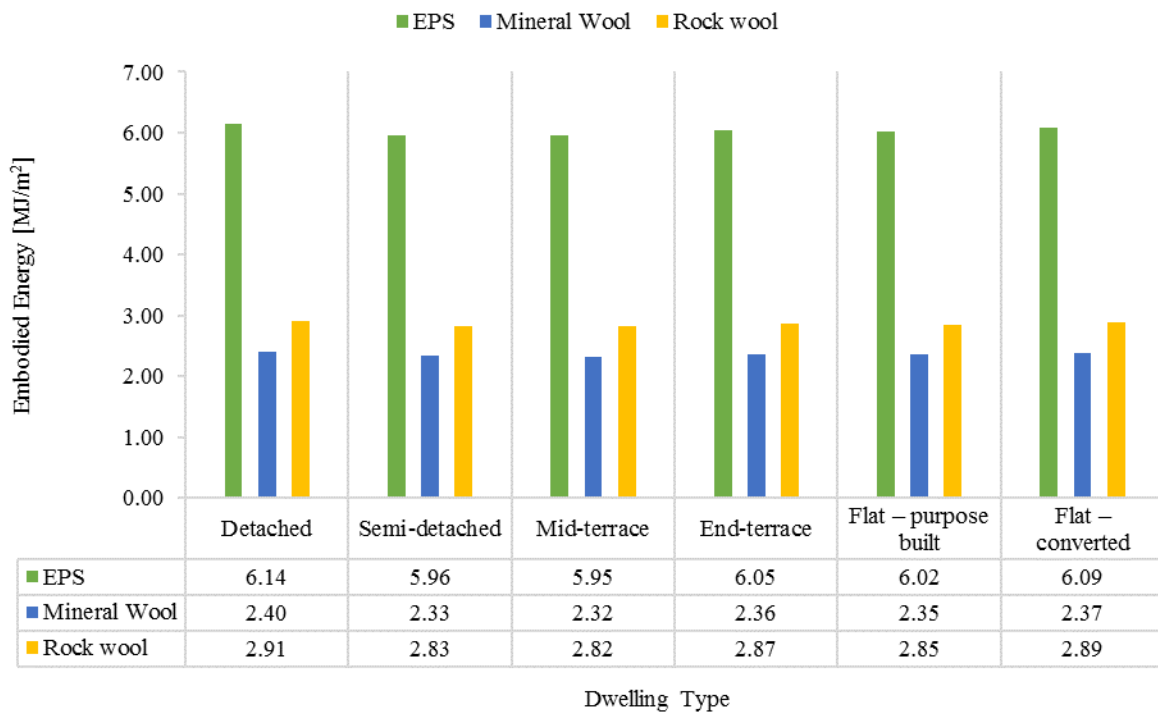
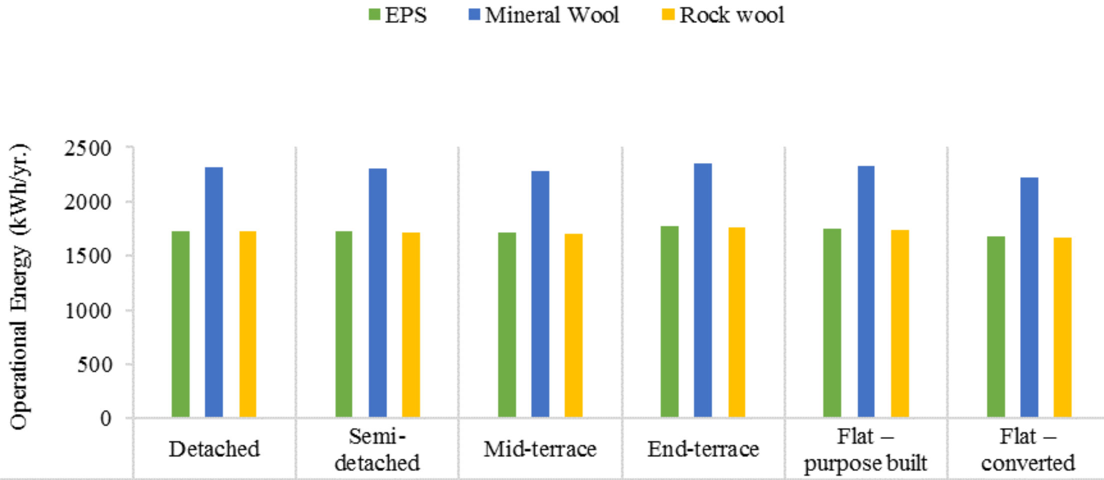


Figure 5.1: Embodied energy of cavity wall insulants (Mj.m-^{2}).

Rock wool and EPS have the same thermal conductivity as stated in Table 3.1, and both have higher thermal conductivities when compared to mineral wool, which has the highest operational energy gains (as seen in Figure 5.2). Mineral wool is, therefore, the optimal insulant for cavity walls with the greatest operational gains among the three insulation materials.



	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
EPS	1728.94	1728.52	1710.95	1768.19	1748.08	1673.35
Mineral Wool	2320.41	2302.29	2280.33	2355.86	2328.99	2219.79
Rock wool	1720.61	1720.03	1702.91	1760.60	1741.75	1670.14

Figure 5.2: Operational energy of cavity wall insulants (kWh/yr.).

Being the optimal insulant with regard to both embodied energy and operational energy gains results, mineral wool is also the optimal insulant when it comes to its payback period (as shown in Figure 5.3). Despite rock wool and EPS having nearly equal operational energy gains, rock wool has a lower payback period when compared to EPS. This highlights the importance of embodied energy when considering energy efficiency because no energy efficiency can be reached without low embodied energy.

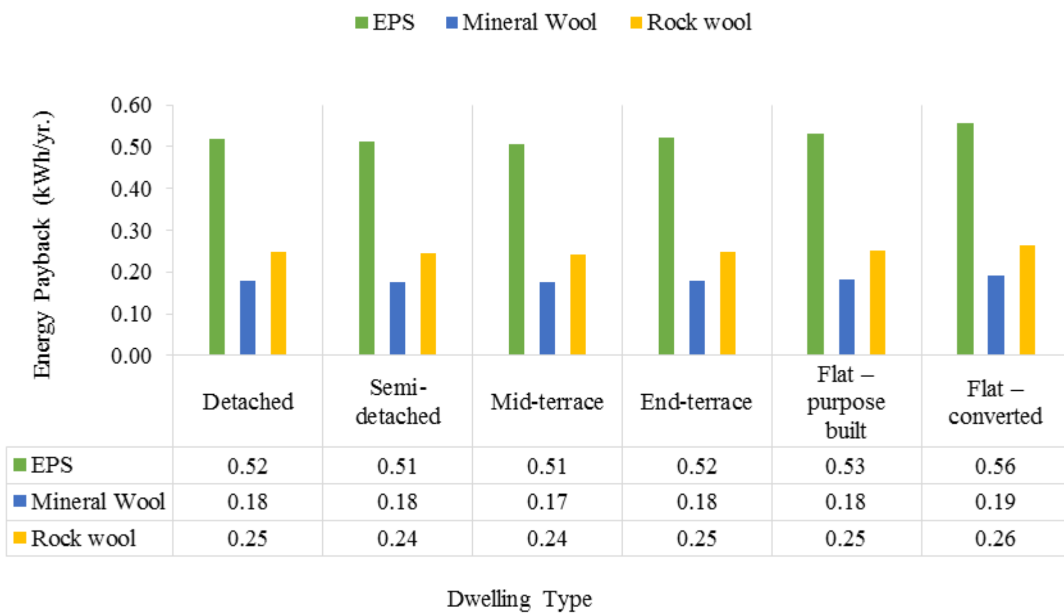


Figure 5.3: Payback energy of cavity wall insulants (kWh/yr.).

The optimal insulation material is the one with less embodied energy, higher operational energy gains and short payback periods. Therefore, for cavity walls, mineral wool is the optimal insulant.

5.1.2 Cold-pitched roofs

Cellulose fibre, rock wool, and mineral wool are the three insulants that have been applied to cold-pitched roofs (see Table 3.2).

Cellulose fibre has very low embodied energy values when compared to mineral wool and rock wool, thereby resulting in embodied energy of insulation values that are much lower, as seen in Figure 5.4. Rock wool has the highest density and the highest embodied energy (see Table 3.1) among the three insulants, and as a result, it has the highest embodied energy. Thus, from an embodied energy perspective, cellulose is, of course, the optimal insulant for cold-pitched roofs.

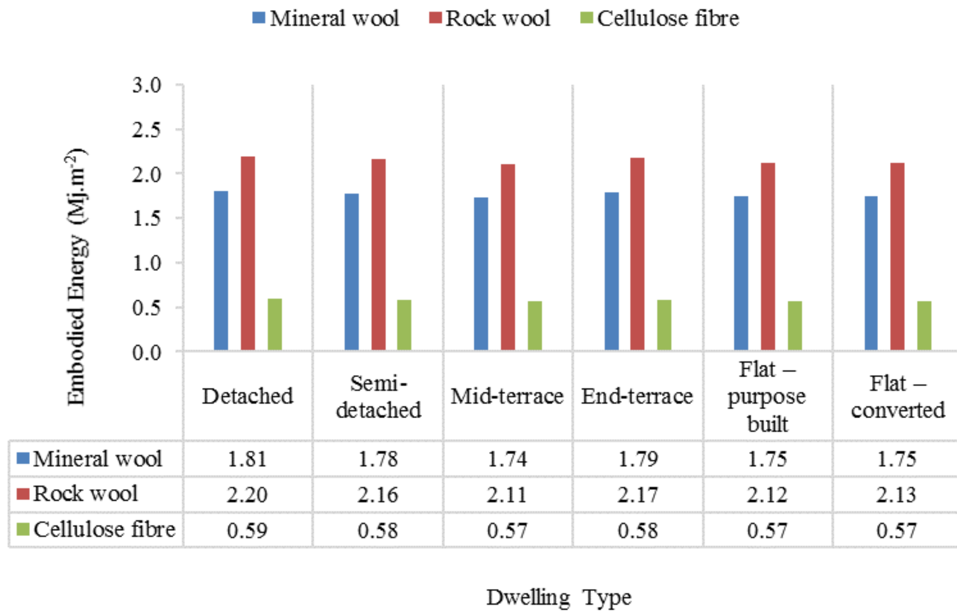
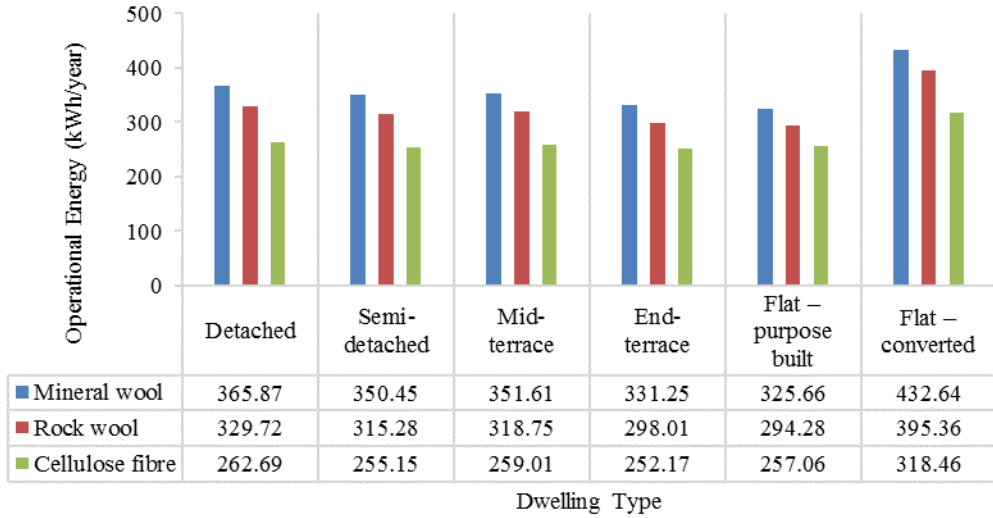


Figure 5.4: Embodied energy of cold-pitched roof insulants (Mj.m^{-2}).

Comparing the operational gains of the three insulation materials, as presented in Figure 5.5, mineral wool is shown to be the optimal insulant with regard to operational energy gains as a result of its low thermal conductivity of 0.034 (W/mK). Rock wool and cellulose fibre have very similar operational energy gains. Therefore, a decision on the optimal insulant with regard to operational gains cannot be made until the payback periods of the other insulants are considered.

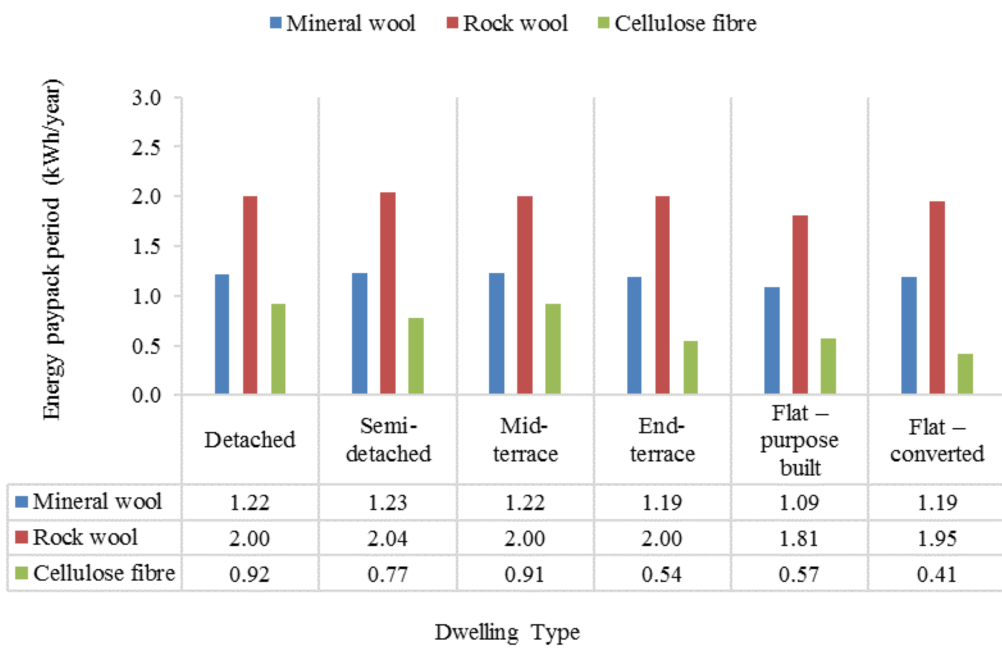
Cellulose has much lower payback periods when compared to the other two insulants, making it the optimal insulant for cold-pitched roofs as Figure 5.6 shown. The differences between embodied energy of various insulation were a way better than the differences in operational energy gains for cold-pitched roof insulants. That is evident by cellulose having marginally lower operational energy gains yet still has much lower payback periods when compared to mineral wool and to EPS.

The results for cold-pitched roofs is in this case related to the lowest embodied energy and payback periods as they are far more significant than the differences between the operational gains values.



	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
Mineral wool	365.87	350.45	351.61	331.25	325.66	432.64
Rock wool	329.72	315.28	318.75	298.01	294.28	395.36
Cellulose fibre	262.69	255.15	259.01	252.17	257.06	318.46

Figure 5.5: Operational energy of cold-pitched roof insulants (kWh/yr.).



	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
Mineral wool	1.22	1.23	1.22	1.19	1.09	1.19
Rock wool	2.00	2.04	2.00	2.00	1.81	1.95
Cellulose fibre	0.92	0.77	0.91	0.54	0.57	0.41

Figure 5.6: Payback energy of cold-pitched roof insulants (kWh/yr.)

5.1.3 Warm-pitched roofs

The three insulants applied to the warm-pitched roofs were expanded polystyrene, rigid polystyrene and cellular glass. In terms of embodied energy, EPS has the lowest embodied energy followed by rigid polystyrene, which has embodied energy values higher than cellular glass due to its greater density (see Table 3.2) EPS has a lower embodied energy value and a lower density than rigid polystyrene and cellular glass. Therefore, EPS is the optimal insulation among the three comparable insulations for warm-pitched roofs, when considering the embodied values of insulation, as shown in Figure 5.7.

