# The Role of Aesthetics in Energy-Retrofit Strategies: The Case of Solid Wall Houses in the UK

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# Acknowledgments

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# Abbreviations

| | |
|---|---|
| NDC | Nationally Determined Contributions |
| CCA | Climate Change Act |
| SWI | Solid Wall Insulation |
| GHG | Greenhouse gas |
| GD | Green Deal |
| ECO | Energy Company Obligations |
| AP | Air Permeability |
| $MtCO_2e$ | Million tonnes of carbon dioxide equivalent |
| $CO_2$ | Carbon dioxide |
| Mt | Million tonnes |
| UNFCCC | United Nations Framework Convention on Climate Change |
| DECC | Department for Energy and Climate Change |
| SWI | Solid Wall Insulation |
| BRE | Building Research Establishment |
| CERO | Carbon Emissions Reduction Obligation |
| CSCO | Carbon Savings Community Obligation |
| HHCRO | Home Heating Cost Reduction Obligation |
| STBA | Sustainable Traditional Buildings Alliance |
| SECHURBA | Sustainable Energy Communities in Historic Urban Areas |
| CIBSE | Chartered Institute of Building Services Engineers |
| SAP | Standard Assessment Procedure |
| NEED | National Energy Efficiency Database |
| NHER | National Home Energy Rating |
| CESP | Community Energy Saving Programme |
| RdSAP | Reduced Data Standard Assessment |
| MVHR | Mechanical Ventilation with Heat Recovery |
| HTC | Heat Transfer Coefficient |
| BIM | Building Information Modelling |
| ICT | Information Communication Technology |
| LCA | Life Cycle Assessment |
| MCDA | Multi-Criteria Decision Analysis |
| SEH | Salford Energy House |
| ISWI | Internal Solid Wall Insulation |
| ESWI | External Solid Wall Insulation |
| IWI | Internal Wall Insulation |
| EWI | External Wall Insulation |
| IAWI | Internal Aesthetic Wall Insulation |
| RMSE | Root Mean Square Error |
| PCHI | Per Capita Household Income |

# Abstract

Solid wall dwellings are responsible for 36% of the carbon emission from the domestic sector in the UK. Among energy retrofit measures, Solid Wall Insulation (SWI) is the most effective in reducing energy demand. However, the current rate for insulation of solid walls is lower than desired in the UK, and only 9% of solid wall houses are insulated. To meet the 2050 net-zero emissions target, a higher rate of insulation is required to improve the energy efficiency of old stock. Innovative and encouraging retrofit plans are urgently required to unlock the demand for SWI, which will improve the energy performance of old dwellings. This study aims to contribute toward an innovative solution for the uptake of Internal Solid Wall Insulation (ISWI) demand in the energy technology industry.

Two interconnected gaps in the literature were identified. One gap is the lack of clear information on the performance benefits of SWI as a single retrofit measure in solid wall homes, which is a cause of uncertainty for householders. This uncertainty about potential energy savings arising from the U-values of walls in solid wall properties has led to under- or over-estimation of SWI performance. The second gap is the need for innovative solutions to unlock the demand for slow progressed SWI in the UK. In home improvement, the aesthetic factor is seen as a trigger for renovation to start. Aesthetic renovation is more of an issue for internal spaces and is happening routinely as a voluntary approach by residents. Hence, the idea of integrating the aesthetic factor in ISWI is recommended in this study for the first time, and its importance in renovation for householders and in the uptake of ISWI is evaluated. To address the knowledge gap about ISWI energy-saving benefits, an energy assessment phase is designed in this research to contribute to providing clear information about the benefits of ISWI itself for a variety of identified U-values for solid brick walls using the developed validated model of the Salford Energy House testing facility with a negligible model performance error. For the second gap, aesthetic inclusion in ISWI and its impact on householders’ views towards the uptake of ISWI is evaluated using an online survey. The results from both phases of this research are then used to provide recommendations for policy makers, the retrofit industry, and designers, in support of the acceleration of ISWI in the uninsulated UK stock.