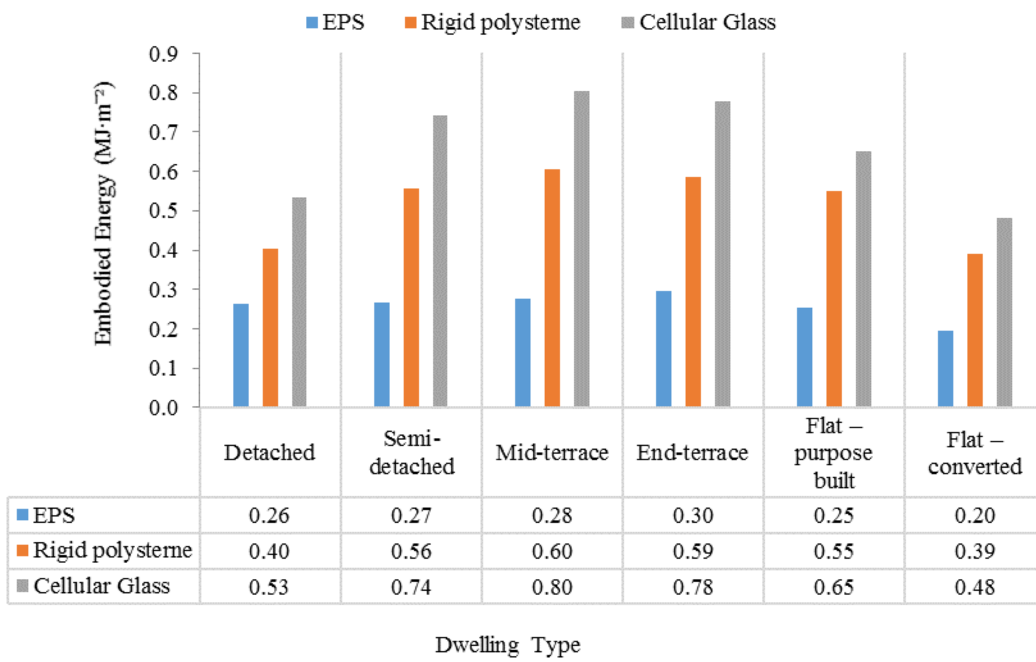
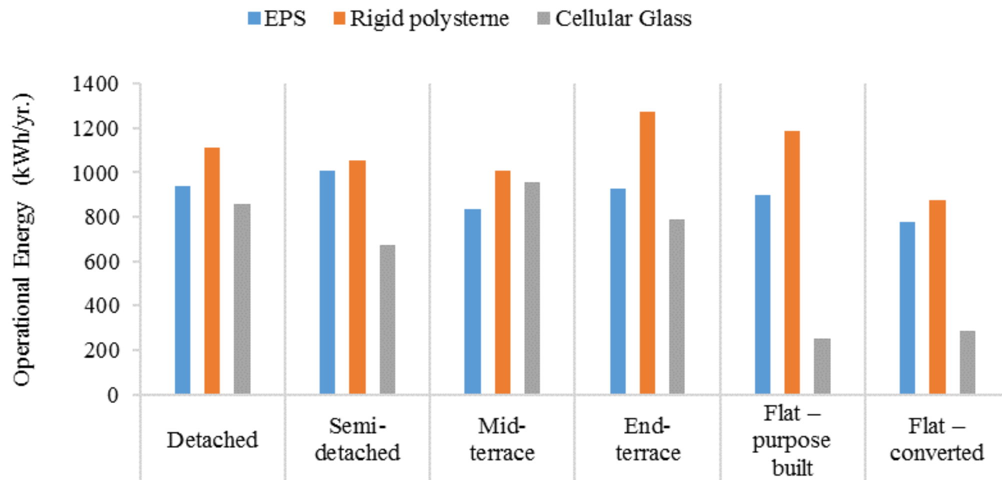


Figure 5.7: Embodied energy of warm-pitched roof insulants (MJ·m^{-2}).

Due to the low thermal conductivity of the rigid polystyrene, it has the greatest operational energy gains when compared to the other insulants applied to warm-pitched roofs, whereas EPS and cellular glass have a similar thermal conductivity, which results in similar operational energy gains. With a slightly higher thermal conductivity, cellular glass has lower operational energy gains compared to EPS (see Table 3.2). Therefore, with regard to operational energy gains, rigid polystyrene is the optimal warm-pitched roof insulant, as shown in Figure 5.8.



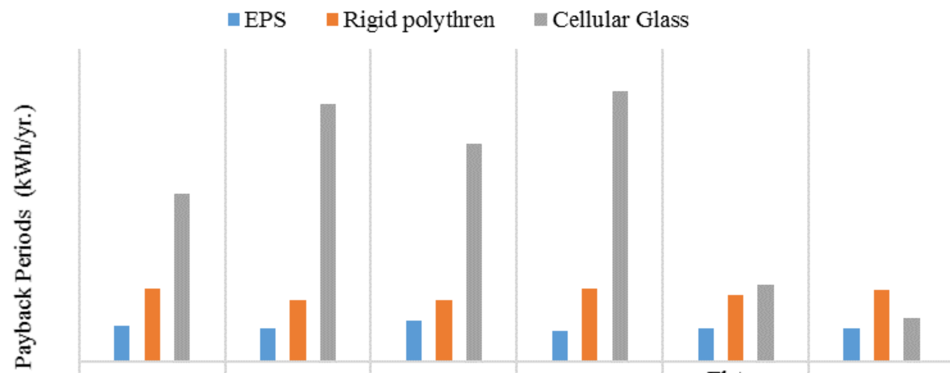
	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
EPS	938.20	1010.46	833.90	927.69	896.79	776.56
Rigid polysterne	1112.91	1053.40	1011.18	1276.97	1190.56	875.61
Cellular Glass	859.07	674.93	957.64	791.25	252.92	288.15

Figure 5.8: Operational energy of warm-pitched roofs insulants (kWh/yr.)

Considering both the embodied energy of the insulation and the operational gains, EPS has the lowest payback period in warm-pitched roofs. Despite rigid polystyrene being the optimal insulation with regard to operational energy gains, its embodied energy of insulation is higher than that of EPS. EPS has a much lower embodied energy of insulation and greater operational energy gains, and that result in lower payback periods. Therefore, EPS is the optimal insulation for warm-pitched roofs, as shown in Figure 5.9.

Flat roof refurbishment was excluded, as the percentage of buildings with flat roofs was very low when checking housing data. Regarding the optimal insulant for solid walls, cellular glass was the only insulation applied to either internal or external walls.

The optimal insulant for floors is sheep wool due to its cheap cost, availability and higher effectiveness of reducing heat loss as a result of its very low density and thermal conductivity.



	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
EPS	0.12	0.11	0.13	0.10	0.11	0.11
Rigid polythren	0.23	0.20	0.20	0.23	0.21	0.23
Cellular Glass	0.54	0.82	0.70	0.87	0.24	0.14

Dwelling Type

Figure 5.9: Payback energy of warm-pitched roof insulants (kWh/yr.).

5.2 Determining the optimal double-glazing

Two decarbonisation models were created to indicate the optimal double glazing scenario, namely Scenario 2.2 and Scenario 2.3. All the applicable windows in the UK housing stock were doubled-glazed, and the changes in their energy consumption and emissions were calculated and classified according to the region, type, and age in order to enable the analysis and comparison regarding energy, emissions, and cost. Both scenarios were compared in terms of the heat lost through the building fabric (W/°C); Scenario 2.3 (the optimal insulation with double-glazing improvements) returned better results than Scenario 2.2 (which applied the double-glazing to the existing insulation of the stock).

Double-glazing windows and full fabric insulation have shown potential for annual cost reductions. Therefore, implementing double-glazed windows in a fully insulated dwelling is more effective than in a non- or partly-insulated home since they both form a barrier that prevents heat losses through the dwelling fabric.

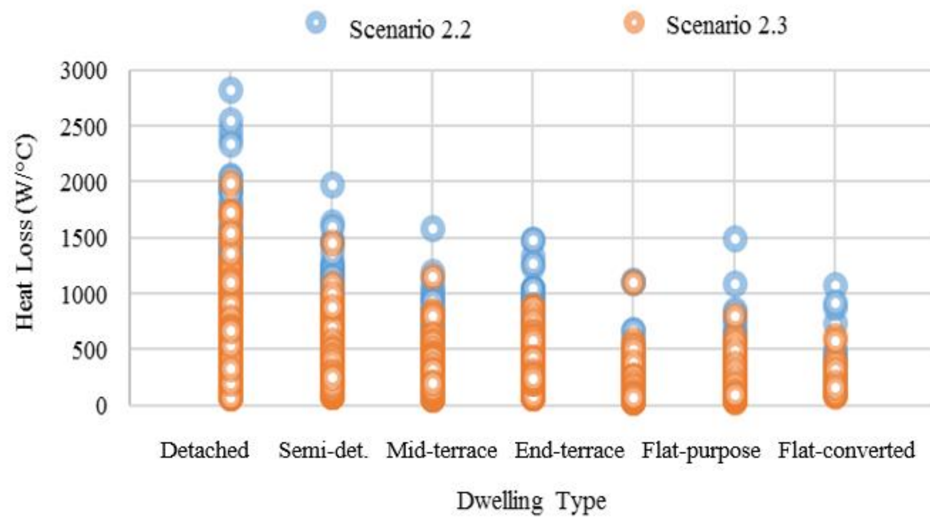


Figure 5.10: Heat loss (W/°C) per dwelling type.

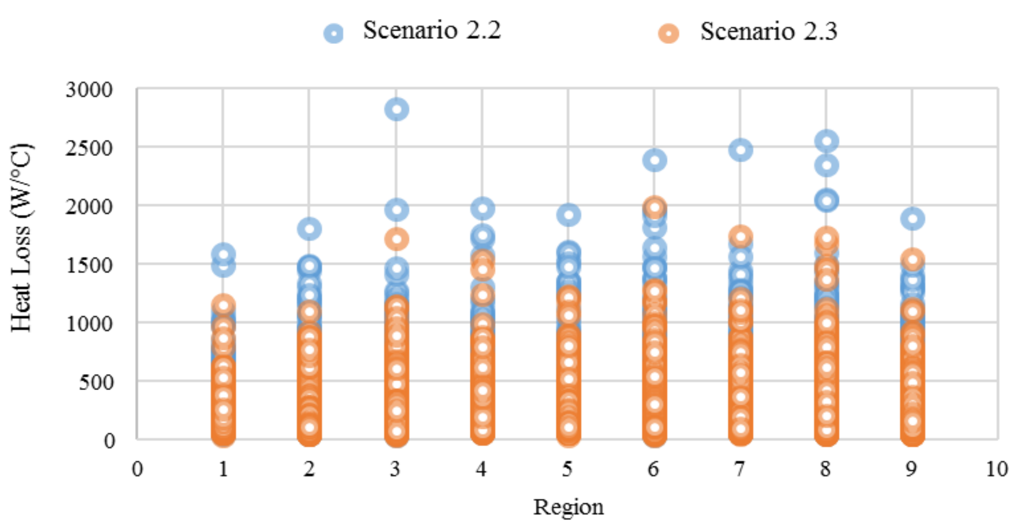


Figure 5.11: Heat loss (W/°C) per region.

Figure 5.10 and Figure 5.11 show that Scenario 2.3 loses less heat in both examples, whereas Figure 5.12 shows that the energy consumed by the primary space heating in Scenario 2.3 is less than it is when compared to Scenario 2.2. Therefore, Scenario 2.3, which combines full fabric refurbishment with double-glazed windows, is optimal with regard to energy consumption and heat losses.

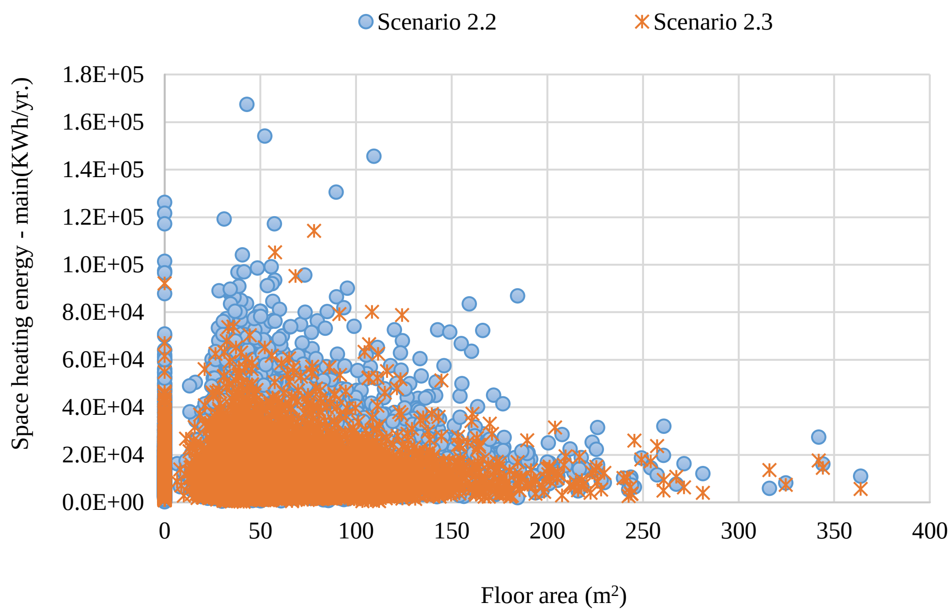


Figure 5.12: The annual energy consumption (kWh/yr.) per floor area.

The mean values of the total energy consumption, capital cost and annual savings of both scenarios were calculated per region as the prices differ due to local perspectives. The number of minimum, mean, and maximum payback years per region were also computed for each scenario, as stated in Table 5.1and Table 5.2.

From both tables, London has the highest number of payback years in both scenarios, due to the higher cost of the renovations. However, it is also recorded to be the most energy-efficient region due to its annual savings in both scenarios.

The Northwest has the lowest payback periods in Scenario 2.2, with a maximum of 1.1 years, and saves nearly £2100 per annum. In Scenario 2.2, the North East, Yorkshire, the East and West Midlands and the South West consume and save almost the same amount of energy with slightly higher energy conservation observed in the South West, with 955 kWh per annum. In Scenario 2.3, the North East and the East of England have the lowest annual savings of £935 and £978, respectively.

Table 5.1: Energy consumption and savings, cost of installation, savings and payback periods for Scenario 2.2.

Region	**Energy**		**Money**		**Payback period**		
	Use	**Savings**	**Cost**	**Savings**	**Min.**	**Mean**	**Max.**
	(kWh/year)		(£/year)		(year)		
North East	34429	7810	2712	665	0.9	1.1	1.3
Yorkshire and The Humber	35101	10088	2794	839	0.9	1.1	1.3
North West	39296	10122	2096	839	0.8	1.0	1.1
East Midlands	34796	10779	2800	897	0.9	1.1	1.3
West Midlands	34209	10542	2782	887	0.9	1.1	1.3
South West	30924	8753	2623	775	1.0	1.1	1.3
East of England	17041	1583	1456	156	1.0	1.1	1.2
South East	35926	9397	2902	796	0.9	1.0	1.2
London	30238	11820	3417	955	1.0	1.2	1.4

Table 5.2: Energy consumption and savings, cost of insulation, savings and payback periods for Scenario 2.3.

Region	**Energy**		**Money**		**Payback period**		
	Use	**Savings**	**Cost**	**Savings**	**Min.**	**Mean**	**Max**
	(kWh/year)		(£/year)		(year)		
North East	31311	10928	2443	935	6.9	12.7	18.5
Yorkshire and The Humber	32113	13077	2540	1094	6.7	12.3	17.8
North West	36316	13102	2843	1092	6.0	10.9	15.9
East Midlands	31741	13834	2538	1159	6.7	12.3	17.9
West Midlands	31210	13542	2526	1143	6.7	12.3	17.9
South West	27916	11760	2366	1032	7.1	13.2	19.2
East of England	17473	1151	1592	987	9.6	14.1	18.5
South East	32919	12403	2646	1053	6.4	11.8	17.1
London	27320	14739	2370	1201	7.8	14.3	20.9

From an energy perspective, Scenario 2.2 produces less energy with lower costs and annual savings which results in shorter payback periods.

Scenario 2.3 delivers higher energy savings and lower annual costs, as demonstrated in Figure 5.13 While it has longer payback periods, as a result of the insulation cost, it is the most efficient option, i.e., it is the optimal scenario for the double-glazing improvement regarding cost and energy savings.

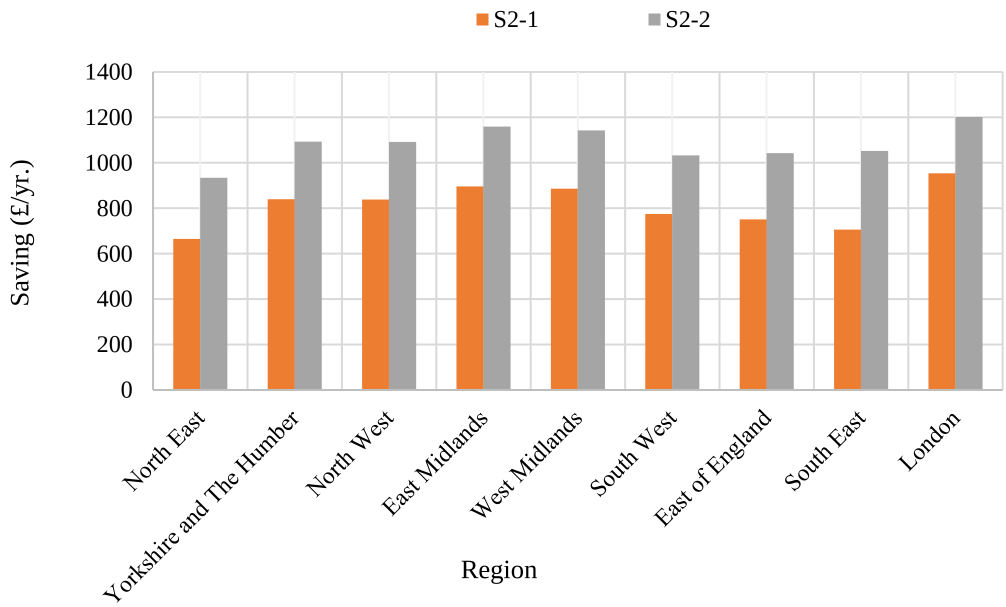


Figure 5.13: Total energy savings per region.

The carbon emissions from each scenario were classified according to region, age, and type. The mean values were then compared to indicate the scenario with the lowest emissions and the highest annual savings., Figure 5.14 and Figure 5.15 present this comparison. Emissions varied from one dwelling to another as some dwellings consumed more energy and therefore produced higher emissions, e.g., semi-detached houses consume an average of 13.05 tonnes of CO_2 per year and account for 28% of the entire UK stock. By contrast, flat -converted produced the lowest emissions, as they represent only 3% of the stock, as recorded in Table 5.3.

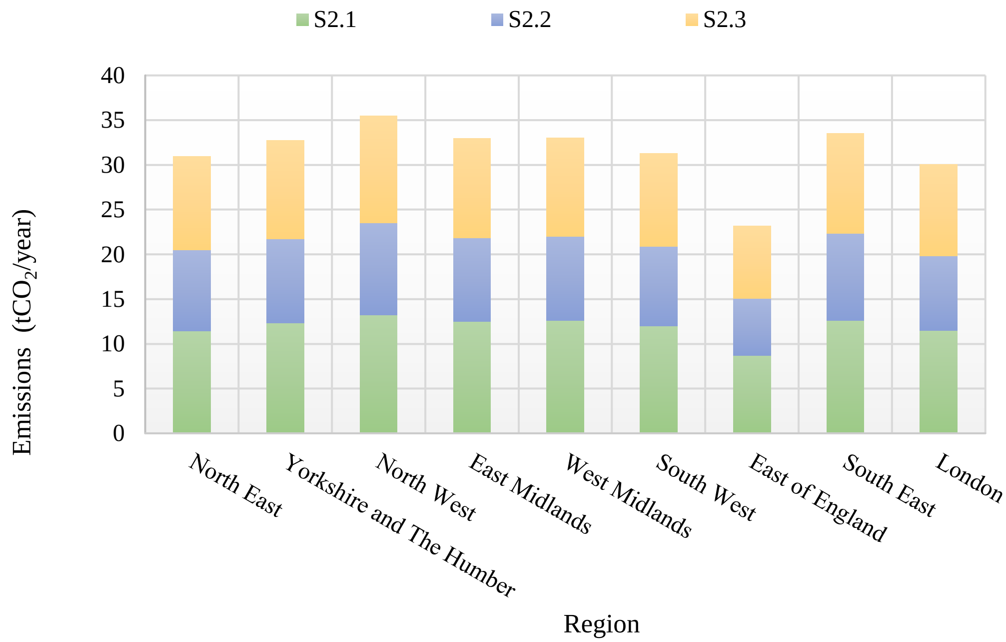


Figure 5.14: Carbon dioxide emissions (tCO_2/yr.) per region.

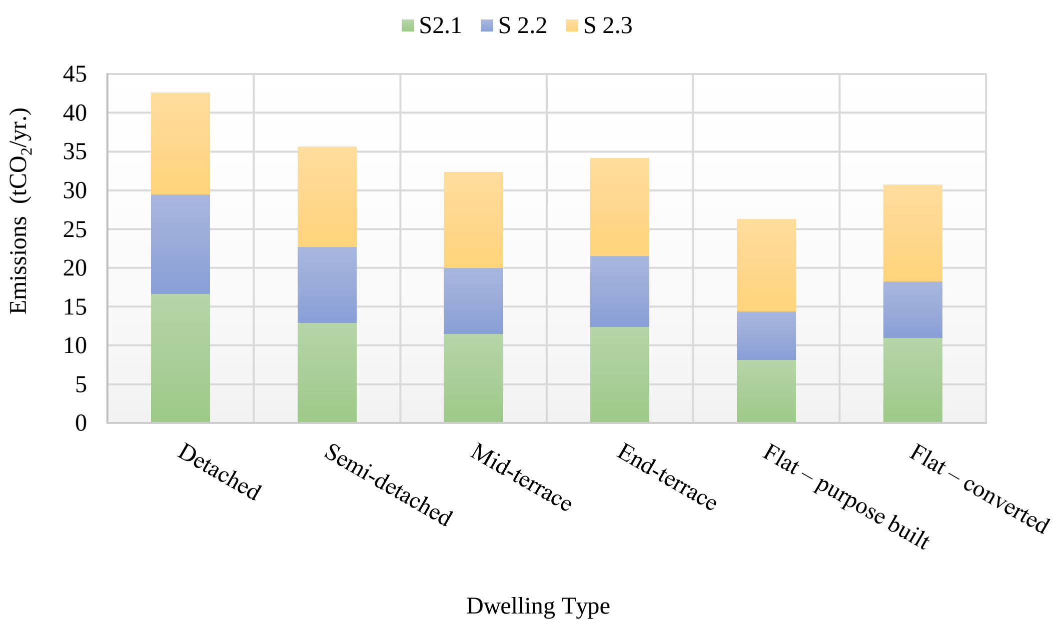


Figure 5.15: Carbon dioxide emissions (tCO_2/yr.) per dwelling type.

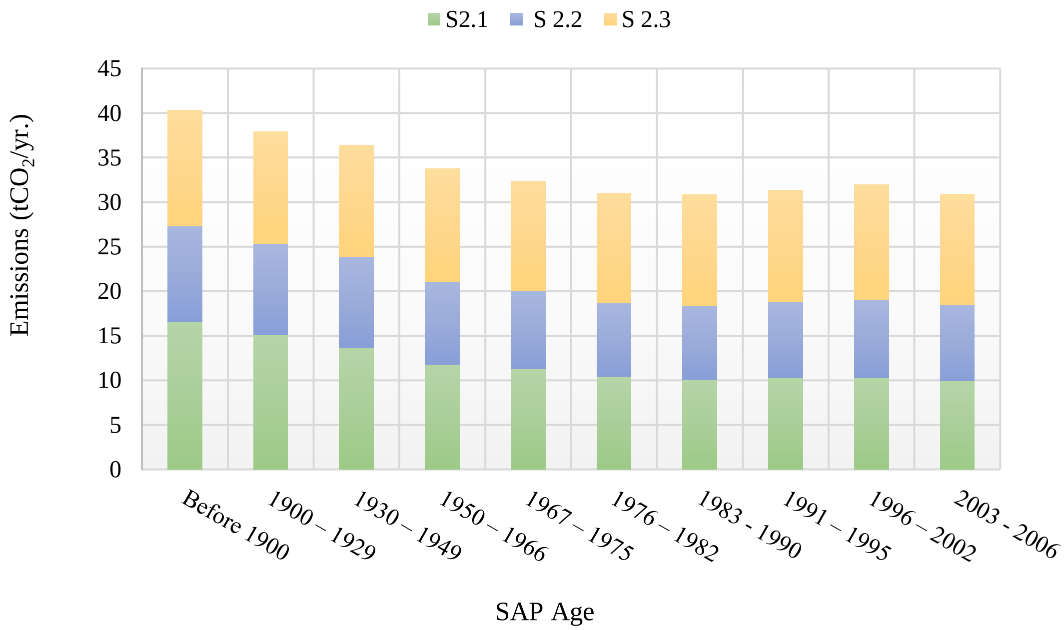
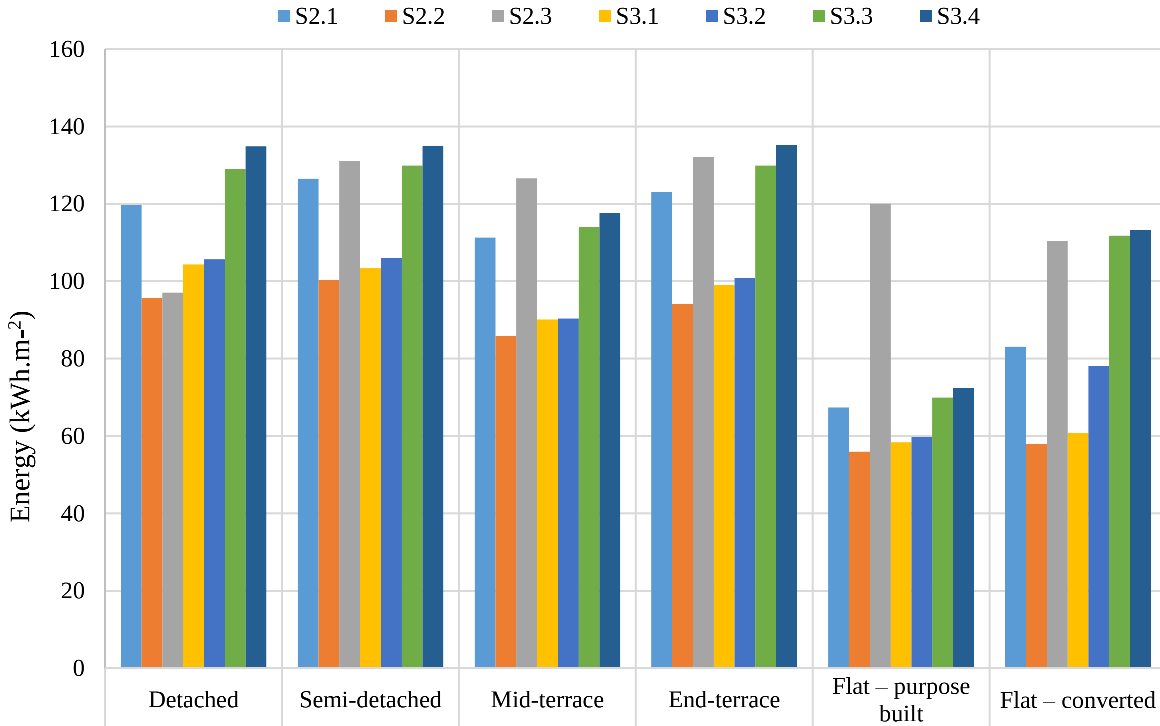


Figure 5.16: Carbon dioxide emissions (tCO_2/yr.) per dwelling Age.

Based on these analyses, the optimal scenario for the double-glazing is Scenario 2.3 since it demonstrates reasonably lower emissions with regard to efficient costs and annual savings in terms of money and energy.

Table 5.3: Number of dwellings per dwelling type.

Type	**Number (-)**	**Percentage (%)**
Detached	3260	20
Semi-detached	4718	28
Mid-terrace	3254	20
End-terrace	1871	11
Flat – purpose built	2974	18
Flat – converted	570	3
Total	**16647**	**100%**



	Detached	Semi-detached	Mid-terrace	End-terrace	Flat – purpose built	Flat – converted
S2.1	120	126	111	123	67	83
S2.2	96	100	86	94	56	58
S2.3	97	131	127	132	120	110
S3.1	104	103	90	99	58	61
S3.2	106	106	90	101	60	78
S3.3	129	130	114	130	70	112
S3.4	135	135	118	135	72	113

Dwelling Type

Figure 5.17: Energy consumption ($kWh \cdot m^{-2}$) per dwelling type.

The highest energy consumed is in Scenario 3.4, as demonstrated in Figure 5.17. After this come Scenarios 3.3 and 2.3. The common denominator in each of the three scenarios is that the double-glazing and upgraded heating systems improvements were made to the stock, but there was no insulation added. As previously discussed in the literature, walls, roofs and floors, represent the most significant sources of heat loss through the building envelope.

End-terrace and semi-detached houses have the highest consumption, as they constitute almost half of the stock cases; representing 20% and 28%, respectively (see Table 5.3).

5.3 Determining the optimal heating system

Four decarbonisation models were created to discover the optimal heating scenario, namely Scenarios 3.1, 3.2, 3.3 and 3.4. Each aimed to reduce heat losses through the building and improve the efficiency of the dwelling heating system. In Scenario 3.1, the optimal double-glazing model 2.3 was used as a base model and improvements to the boiler type and efficiency were added. Pipe work insulation and boiler loss jackets were also considered. In Scenario 3.2, the base model was the optimal insulation model, i.e., Scenario 2.1, and the improvements to the heating system were included.

Scenarios 3.3 and 3.4 used the same procedure as Scenario 1, i.e. the original model, as it was used to create Scenario 3.3 by upgrading the heating system only. In Scenario 3.4, the double-glazing improvement was added to the developed model used in Scenario 3.3.

The improvement included all the applicable cases in the UK housing stock, which is more than 90%, and the changes of energy consumption and emissions were calculated and classified according to the region, type, and age to enable the analysis and comparison.

The results of the four sub-scenarios were generated and two sets of comparisons (shown in Figure 5.18 and Figure 5.19) were made regarding the heat loss through the building fabric (W/°C).

In Figure 5.18, Scenarios 3.1 and 3.2 are shown to lose almost the same amount of heat but with a slightly lower loss in 3.1, which makes it the preferable scenario.

Scenario 2.3 shows better results when finding the optimal double-glazing scenario, thus, as a component of Scenario 3.1, it is not surprising to cause a reduction in heat loss. Therefore, regarding heating loss, 3.1 is the optimal heating system compared to 3.2 with less heat loss either per region or dwelling type. While there was not a significant difference, a decision was made concerning the optimal level of double-glazing as a component of the developed scenario.

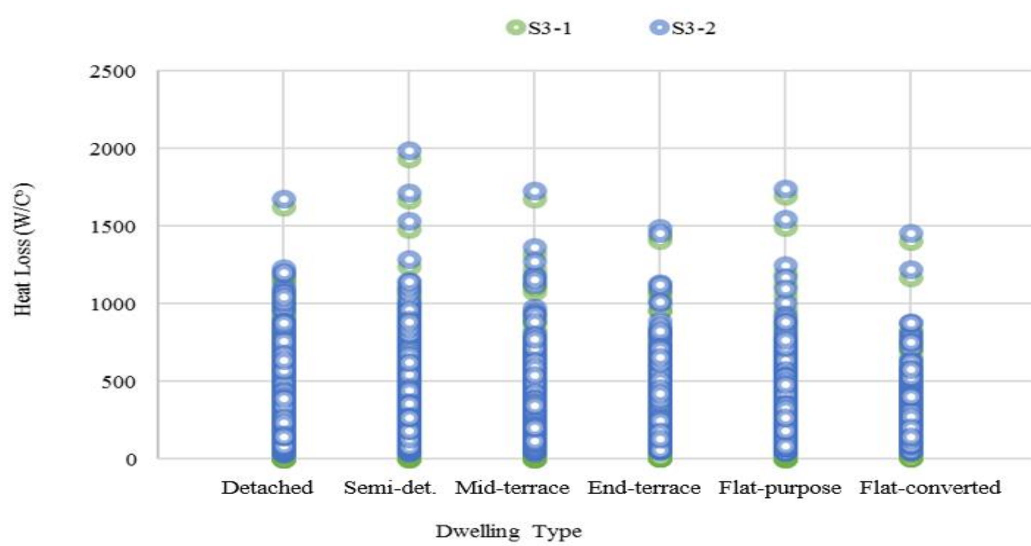


Figure 5.18: Dwelling heat loss (W/°C) under different scenarios.