The focus of the energy assessment phase (Phase 1) was on U-value variation as the key parameter for energy-saving evaluations. The energy performance of pre-and post-IWI in the Salford Energy House (SEH) is investigated; this is a replica of a pre-1919 Victorian solid wall terraced house. The modelling software IES-VE was used to develop a model for the SEH, and this model was validated against collected experimental data. The baseline solid wall U-value for SEH changed between 0.64-2.48 W/m$^2$K to model different solid walls before insulation and the benefits of insulation assessed. The result of this phase contributes towards a better understanding of the energy saving potential of IWI within the UK and provides a more realistic picture of its benefits for policymakers and relevant stakeholders. Based on the results, the annual heating energy saving varies significantly depending on the baseline wall U-values, ranging from 19% to 46.2%. The difference of cost saving potentials between the cases with the lowest and highest baseline wall U-values is also high, with variance per year being £228. Thermal comfort (18°C<T<=23°C) was also evaluated for the selected case study with different baseline wall U-values. It was found that the thermal comfort improved with wall insulation while at the same time overheating is not significant for the case study using Manchester weather data.

In the aesthetic evaluation phase, the second phase of this research, people's preferences for aesthetics in renovation and its potential in promoting SWI was explored using an online survey. The data from the collected validated 273 responses was analysed using SPSS software. The results show that aesthetics is a very important factor for most of the participants, since the aesthetic is found to be rated more than 90% important to participants, which is in line with cost and energy saving factors in internal renovations. This result also confirms that including the aesthetics of wall insulation can challenge the negative view of participants on losing internal space, where the disagreement level is only 10%. Additionally, the preferences of participants towards aesthetics can surpass the concerns of cost since 88.6% of participants are willing to pay more to achieve an aesthetically appealing insulation product.

Furthermore, the views of participants were explored with respect to insulating the walls with internal aesthetic panels, which offer aesthetic and energy saving in a single package, and more than 50% of participants stated their willingness. From the results, more than 2/3rd of participants also agreed with delivering both aesthetic and energy improvement in combined retrofit plans by established organisations. The significance of the aesthetic factor in renovation and its inclusion in planning the SWI strategies, especially for IWI, are proven by the results of this study.

In conclusion, it is necessary to boost the SWI intake with the highest potential energy saving compared to other retrofit measures in treating the uninsulated properties. It is recommended that policy makers include the aesthetic in planning the SWI strategies to trigger its uptake. It is beneficial when interior designers and product designers contribute to the engagement of householders to raise awareness of the benefits from Internal Aesthetic Wall Insulation (IAWI). This will unlock the demand for IWI by increasing the number of potential customers and lowering the financial concerns of households. It is also recommended that financial support be extended to cover the redecorating cost after installation of IWI. Home improvement and energy retrofit companies should come together to work closely in an integrated approach to encourage IAWI for retrofitting old houses. IAWI does not only provide energy saving but also the aesthetic improvement of internal spaces can be achieved. Furthermore, establishment of organisations to centralise the retrofit measures of old housing stock is recommended to offer both energy saving and aesthetic incentives to householders at the same time. This is to ensure that householders are supported during the entire retrofit process in the design, supervision, after care process, professional-quality delivery of the project, subsidies application, cost and time frame of the retrofit project while receiving the aesthetic and energy saving benefits at the same time.

# Chapter 1: Introduction

This chapter outlines the motivation and significance (Section 1.1), aim, objectives and research questions (Section 1.2), contribution to the field (Section 1.3) and an outline of the following chapters of this report (Section 1.4).

## 1.1 Motivation and Significance

The Paris agreement (2015) is a global climate change agreement among 195 countries to prepare, communicate and maintain successive Nationally Determined Contributions (NDCs). EU member states including the UK submitted their NDC for 2021-2030 which established at least a 40% reduction target of their domestic greenhouse gas emissions by 2030 compared to 1990 levels. To achieve the global warming target of 1.5°C, the Climate Change Act (CCA) 2008 was amended in June 2019 and the UK is now committed to achieve net zero carbon emissions by 2050 (Waite, 2020a). Greater Manchester set a stringent target to achieve net zero carbon emissions by 2038, 12 years earlier than the UK target date (McLachlan, 2018).