The same analysis was applied to 3.3 and 3.4, as shown in Figure 5.19, and it was evident that installing two improvements to the original stock model is more efficient and provides a better respond.

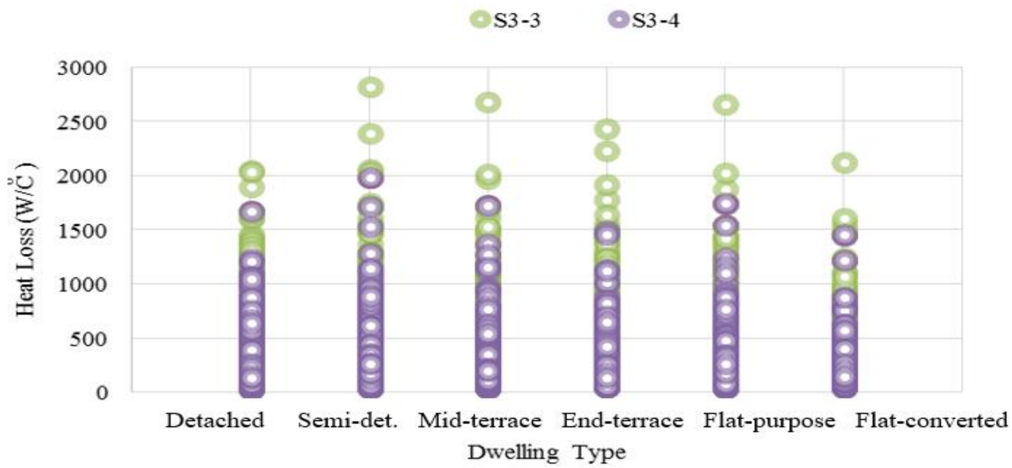


Figure 5.19: Dwelling heat loss (W/°C) under different scenarios

The energy consumption and savings amounts, cost of installation, savings and payback periods per region for each scenario are presented in Table 5.4, Table 5.5, Table 5.6, and Table 5.7.

Table 5.4: Energy consumption and savings, the costs of installation, savings and payback periods for Scenario 3.1.

Region	**Energy**		**Money**		**Payback period**		
	Use	**Savings**	**Cost**	**Savings**	**Min.**	**Mean**	**Max.**
	(kWh/year)		(£/year)		(year)		
North East	35662	6577	2765	613	6.3	11.6	16.8
Yorkshire and The Humber	37095	8094	2870	764	6.1	11.2	16.2
North West	41332	8086	3177	758	5.5	10.1	14.6
East Midlands	37011	8564	2881	815	6.1	11.1	16.1
West Midlands	36430	8322	2843	826	6.2	11.3	16.4
South West	33920	5757	2685	713	6.5	11.9	17.3
East of England	26530	7070	2601	990	6.7	12.3	17.9
South East	38133	7190	2974	725	5.9	10.8	15.6
London	31787	10271	2487	885	7.1	12.9	18.7

Table 5.5: Energy consumption and savings, cost of installation, savings and payback periods for Scenario 3.2

Region	Energy		Money		Payback period		
	Use	Savings	Cost	Savings	Min.	Mean	Max.
	(kWh/year)		(£/year)		(year)		
North East	35902	6337	2790	587	7.2	12.5	17.9
Yorkshire and The Humber	37335	7854	2895	738	6.9	12.1	17.3
North West	41572	7846	3202	733	6.3	10.9	15.6
East Midlands	37251	8324	2907	790	6.9	12.0	17.2
West Midlands	36670	8082	2868	800	7.0	12.2	17.4
South West	34160	5517	2711	687	7.4	12.9	18.4
East of England	26770	5714	2627	815	7.6	13.3	19.0
South East	38373	6950	2999	699	6.7	11.7	16.7
London	32027	10031	2512	859	8.0	13.9	19.9

Table 5.6: Energy consumption and savings, cost of installation, savings and payback periods for Scenario 3.3.

Region	Energy		Money		Payback period		
	Use	Savings	Cost	Savings	Min.	Mean	Max.
	(kWh/year)		(£/year)		(year)		
North East	39482	2756	3195	183	1.0	1.2	1.5
Yorkshire and The Humber	42324	2865	3457	177	0.9	1.1	1.4
North West	46498	2920	3756	178	0.8	1.0	1.2
East Midlands	42641	2934	3513	184	0.9	1.1	1.3
West Midlands	42299	2453	3502	166	0.9	1.1	1.3
South West	39321	355	3293	105	0.9	1.2	1.4
East of England	17439	1184	1560	120	2.0	2.5	3.0
South East	43180	2143	3542	156	0.9	1.1	1.3
London	37685	4373	3154	217	1.0	1.2	1.5

Table 5.7: Energy consumption and savings, cost of installation, savings and payback periods for Scenario 3.4.

Region	**Energy**		**Money**		**Payback period**		
	Use	**Savings**	**Cost**	**Savings**	**Min.**	**Mean**	**Max.**
	(kWh/year)		(£/year)		(year)		
North East	37372	4867	3037	341	1.9	2.3	2.7
Yorkshire and The Humber	40328	4862	3313	321	1.7	2.1	2.5
North West	44441	4977	3605	329	1.6	1.9	2.3
East Midlands	40513	5063	3354	343	1.7	2.1	2.4
West Midlands	40241	4511	3352	317	1.7	2.1	2.4
South West	40597	515	3556	157	1.6	1.9	2.3
East of England	14064	4559	1226	385	4.6	5.6	6.7
South East	40950	4373	3370	328	1.7	2.0	2.4
London	35586	6472	2998	373	1.9	2.3	2.7

From the tables, it is clear that Scenario 3.2 demonstrates a lower energy consumption, cost and higher savings in all the regions. The energy consumed by building services is less; therefore, the total energy is lower as a result of a greater annual savings. Figure 5.24 shows a comparison of the annual conservation of energy for each of the sub-scenarios per region, and Scenario 3.1 happened to be optimal among all of the comparable scenarios.

Scenario 3.2 has the longest payback periods for the regions, and this is because the cost of the insulation and double-glazing is high and there is no conservation in the heating system.

The East of England and London have the longest number of payback years in each of the four sub- scenarios, due to the higher costs of the renovations in these areas; in contrast, these two regions were the most energy-efficient with annual saving of more than £10,000.

The Northwest has the lowest annual savings among all the sub-scenarios with a maximum of £600 per annum in Scenario 3.1.

The North East, Yorkshire, the East of England and the South West consume and conserve almost the same amount of energy with slightly lower energy consumption in the East of England, and that explains the higher annual savings.

The East and West Midlands consume a similar amount of energy, and both have the shortest payback periods among all the sub-scenarios as they showed a large response to the renovation scenarios, although they only constitute 20% of the entire stock (see Table 5.3).

The highest energy consumed is in the following order: Scenario 3.3, 3.4 and 3.2, and finally 3.1 has the lowest consumption per year. The reason for the higher consumption in Scenarios 3.4 and 3.3 is that the improvements made through double-glazing and the heating systems were directly added to the stock, whereas no additional insulation was included. As discussed in the previous section, walls, roofs, and floors lose the most amount of heat through the building envelope. However, 95% of the stock accepted the external and internal wall insulation, and 75% the roof insulation, which means that to ensure the effectiveness of any other improvements, the stock requires full fabric insulation as a first step.

Therefore, from an energy perspective, Scenario 3.2 consumes less energy and has reasonably higher costs and annual savings. Although long payback periods influence the combined costs of the renovations, it is still the most efficient option, i.e., the optimal scenario for heating system improvements regarding costs and energy savings.

The carbon dioxide emissions of each scenario were classified according to region, age, and type. The mean values were then compared to identify the scenario with the lowest emissions and the highest annual savings.

Figure 5.20 , Figure 5.21, Figure 5.22, and Figure 5.23 present this comparison by region, type, and age, respectively. Emissions varied from one region to another as the climates differ, meaning that some required longer heating hours during the day and night. From the results, it was found that the higher the consumption, the greater the emissions. As a consequence of the stock variation in age, type, and region (as illustrated Figure 5.26), some of the scenarios' emissions depended on the number of houses of a particular type in a particular location, e.g., semi-detached houses have the highest emissions in all of the sub-scenarios as they represent 48% of the entire UK stock. However, purpose built flats produced the lowest annual emissions with a maximum of three tonnes of CO_2.

Based on this analysis, the optimal scenario for the heating system is Scenario 3.1 since it has reasonably lower emissions, efficient costs and annual savings in terms of money and energy, as Figure 5.24 and Figure 5.25 are shown.

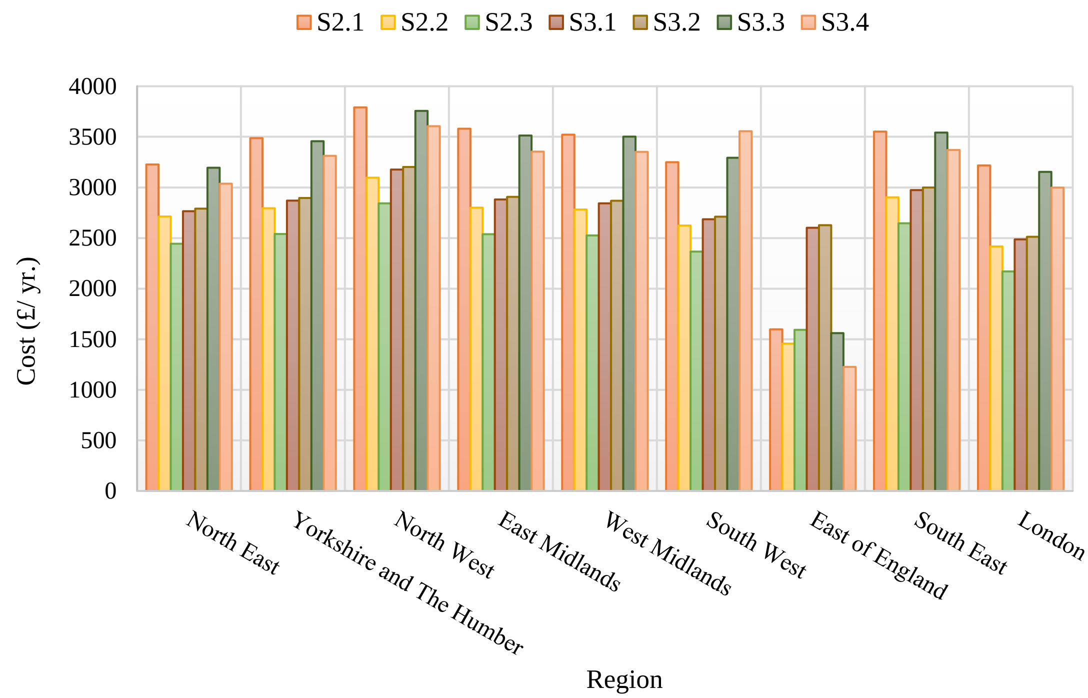


Figure 5.20: Energy capital costs per region.

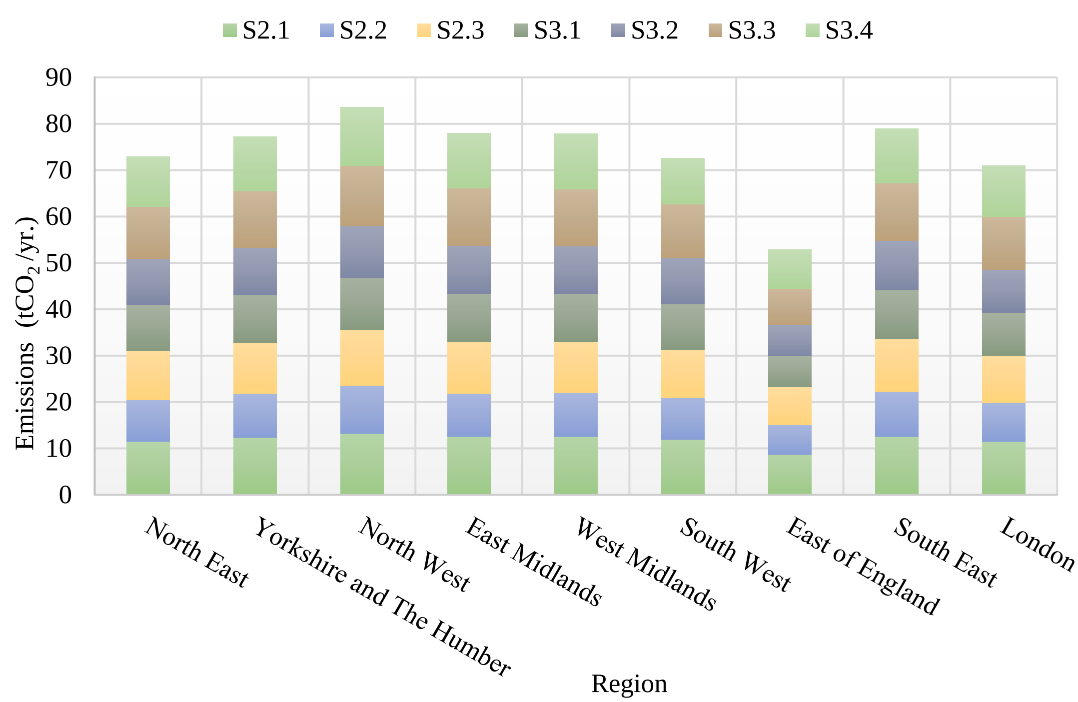


Figure 5.21: CO_2 emissions (tCO_2/yr.) per region.

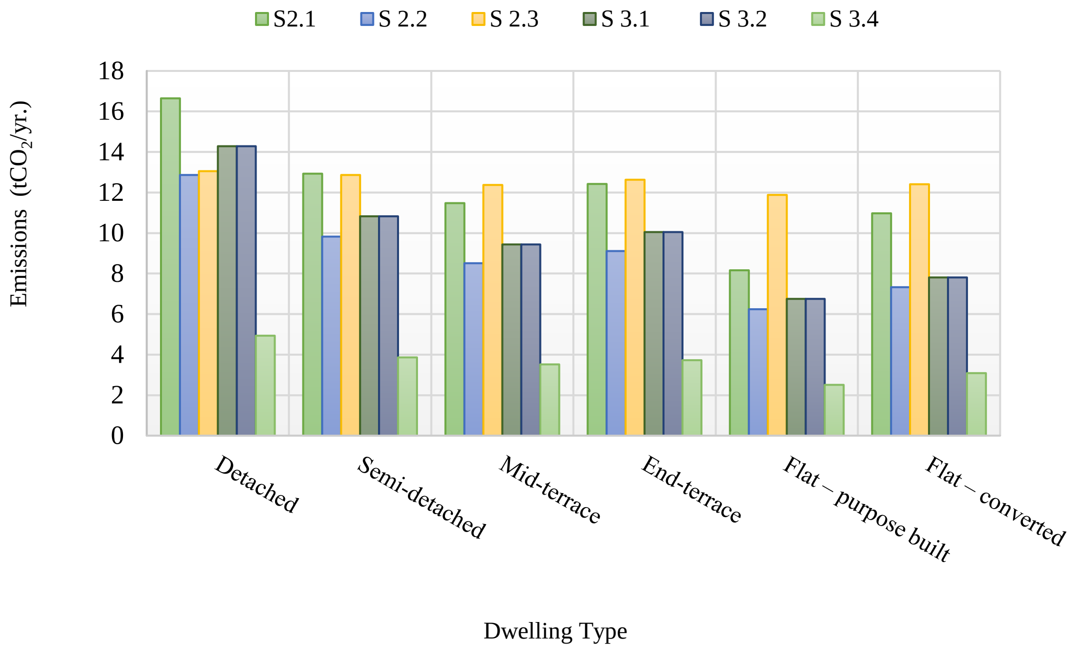


Figure 5.22: Carbon dioxide emissions (tCO_2/yr.) per dwelling type.

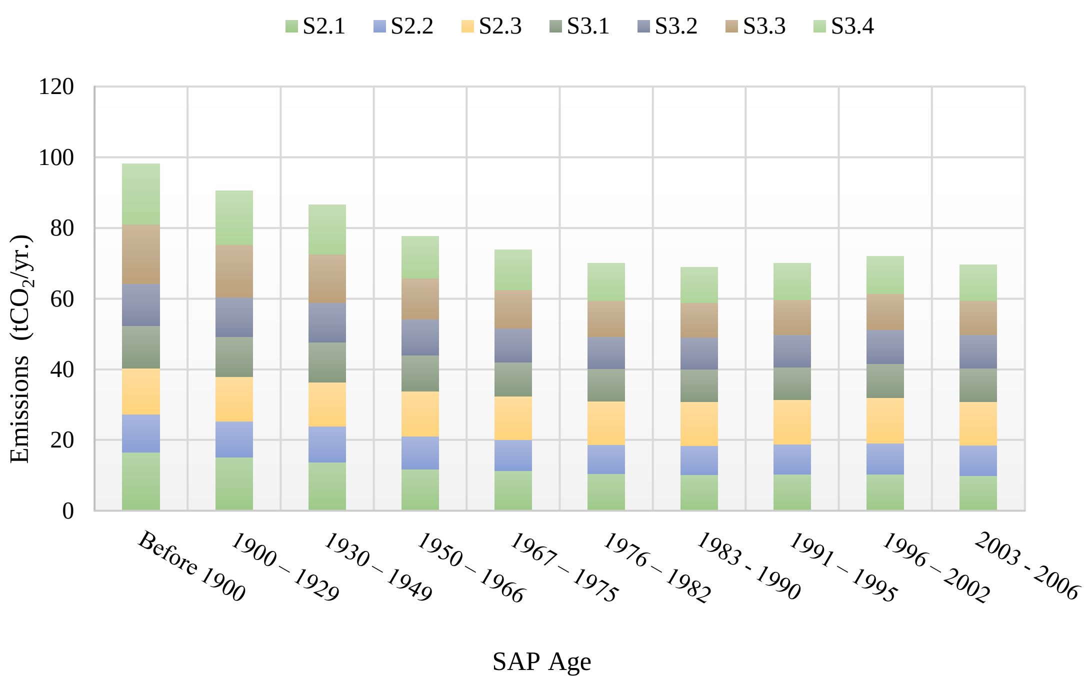


Figure 5.23: Carbon dioxide emissions (tCO_2/yr.) per dwelling age.

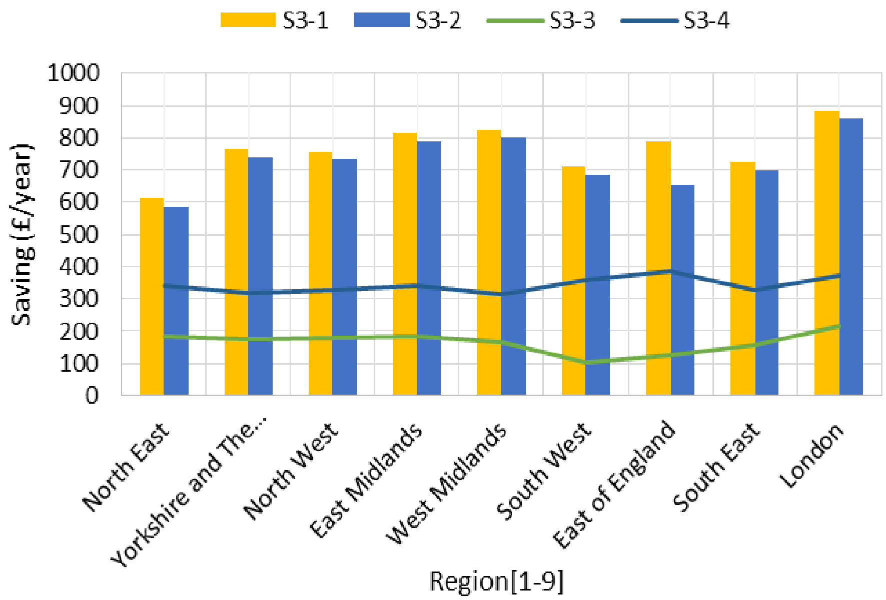


Figure 5.24: Energy annual savings per region.

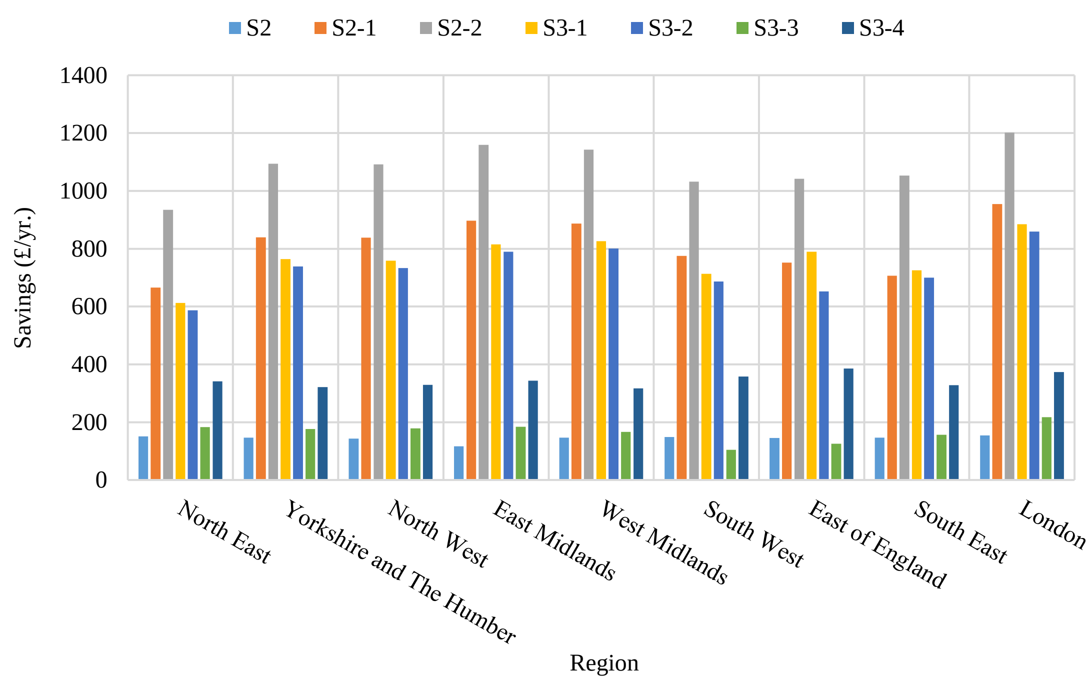


Figure 5.25: Comparison of all scenarios' annual energy savings per region.

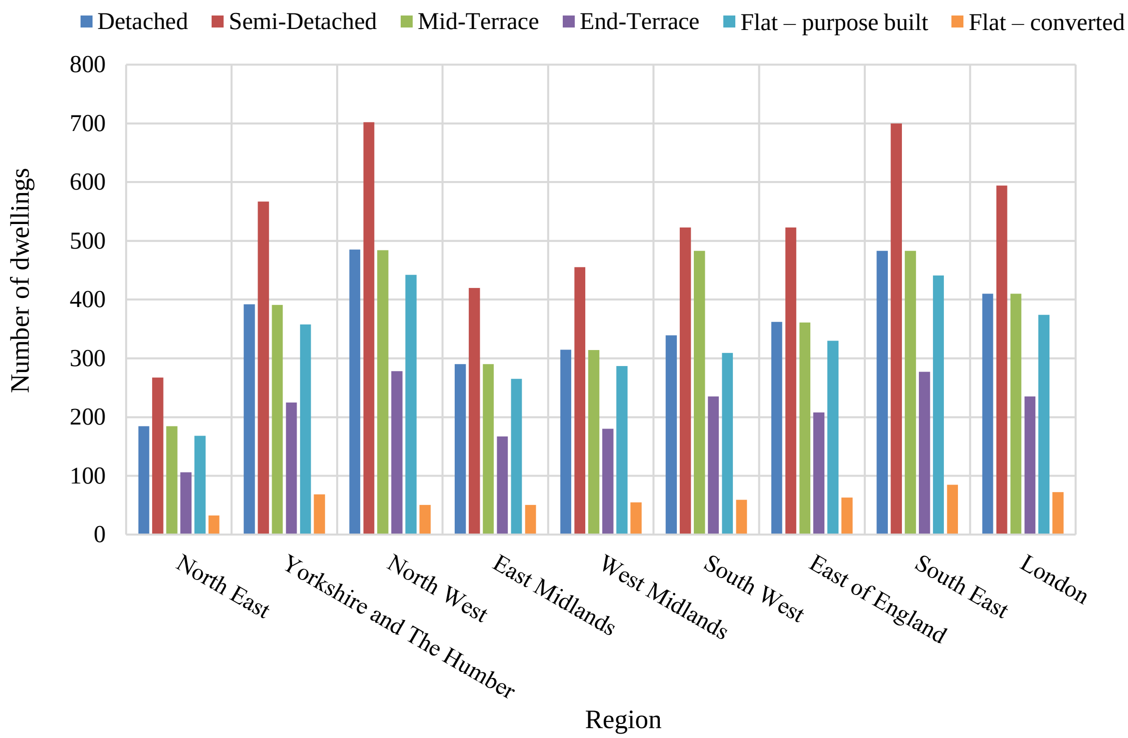


Figure 5.26: Stock variation (number of different types per region).

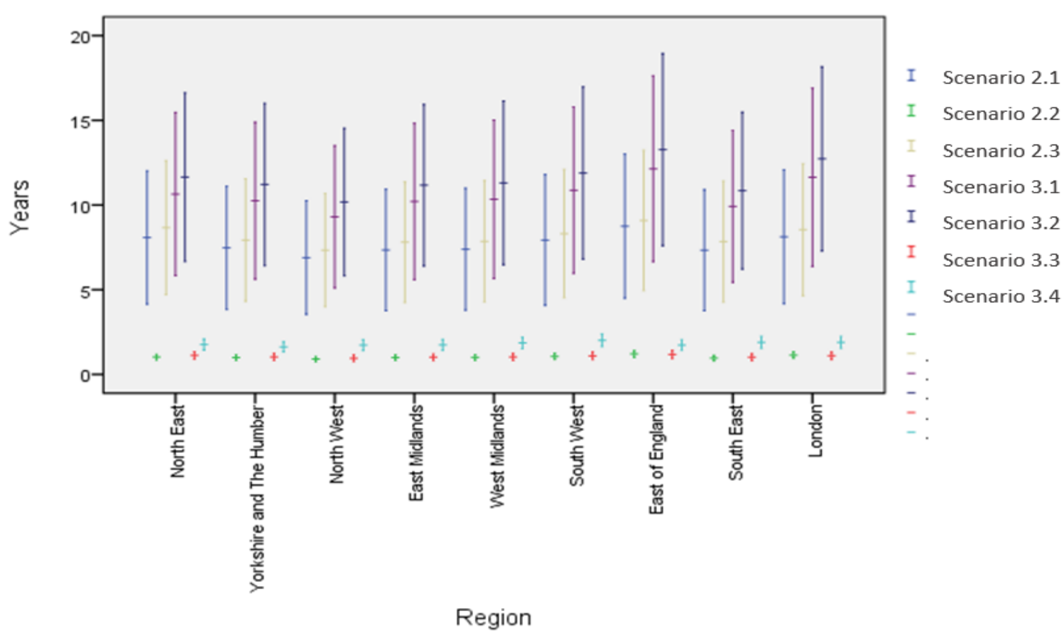


Figure 5.27: Payback periods of all scenarios per region.

Scenario 3.2 has the highest payback periods, as it represents a combination of three renovations: double-glazing, heating systems, and full fabric insulation. Scenario 3.1 comes next with a maximum of 17 years in the East of England and London, where the shortest payback periods appear to be found in Scenarios 3.3 and 3.4 with a maximum of less than three years across the UK.

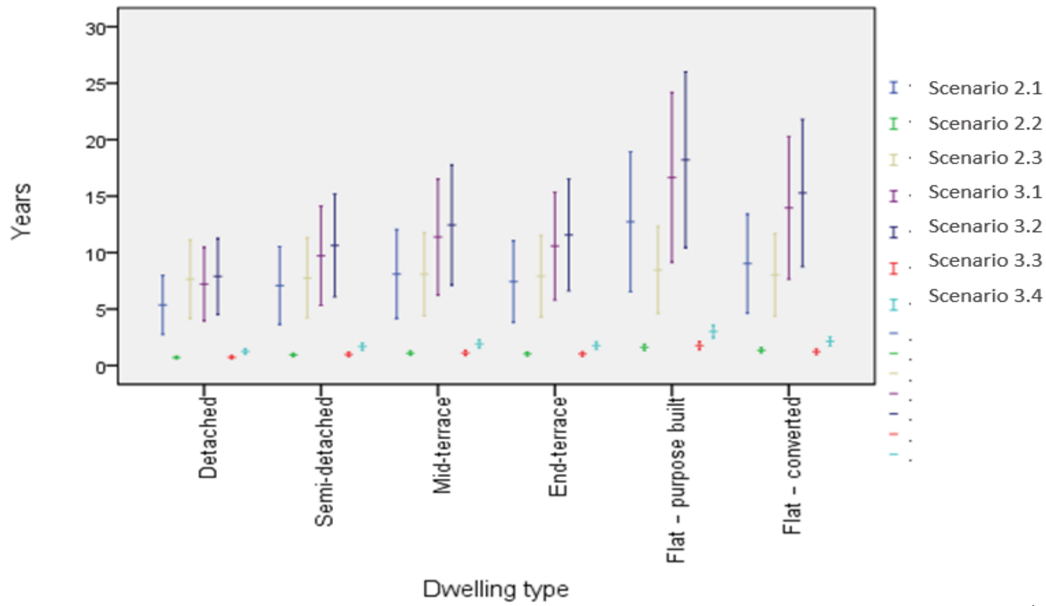


Figure 5.28: Payback periods of all scenarios per dwelling type.

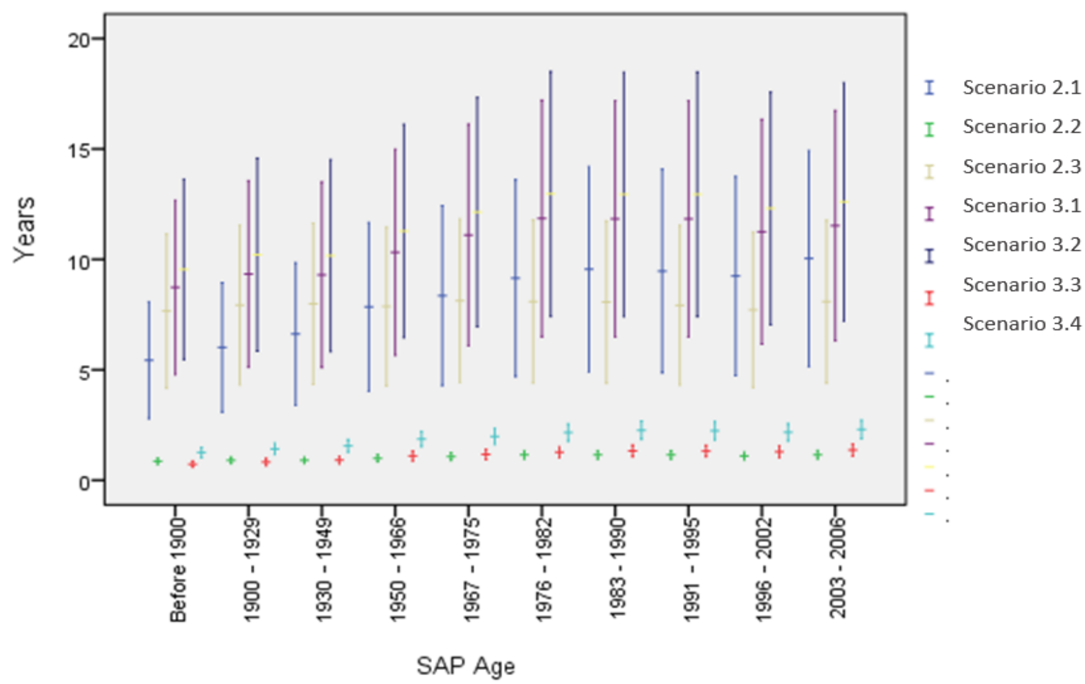


Figure 5.29: Payback periods of all scenarios per dwelling age.