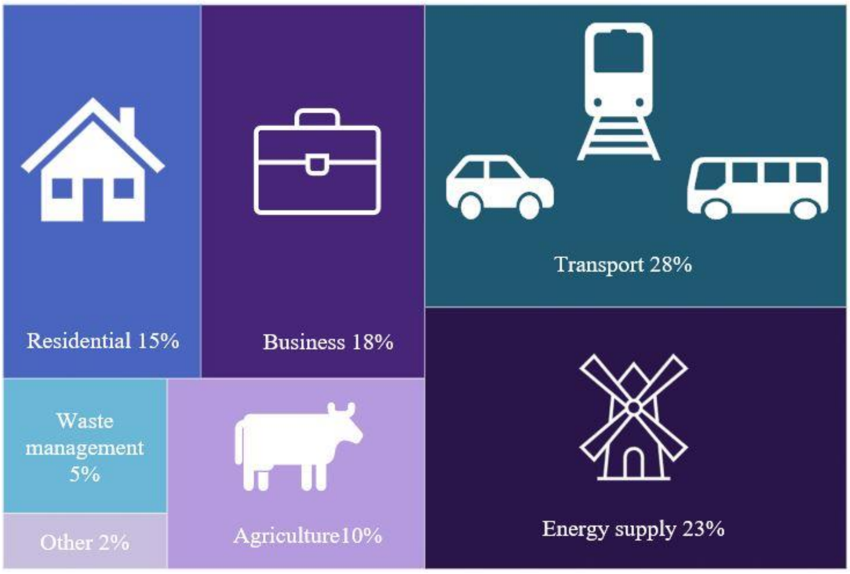


Figure 1.1. Emitting sectors of UK greenhouse gas emissions in 2018, 'Other' includes Public, Industrial Processes and the Land Use, Land Use Change and Forestry (LULUCF) sectors (note that LULUCF acts as a net sink of emissions). The percentages may not sum to 100% due to rounding (Waite, 2020b).

Figure 1.1 shows the rounded percentage estimation of greenhouse emission in the UK by sectors (Waite, 2020b). As shown, the residential sector is responsible for a substantial amount of greenhouse gas emissions compared to other sectors. It is estimated to be responsible for over 15% of the total UK greenhouse gas emissions, representing 69.1 $MtCO_2e$ from the total of 451.5 $MtCO_2e$ for all the sectors (Waite, 2020a). The main source of emissions from this sector is from natural gas used for heating and cooking. Furthermore, the residential sector has the highest proportion of emissions from gas as a source of greenhouse gas emissions at 96%. External temperature heavily impacts on the use of heating and emissions of carbon dioxide from this sector. Colder temperature raises the demand for higher use of heating and greater emissions released (Waite, 2020a).

In Britain, some households living in fuel poverty cannot afford their heating bills because their homes have little or poor insulation (BBC, 2019). Eight million of the total existing homes in the UK (~30%) are solid wall houses (Hansford, 2015). In the UK, 36% of carbon emissions from the domestic sector come from solid wall dwellings (Loucari et al., 2016). Solid Wall Insulation (SWI) technology is a key pathway towards meeting the greenhouse gas (GHG) emissions reduction target of the UK by 2050 (Elderkin, 2011). However, the number of SWI installations is not widely spread considering the vast number of solid wall dwellings in the UK and the potential of energy saving and $CO_2$ reduction from wall insulation (CCC (Committee on Climate Change), 2015; Elderkin, 2011). According to National Statistics 2017, around 92% of solid wall homes remain uninsulated (BEIS, 2017a, 2017c). At the end of 2019, only 9% of houses with solid walls had SWI, which is around 764,000 houses, which leaves 7.7 million houses remaining (Oxley, 2020a). This figure remained almost the same with 772,000 and 794,000 SWI deliveries at the end of 2020 and 2021 respectively, and still 91% of solid wall homes remained uninsulated (Oxley, 2021, 2022). These figures show that in four years' time the application of SWI only increased around 1%, despite the current policies which support the SWI application and subsidies and grants available for the related costs through the Government's Energy Company Obligations (ECO) scheme.

There are a variety of barriers which slow the growth of the energy efficient market for SWI. These barriers are related to the demand side, supply/investment side, absence of a strong incentive to act, and a poor value proposition for investors and consumers (BEIS, 2017a). Except for financial support, the role and desires of users in promoting the energy efficiency measures have been ignored in existing policies in the UK. Householders are not certain about achieving the expected savings and benefits due to the negative reputation of SWI arising from poor and unprofessional installation cases (Abreu et al., 2017; BRE (Building Research Establishment), 2014). Also, the contradictory information and lack of clear data about the potential saving benefits of SWI in solid wall homes in the literature, which is mainly is due to under or over-estimation of the U-value of solid walls, is another reason for reducing the householder's interest to install SWI in their premises (BRE (Building Research Establishment), 2016b; Li et al., 2015; Loucari et al., 2016). Furthermore, in the case of External Solid Wall Insulation (ESWI) legislation and concerns related to historic buildings are adding to the aforementioned barriers (Moran, 2014). SWI lacks innovation measures in the construction industry to leverage the latent possibilities and unlock the demand for SWI (Hansford, 2015). These measures should be motivating and satisfactory enough for the users to promote the wall insulation installation in solid wall houses aiming to reduce barriers and increase success.