To conclude, the total renovation cost and annual savings of the entire stock were calculated per unit floor area and stated in Table 5.8 in order to enable a comparison between all of the renovations.

Table 5.8: Renovation costs and annual savings of the entire stock.

Scenario	**Renovation cost (£/m^2)**			**Annual savings**	**Energy savings**
	min	average	max	(£/m^2)	(kWh.m^{-2})
S2.1	390	760	1130	195	2197
S2.2	68	81	95	187	2186
S2.3	457	841	1225	262	2836
S3.1	542	946	1351	192	1507
S3.2	474	865	1257	164	1448
S3.3	84	106	127	40	607
S3.4	152	187	221	78	1073

Plotting the costs of renovation against the annual savings per unit floor area in Figure 5.30 supports the previously obtained results. Scenario 2.3 has the highest total annual savings among all of the renovations with a cost £820 per m^2, which confirms the benefits of choosing the optimal double-glazing scenario. Scenario 3.2 costs £850 per m^2 and saves almost £155 per annum. Scenarios 2.1 and 2.2, i.e., the full fabric insulation and the double-glazing improvements, have nearly the same annual savings per unit floor area but double-glazing the whole stock is far cheaper than insulating entire buildings. Renovations 3.3 and 3.4 have the lowest annual savings per m^2, but they are the most affordable options.

In terms of energy and money savings, Scenario 2.3 shows the greatest savings among all the scenarios, whereas Scenarios 3.3 and 3.4 represent the least conservation. Renovation scenarios that combined double-glazing and full insulation have shown the best results regarding both costs and emissions.

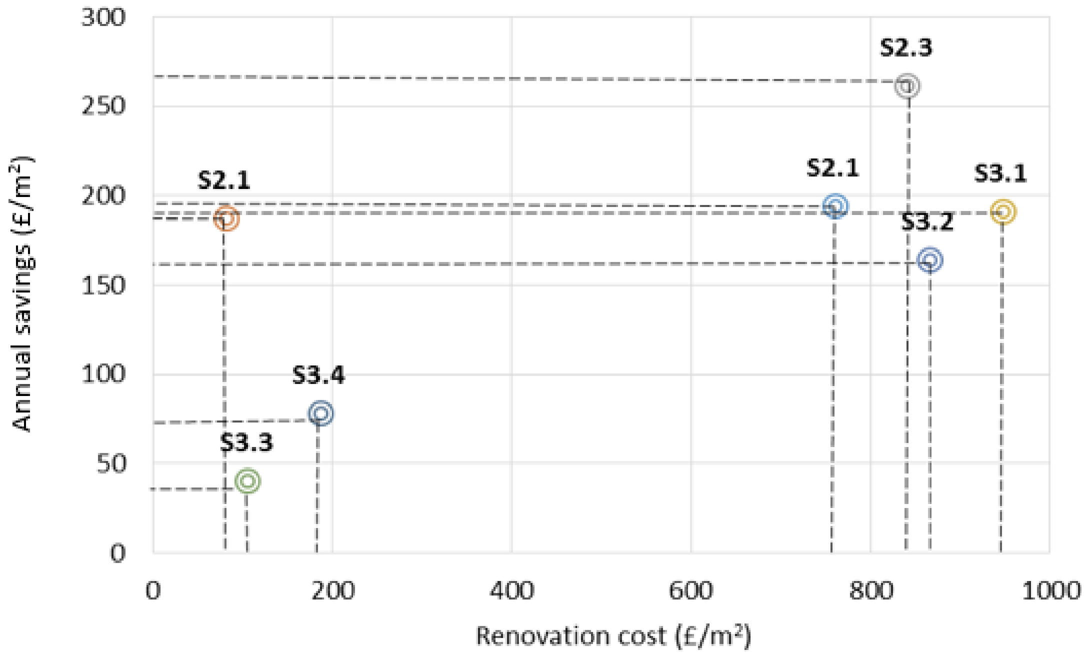


Figure 5.30: Renovation costs against annual savings of the whole stock.

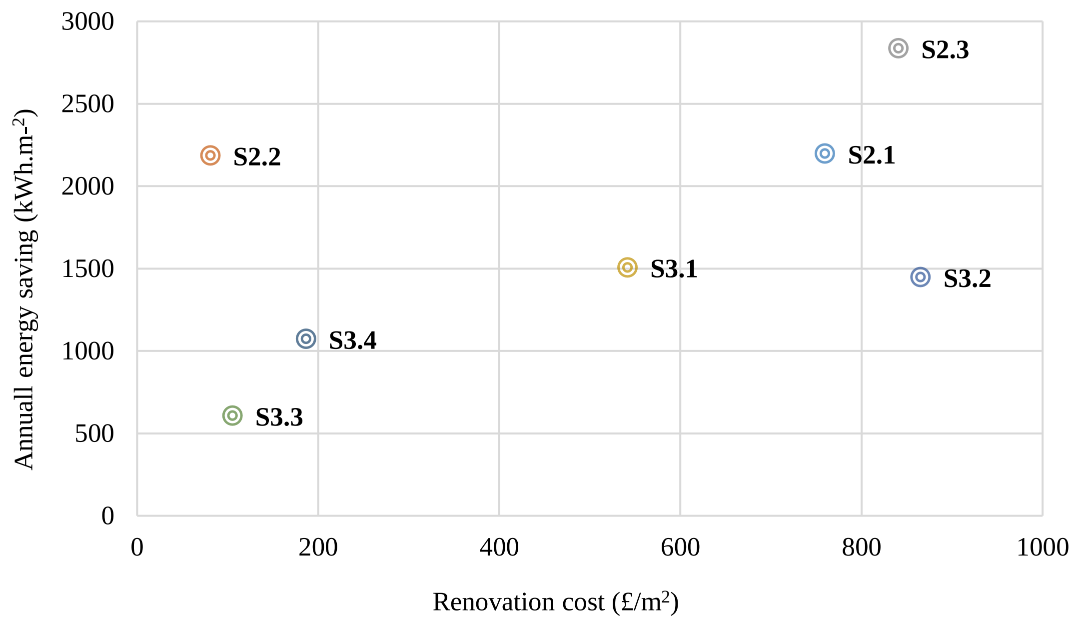


Figure 5.31: Renovation costs against the energy savings of the entire stock.

5.4 Analysing the influence of the input building characteristics

Different variables affect the energy consumption and CO_2 emissions after refurbishment, such as the dwelling's age, type, and location; therefore, these parameters have the largest correlation when the data is tested.

5.4.1 Dwelling age

Dwelling age is considered a key variable when determine the refurbishment energy's payback period. The age of the building provides some useful information about its fabric, thermal performance and the ability to be retrofit. The results have shown that the younger the dwelling, the longer the payback periods (as presented in Figure 5.32). Scenario 2.1 was chosen here to represent all of the fabricated building elements in one go (i.e., Scenario 2.1 considered insulation of walls, roofs and floors).

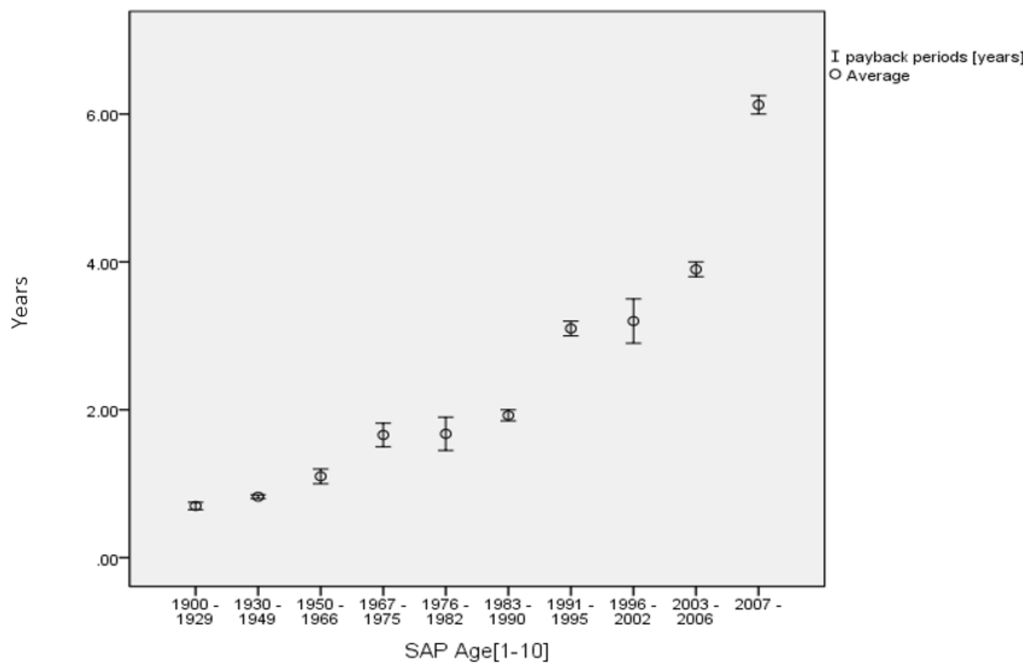


Figure 5.32: Energy payback periods per dwelling age.

The impact of insulation was less in newer houses, which apparently explains the smaller operational energy gains after the refurbishment. The results were as expected because modern homes are built with greater efficiency in mind when compared to older homes. Therefore, older dwellings should be targeted in order to achieve the UK's emissions reduction targets. Moreover, increasing the number of modern homes in the stock should lead to higher efficiency trends.

5.4.2 Dwelling type

House type refers to whether dwellings are semi-detached houses, terraced houses, detached houses or flats. Unsurprisingly, the UK's housing composition changes gradually over time due to the new constructions and planned demolitions (Isaac and Van Vuuren, 2009). However, semi-detached and terraced houses remain the most common house types in the UK, with each type representing approximately one-third of the UK housing stock, as shown in Table 5.3. By plotting the payback periods of Scenario 2.1 according to dwelling type, Figure 5.33 shows that the highest payback period in the entire stock was determined to be the detached end-terrace houses. They tend to have longer payback periods than the other stock types, which is attributed to their large proportion in the stock.

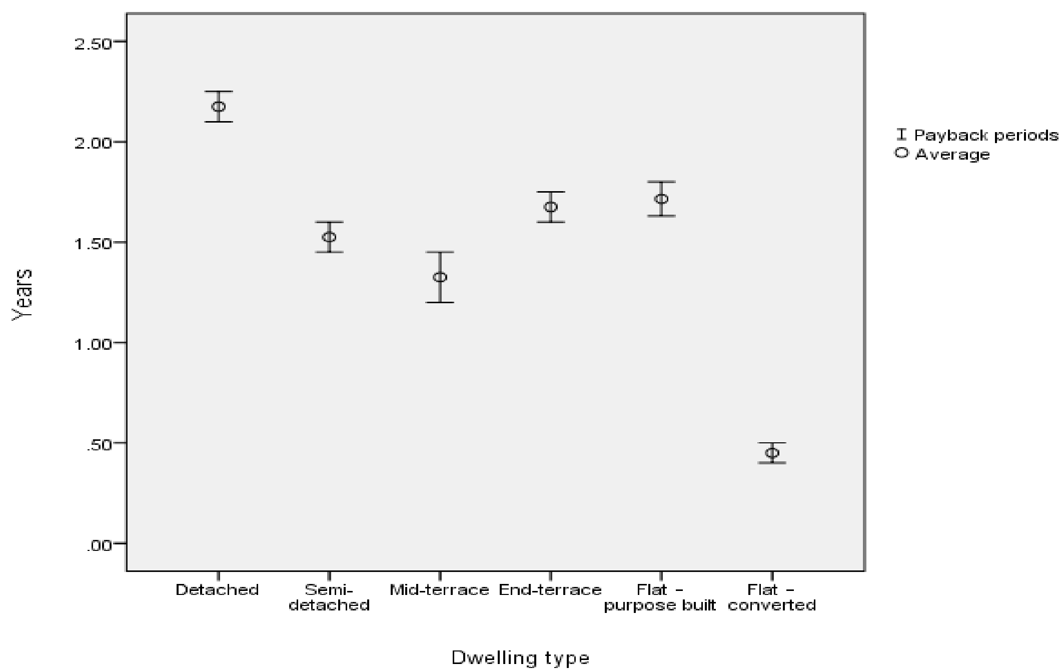


Figure 5.33: Energy payback periods per dwelling type.

Detached houses are typically built with more external walls and more windows than comparable homes of other types, which leads to a greater probability of heat loss, whereas flats tend to have less heat loss as the external wall area compared to their floor area is reduced. In terms of energy consumption, the results in Figure 5.18 show that for most of the applied scenarios, detached and terraced houses have the largest consumption per square metre.

5.4.3 Geographical location

Returning to the literature, analysing the existing studies reveals that location is a critical parameter that should be considered when calculating embodied energy. The amount and type of energy consumed by a dwelling in a certain location is mainly related to changes in the local weather, culture, architectural design and the adopted energy patterns in that particular location. Dwellings in developed regions draw on more additional power than those in emerging economies (Perez-Lombard et al., 2008). For example, in the USA, dwellings consume 22% of the total final energy used, compared with 26% in the EU. The UK consumes 28%, which is mainly related to its uncertain climate, different culture, and the variation in its available building services and construction materials (Perez-Lombard et al., 2008).

From the results, London and the East of England have the highest energy consumption and emissions across the scenarios but they also deliver considerable annual savings, whereas the North and South East and Yorkshire tend to have similar amounts of consumption and emissions, as shown in Figure 5.28. However, in terms of their payback periods, as illustrated in Figure 5.34, the South West and East Midlands required more time to return the cost of insulation.

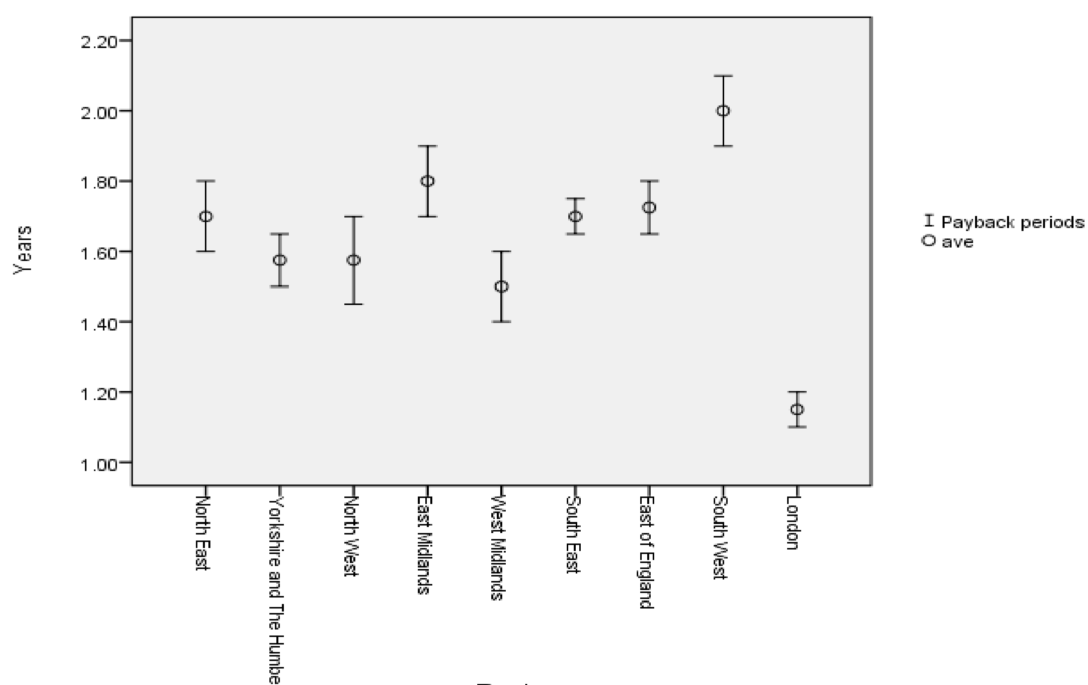


Figure 5.34: Energy payback periods per region.

Chapter 6
Conclusion

The United Kingdom's housing stock is recorded as the least energy-efficient stock in Europe, and it accounts for approximately a quarter of the UK's annual carbon emissions. The government has committed to an 80% reduction in carbon dioxide emissions by 2050. Energy use in buildings accounts for 40-50% of the UK's emissions, and the residential sector contributes more than half. The Climate Change Act committed to a complete renovation of the UK building fabric, as nearly 75% of the current stock will still exist in 2050. Thus, more focus on retrofitting the existing stock is required. Thirteen percent of the UK's CO_2 emissions comes from the energy consumed in homes for space heating and hot water. However, to achieve the planned reduction, a 29% cut in carbon emissions is required by 2020 in the residential sector alone(DECC, 2012, Humar et al., 2011)

The study focused on wider measures to control the embodied energy of housing stock and has analysed some of the possible renovation scenarios that support the reduction of energy consumption in the residential sector. Costs and annual savings have been considered as significant factors that should be explored when choosing appropriate refurbishments. The most important factors were analysed in this thesis and are embodied energy, energy consumption, and carbon dioxide emissions.

This project has firstly focused on the addition and upgrading of insulation as a refurbishment option and the energy efficiency of insulating dwellings. Embodied energy of insulation, operational energy gains and energy payback periods were considered as part of the analysis.

The first analysed objective of the results was finding the most energy-efficient insulation for each building element. The results have shown that mineral wool is the most efficient cavity wall insulation, whereas the optimal insulants for warm- and cold-pitched roofs are EPS and cellular glass, respectively. Cellular glass was the only applicable insulation to internal and external walls. Sheep wool was far more efficiently used in floor insulation.

Contributing to the current research, the results confirmed the initial hypothesis of this investigation, as assessing the energy efficiency and the embodied energy of insulation refurbishments has shown a significant impact on reducing the energy consumption and CO_2 emissions in total and has also outlined the dwelling age, location and type that should be targeted to achieve the required reduction.

Research Question 1: What is the most efficient strategy for improving energy usage and reducing greenhouse gas emissions for existing domestic properties in the UK: rebuilding or refurbishing the dwelling?

Considering that new builds represent 1% of the entire UK housing stock and 75% of the stock will still exist in 2050, action is essential to renovate existing dwellings (Section 2.6)(Roberts, 2008). Renovating dwellings can lower not only energy consumption but also the dwelling's whole life cost, which is a benefit for the economic value of the building in the long run (Sartori and Hestnes, 2007). Refurbished buildings reduce the embodied energy and improve operational energy performance as compared to new constructions. However, the green deal suggested a demolition strategy for 14% of the current UK stock. Thus, refurbishment is the most efficient strategy for improving energy usage and reducing greenhouse gas emissions of existing dwellings (Chapter 5).

Research Question 2: Can refurbishing existing properties enable them to reach current new build standards?

New builds offer opportunities for energy management that may not be achievable by some refurbishments, but require more energy for extracting, transporting old materials, manufacturing, and re-transporting the new building materials. A renovated dwelling can achieve the same level of efficiency of newly built homes at a lower cost than rebuilding. However, this is not always the case, as some buildings have come to the end of their life and need destroying (Section 2.6)(Treloar, 2009, UK green building council, 2015).

Large-scale renovation works, with significant budgets, are more likely to achieve better overall results, as major changes may be required in the building structure. For instance, changing a window's orientation or forming a new entrance in a different location of the building to benefit from daylight and natural ventilation. Re-installation of the building services systems may also involve reaching the finest energy efficiency standards (Section 2.6)(Osmani and O'Reilly, 2009)

Research Question 3: Does the operational energy gains of refurbishments offset the embodied energy of the refurbishments?

The analysis confirmed the research presented in the literature review suggested embodied energy was a significant contributor to energy efficiency. Embodied energy has a significant impact on reducing energy consumption in total, as the lower levels of energy consumption and shorter paybacks of all of the suggested scenarios were delivered from lower embodied energy values. The operational energy of a refurbished dwelling can be improved but will not replace the embodied energy of the refurbishment. Based on this perspective, the embodied energy should be highly considered during each phase of construction (Chapter 5).

Research Question 4: What building element represents the biggest improvement in terms of energy conservation when refurbishing?

Considering both the energy efficiency of the building element, refurbishments and their applicability to the UK housing stock, the analysis of this research shows that refurbishing cavity walls and cold-pitched roofs will have the greatest impact on UK emissions when compared to warm-pitched roofs, solid walls, and floors(BRE, 2005, Pullen, 2011a). Thus, cavity walls and cold-pitched roofs should be the focus of the refurbishments on a UK-national scale (Chapter 4 see table 4.3).

Research Questions 5: What dwelling characteristics have the largest impact on refurbishment payback periods?

The building characteristics that have the largest impact on the refurbishment payback period, in terms of importance are dwelling age, type and origin respectively.

Dwelling age is the key variable when determine the refurbishment energy's payback period, where the dwelling age provides evidence about its fabric, thermal performance and the potential to retrofit (Roberts, 2008). The results have shown that the younger the dwelling, the longer the payback period as modern homes are built with a greater efficiency when compared to older homes (Chapter 5, Section 5.4.1)(Roberts, 2008).

The region in which a building is located is a critical parameter that should be considered when calculating embodied energy. The amount and type of energy consumed in a certain dwelling type in a specific location depends on the local culture and climate Regarding this study, London and East of England have the highest energy consumption as a proportion of the total household energy consumption (Chapter 5, Section 5.4.3)(Perez-Lombard et al., 2008).

The longest payback period was determined according to the dwelling types (detached, semi-detached and mid-terraced houses), which attributed to their high proportion per region. Detached houses are typically built with more external walls and more windows, which allows for more heat loss, whereas flats tend to have less heat loss since their external walls cover a smaller area when compared to their floor area. (Chapter 5, Sections 5.4.2)(Isaac and Van Vuuren, 2009).

Thus, Dwelling age is the first concern when renovation any dwelling type at any location.

Research Questions 6: Are there any considerable differences in the energy performances of existing dwellings of the same type but in different locations?

Based on the answer of the previous research question, the answer for this question is (Yes) as the amount and type of energy consumed by a dwelling in a certain location is mainly related to changes in the local weather, culture, architectural design and the adopted energy patterns in that particular location (Chapter 5, Section 5.4.3)

Research Question 7: Which is the more efficient and affordable when comparing costs and energy conservation of the applied renovation scenarios?

Renovation scenarios that combined double-glazing and full insulation have shown the best results regarding both cost and emissions. In terms of energy and money saving, Scenario 2.3 shows the greatest savings among all scenarios. (Chapter 5, Sections 5.1, 5.2, and 5.3).

To sum up, the research results have shown that renovating dwellings can lower not only the energy consumption but also the dwelling's whole life cost, which is a benefit to the economic value of the building in the long run (Hernandez and Kenny, 2010, Hordeski, 2004, Labat et al., 2015). Moreover, retrofitting a dwelling's fabric and building services systems can considerably improve energy performance. Hence, the research has proved that retrofitting is the most practical and feasible solution to achieve the 2050 green deal desired reductions.

6.1 Modelling limitations

The research in this thesis has extensively utilised the Cambridge Housing Model (CHM) 2010 as the source of its housing data. Therefore, the inherent limitations of the CHM model also apply to this work. The following limitations have an influence on the outputs of the study.

- Retrofitting of existing buildings has many challenges, in particular, those related to changes in climate (projected), services, and occupant behaviour and government policies.
- Different retrofit measures may have various effects on associated building sub-systems; due to these interactions, the selection of the retrofit technologies becomes very complicated. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building renovation project.
- Each building is unique with different characteristics. The retrofit measures used in one building may not be suitable for use in another building.

These limitations have affected the accuracy of the modelling as much of the data reported in the Cambridge Housing Model relies on samples and assumptions. Therefore, inaccuracy cannot be avoided. Moreover, the CHM did not support any addition to the recorded data, only modifications. For example, the use of solar panels technologies is accounted for in CHM 2010 only through two options (1=Yes, 2=No), allowing for no further amendments. The Cambridge model assumes a cavity thickness of 0.025 m and this thickness was applied to all refurbishments in the model to provide a unit thickness for comparison between building elements.

6.2 Further work

There is a number of ways that the research conducted in this thesis could be further expanded upon. The following three subjects are selected and recommended as they were discovered in the process of conducting this work, but were not sufficiently investigated.

6.2.1 Increasing the insulation thickness

A thickness of 0.025 m was applied to all refurbishments in the model. The reason for this was to provide a unit thickness for the comparison between building elements, but in practice, the elements can have thicker layers of insulation. Thicker insulation layers can decrease the heat losses through the building fabric, reduce the heating load and fuel bills, but also increase the cost of insulation. Further research could look at the impact of increasing the insulation refurbishment thicknesses to find an optimal insulation thickness for each building element.

6.2.2 Geographical variation

To determine the environmental impact of a building, it is essential to perform a comprehensive life cycle analysis (LCA) of a building's life, starting from extracting the building materials, processing, manufacturing and delivering them to the construction site. Transportation of materials is a major factor in the cost and energy of a building. However, due to the lack of embodied energy data for transportation, it is difficult to produce a complete LCA to quantify the amount of energy needed at this stage of the production. Conversely, using global satellite mapping, geographical information can be used to map the shortest distance between the suppliers and the sites and therefore this creates an opportunity to reduce the energy used for transportation. This concept has not been considered when calculating the embodied energy in this study, and could be further explored to support energy savings and improve the accuracy of the embodied energy calculations (Labat et al., 2015).

6.2.3 Ventilation

Fluctuation in the hours of the building’s occupancy, the number of residents, their activity levels, and internal gains are other areas by which the embodied energy model's accuracy could be improved (The UK Fact File, 2013). This would ideally create a dataset which would reflect the natural fluctuation of an occupant’s behaviour. Based on the data collected, the rate of air change can be investigated to identify the opportunities of natural, mechanical or combined ventilations. This work could be utilised in the UK’s existing dwellings to prevent the problem of overheating and discuss whether controlling household size and occupancy time could reduce the energy demands of the housing sector (The UK Fact File,2013).

References

AL-HASSAN, A. 2009. The introduction of code of sustainable homes for the UK; potentials and problems. *Forum Ejournal*, 9**,** 49-62.

ALCORN, A. & WOOD, P. 1998. New Zealand building materials embodied energy coefficients database volume II–coefficients. *Centre for building performance research, Victoria University of Wellington*.

BARKER, S., MISHRA, A., IRWIN, D., CECCHET, E., SHENOY, P. & ALBRECHT, J. 2012. Smart*: An open data set and tools for enabling research in sustainable homes. *SustKDD, August*.

BLACK, C., VAN OOTEGHEM, K. & BOAKE, T. M. 2010. Carbon neutral steel building systems research project: a case study investigating the relationship of operating energy and embodied energy in achieving a holistic carbon neutral retail building.

BOARDMAN, B., DARBY, S., KILLIP, G., HINNELLS, M., JARDINE, C., PALMER, J. & SINDEN, G. 2005. 40% house. Environmental change institute. *University of Oxford* [Online].

BRE 2009. BRE Trust review 2010. Watford: IHS BRE press

BRE 2005. Energy summary report *Energy use in homes.* Crown

BURTON, S. 2001. *Energy Efficiencient Refurbishment* Energy and Environment Ltd.

CAR, J. P., COOPER, I., ARMITAGE, P., HUGHES, M. & CAR, D. G.-S. 2013. United Kingdom housing energy fact file 2013.

CHM 2010 The Cambridge Housing Model CHM. 2 ed. Great Britain: Cambridge Architectural Research Limited.

CHM USER GUIDE 2010 The Cambridge Housing Model CHM. 2 ed. Great Britain: Cambridge Architectural Research Limited.

CLIMATE CHANGE ACT 2008. UK climate change Act 2008: Chapter 27–Climate Targets and Budgeting, the Committee on Climate Change, Trading Schemes, Impact of and Adaptation to Climate Change, etc. *London: Palace of Westminster*.

COMMUNITIES, D. F. & GOVERNMENT, L. 2008. *Improving the Energy Efficiency of Our Buildings-A Guide to Energy Performance Certificates for the Construction, Sale and Let of Non-Dwellings*, Communities and Local Government London.

CONSTRUCTION PRODUCTS ASSOCIATION 2010. *An introduction to low carbon domestic refurbishment*, Construction Products Association.

COUNCIL, U. G. B. 2015. *Campaigning for a sustainable built environment* [Online]. UK Green Building CouncilAvailable: http://www.ukgbc.org/resources/key-topics/new-build-and-retrofit/retrofit-domestic-buildings 2015].

CRAWFORD, R. H., CZERNIAKOWSKI, I. & FULLER, R. J. Optimising the life cycle energy performance of residential buildings. ANZAScA 2011: From principles to practice in architectural science: Proceedings of the 45th Annual conference of the Australian and New Zealand Architectural Science Association, 2011. ANZAScA, 1-8.

CROWTHER, P. 1999. Design for disassembly to recover embodied energy.

DECC 2012. The Energy Efficiency Strategy. *The Energy Efficiency Opportunity in the UK.* London.

DENSLEY TINGLEY, D. & DAVISON, B. 2012. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment,* 57**,** 387-395.

DIXIT, M. K., FERNÁNDEZ-SOLÍS, J. L., LAVY, S. & CULP, C. H. 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings,* 42**,** 1238-1247.

ECUK. 2015. *Energy Consumption in the UK (2015)* [Online]. UK. Available: https://www.gov.uk/.../ECUK_Chapter_3_-_Domestic_factsheet.pdf.

FRENCH, L., CAMILLERI, M., ISAACS, N. & POLLARD, A. 2007. Temperatures and heating energy in New Zealand houses from a nationally representative study—HEEP. *Energy and Buildings,* 39**,** 770-782.

GATERELL, M. & MCEVOY, M. 2005. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. *Energy and buildings,* 37**,** 982-995.

HE, M., LEE, T., TAYLOR, S., FIRTH, S. K. & LOMAS, K. 2014. Dynamic modelling of a large scale retrofit programme for the housing stock in the North East of England. *The 2nd International Conference on Urban Sustainability And Resilience, UCL, London.*

HERNANDEZ, P. & KENNY, P. 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings,* 42**,** 815-821.

HORDESKI, M. 2004. Dictionary of energy efficiency technologies. *In:* LILBURN, G. (ed.). Fairmont Press, EBSCO host.

HUMAR, I., GE, X., XIANG, L., JO, M., CHEN, M. & ZHANG, J. 2011. Rethinking energy efficiency models of cellular networks with embodied energy. *Network, IEEE,* 25**,** 40-49.

ISAAC, M. & VAN VUUREN, D. P. 2009. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy,* 37**,** 507-521.

KAY, J. D. 1993. A designer's manual for the energy efficient refurbishment of housing. BSI 8211 Part 1

Part1. UK British Standrads Institution

LABAT, A., KITOUS, A., PERRY, M., SAVEYN, B., VANDYCK, T. & VRONTISI, Z. 2015. GECO2015 Global energy and climate outlook: Road to Paris. assessment of low emission levels under world action integrating national contributions. Institute for Prospective and Technological Studies, Joint Research Centre.

MA, Z., COOPER, P., DALY, D. & LEDO, L. 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and buildings,* 55**,** 889-902.

MALLICK, F. H. 1996. Thermal comfort and building design in the tropical climates. *Energy and buildings,* 23**,** 161-167.

MARTJANOVA, I. 2015. Refurbishment strategies for multi-flat residential buildings Building Technology.

MCLEOD, R. S., HOPFE, C. J. & KWAN, A. 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment,* 70**,** 189-209.

MONAHAN, J. & POWELL, J. 2011a. A comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK. *Energy Policy,* 39**,** 290-298.

MONAHAN, J. & POWELL, J. 2011b. 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**,** 179-188.

NASH, G. D. 1955. *The thermal insulation of buildings: design data and how to use them*, HM Stationery Office.

OSMANI, M. & O'REILLY, A. 2009. Feasibility of zero carbon homes in England by 2016: A house builder's perspective. *Building and Environment,* 44**,** 1917-1924.

PALMER, J., COOPER, I., CHENG, V., CAR, A. T., SUMMERTON, P., CE, R. M., SHORROCK, L., BRE, J. U. & ECONOMETRICS, C. 2011. Great Britain’s housing energy fact file 2011. *DECC, London.*

PAN, W. & GARMSTON, H. 2012. Building regulations in energy efficiency: Compliance in England and Wales. *Energy Policy,* 45**,** 594-605.

PEREZ-LOMBARD, L., ORTIZ, J. & POUT, C. 2008. A review on buildings energy consumption information. *Energy and buildings,* 40**,** 394-398.

POWER, A. 2008. Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? *Energy Policy,* 36**,** 4487-4501.

PULLEN, T. 2011a. *The Sustainable bible: An Insiders' guide to eco-renovation & newbuilding*, Ovolo.

PULLEN, T. 2011b. *The Sustainable Building Bible*, The UK Simply Sustainable Homes

REDDY, B. V. & JAGADISH, K. 2003. Embodied energy of common and alternative building materials and technologies. *Energy and buildings,* 35**,** 129-137.

ROBERTS, S. 2008. Altering existing buildings in the UK. *Energy Policy,* 36**,** 4482-4486.

RODRIGUES, L. T., GILLOTT, M. & TETLOW, D. 2013. Summer overheating potential in a low-energy steel frame house in future climate scenarios. *Sustainable Cities and Society,* 7**,** 1-15.

SARTORI, I. & HESTNES, A. G. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and buildings,* 39**,** 249-257.

SUSTAINABLE HOMES 1999. *Embodied energy in residential property development: a guide for Registered Social Landlords,* Harlequin House.

TRELOAR, G. J. 2009. *Embodied and lifetime energies in the built environment* [Online]. tececo. Available: http://www.tececo.com/files/sustainability%20documents/ 2015].

UK GREEN BUILDING COUNCIL. 2015. *Campaigning for a sustainable built environment* [Online]. UK Green Building Council, Available: http://www.ukgbc.org/resources/key-topics/new-build-and-retrofit/retrofit-domestic-buildings 2015].

WATERFIELD, P. 2006. *The Energy efficient home (A complete Guide),* Marlborough, The Crowood Press Ltd.

WATSON, P. 2010. An introduction to UK energyperformance certificates (EPCs). *Journal of Building Appraisal,* 5**,** 241-250.

WILLIAMS, K., JENKS, M. & BURTON, E. 2000. Housing form, energy use and green house gas emissions. *Achieving sustainable urban form E& FN Spon, pp.75-83*

Taylor & Francis.

XING, Y., HEWITT, N. & GRIFFITHS, P. 2011. Zero carbon buildings refurbishment—A Hierarchical pathway. *Renewable and Sustainable Energy Reviews,* 15**,** 3229-3236.

YOHANIS, Y. & NORTON, B. 2002. Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy,* 27**,** 77-92.

ZACHARIADIS, T. 2007. Exploring the relationship between energy use and economic growth with bivariate models: New evidence from G-7 countries. *Energy economics,* 29**,** 1233-1253.

Appendices

6.3 Appendix A:

CD-R is enclosed with this thesis to demonstrate the steps of developing the model and testing the decarbonisation scenarios.

6.4 Appendix B:

This section includes further analysis of the embodied, operational and payback energy of the refurbished building elements.

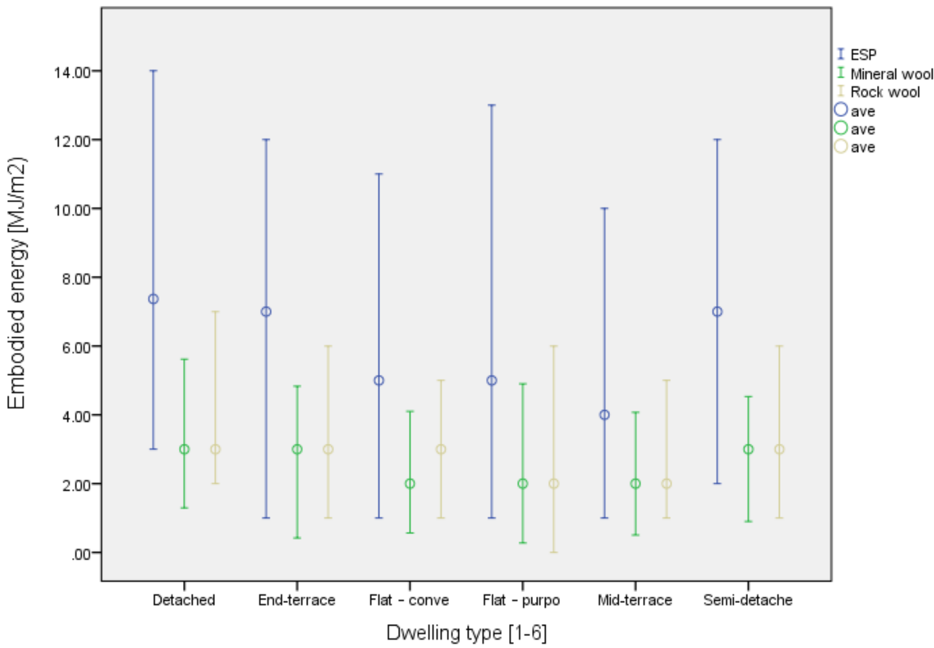


Figure 0.1: Embodied energy of cavity wall insulants per dwelling type.

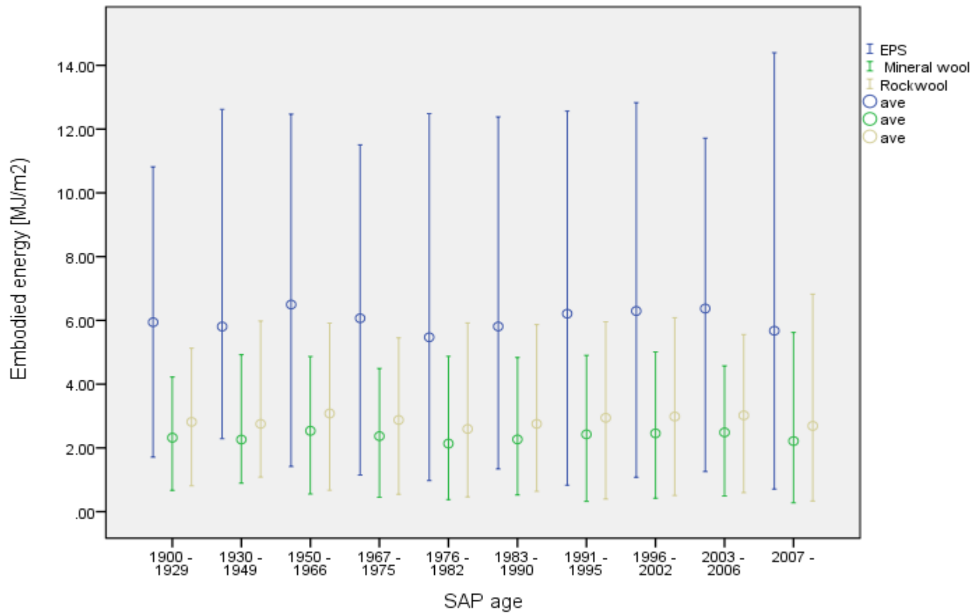


Figure 0.2: Embodied energy of cavity wall insulants per dwelling age.

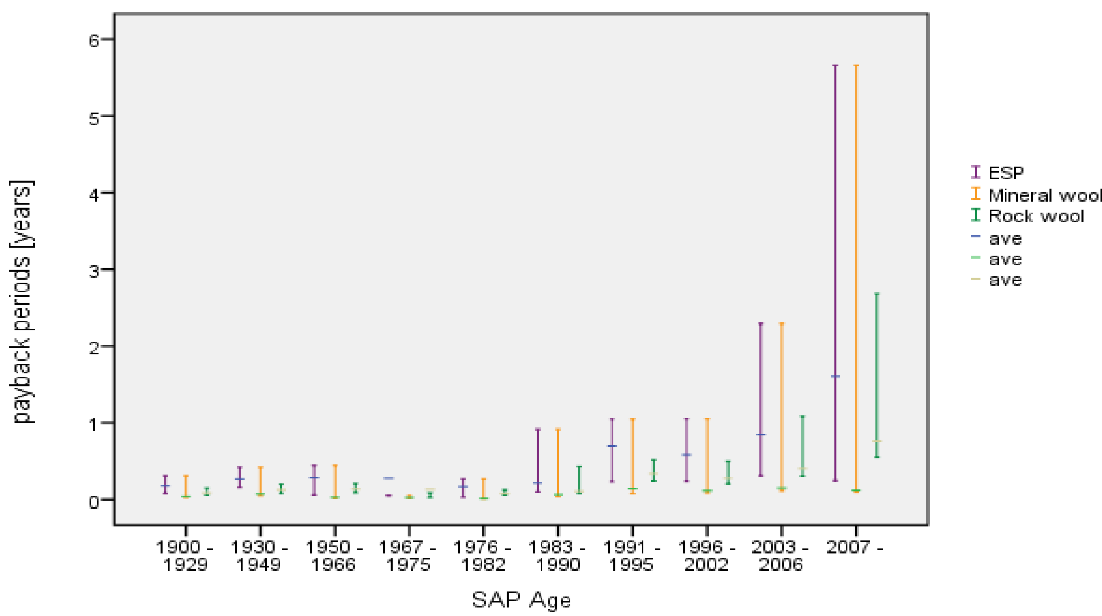


Figure 0.3: Payback periods of cavity walls insulants per dwelling Age.

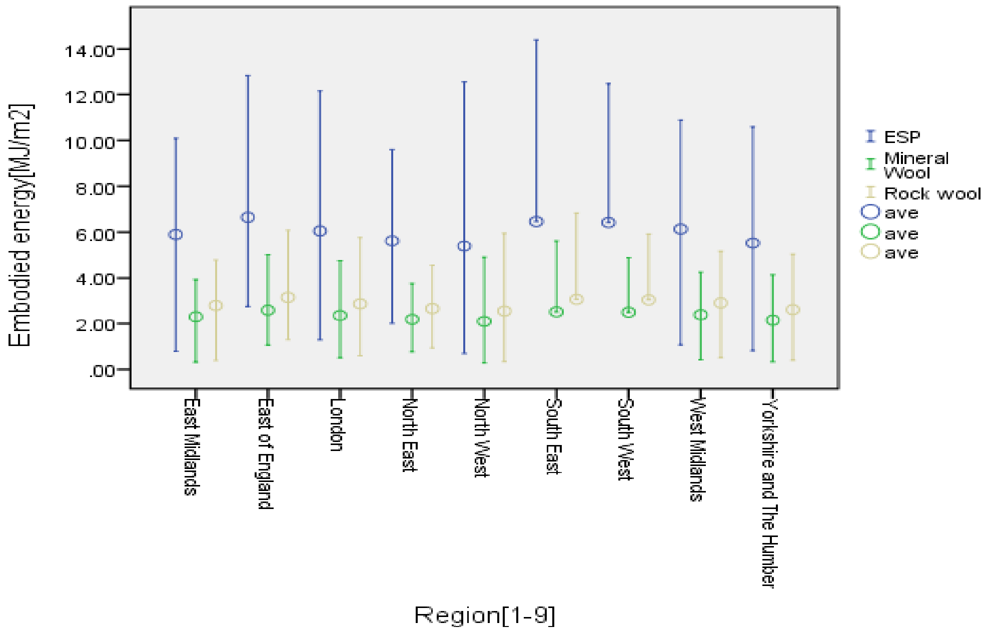


Figure 0.4: Embodied energy of cavity wall insulants per region.

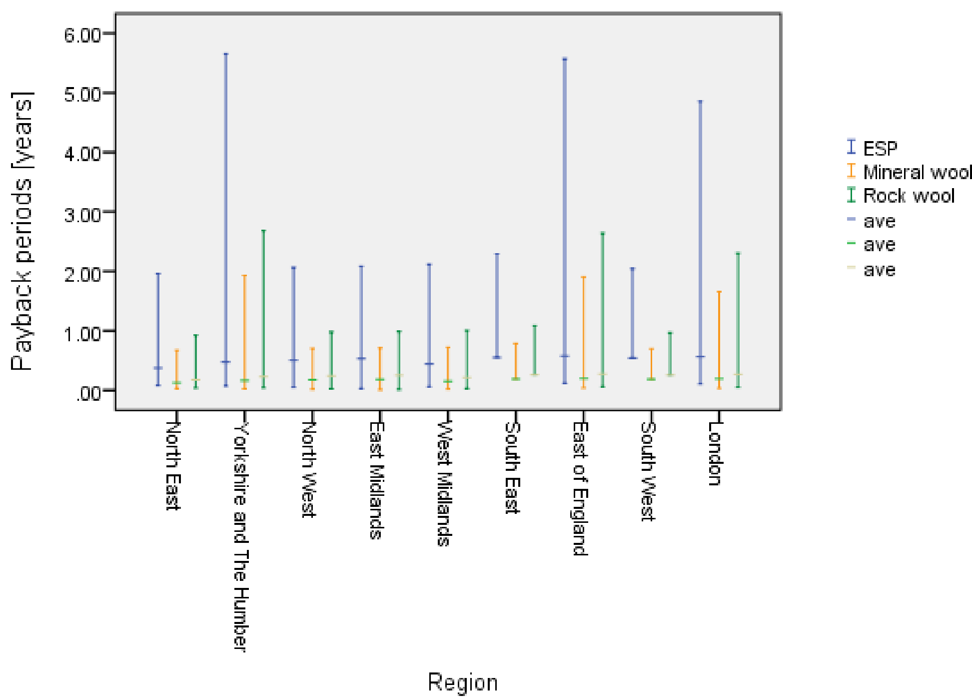


Figure 0.5: Payback periods of cavity wall insulants per region.

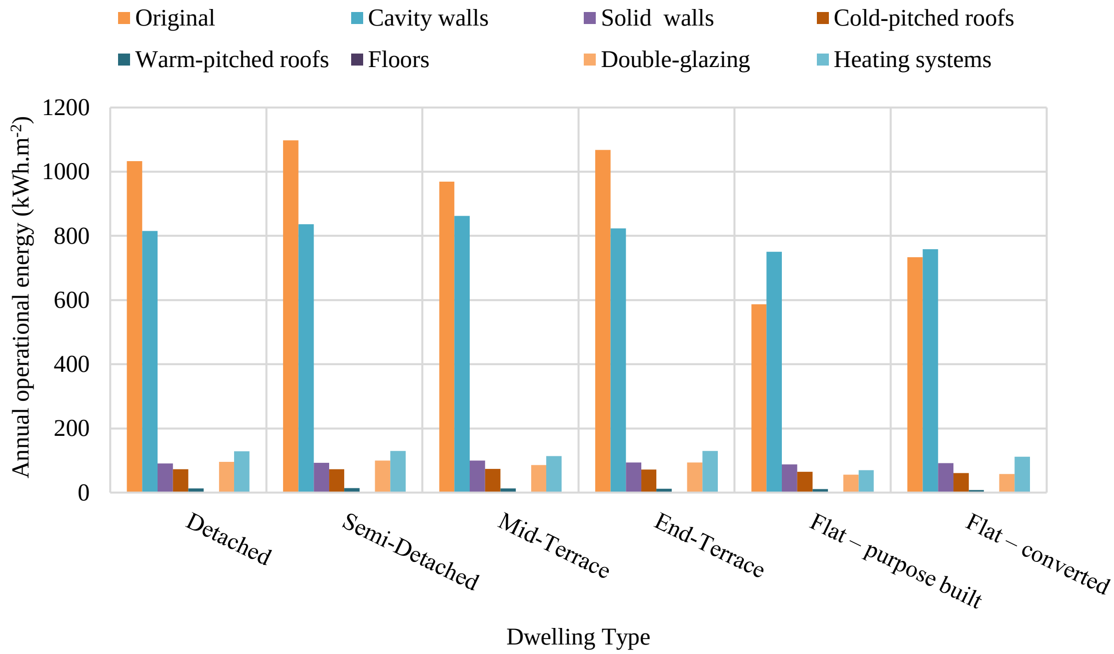


Figure 0.6: The operational energy of different renovation techniques.