These days, many industries invest in aesthetics to improve their business (Chapman & Larkham, 1992; Wannarumon et al., 2008), whereas aesthetics is overlooked in energy efficient material production and marketing. Brand satisfaction and perceived product quality are influenced by positive aesthetic experiences (Beka, 2015; Simonson & Schmitt, 1997). Aesthetics features in such industries will promote their market and improve customer satisfaction. This perception has also had a wide application in the building industry under the interior design concept. Products that deliver excitement to customers are more successful than ones that do not (Beka, 2015; Millard, 2006). The aesthetic feature is not included in the current SWI strategies, one of the reasons could be because the energy retrofit industries are more engineering discipline based and are focusing on the energy performance of products rather than anything else (Aydin et al., 2019). Adding the aesthetic to the wall surface, especially internally after wall insulation, seems to be the responsibility and desire of householders to perform through the DIY or the home improvement industry or contractors at their own cost. Therefore, this hypothesis is that including aesthetic features into SWI would be a solution to increase the demand for SWI. Adding concepts of aesthetics in Internal Wall Insulation (IWI) as a motivation, and possibly as a time and cost-effective method, will be examined during this research. In parallel, this study develops clear information for the saving potential of SWI as a single retrofit measure for a variety of solid brick wall U-values. This will contribute to reducing the information barrier of SWI and provide insights for householders to refer and act upon to improve their premises, leading to an increase of the installation of SWI in the UK.

## 1.2 Aim, Objectives, and Research Questions

This study aims to develop a solution for the promotion of Internal Solid Wall Insulation (ISWI) in the UK through broadening the knowledge about the ISWI energy-saving benefits and integrating the aesthetic features in ISWI.

To achieve this aim, the following objectives are defined:

1. To assess the current energy performance of a solid brick wall case study house in the UK,
2. To analyse the potential energy saving benefits and $CO_2$ emission reduction of ISWI as a single retrofit measure for various solid brick walls,
3. To identify the importance of aesthetics in internal spaces and renovation for householders,
4. To examine the dependencies between the importance of aesthetic factor in internal renovation with various personal and socio-economic characteristics in the UK,
5. To examine the aesthetic role in reducing the negative concerns about ISWI, such as cost and area loss to promote ISWI,
6. To recommend viable approaches in the integration of energy and aesthetic improvement measures for increasing the uptake of ISWI in uninsulated UK housing stock.

This research is going to answer the following questions:

1. What is the current energy performance of a solid wall brick house in the UK?
2. What are the potential saving benefits and CO2 emissions reduction with ISWI in solid brick wall houses in the UK?
3. How much the internal temperature and thermal comfort change following ISWI?

4. How important is the aesthetic itself in internal renovation for the householders, compared to other well-known renovation criteria, such as cost, energy saving and time frame?
5. Does importance of aesthetic and other renovation criteria depend on personal and socio-economic characteristics such as age, gender, origin, Per Capita Household Income (PCHI), old houses and ownership?
6. How can the aesthetic aspects contribute to enhance the interest of homeowners in ISWI and reduce concerns about cost and area loss?
7. What is the correlation between the importance of any two variables, i.e., aesthetics, energy saving, cost, and time frame of renovation?
8. How the aesthetic can be integrated in energy retrofit and what recommendations can be provided for the uptake of ISWI?

## 1.3 Contribution to Knowledge

This thesis contributes to the field of building energy studies and the retrofitting of solid wall housing. As discussed, SWI has not achieved widespread adoption across the UK despite its great potential in $CO_2$ and energy consumption reduction (Oxley, 2020a). Reviewing the literature about this issue has led to identifying two interconnected gaps, as follow:

One gap is the lack of clear information about the energy saving and $CO_2$ emission reduction potential of retrofitted solid wall houses in the UK (Hansford, 2015) which causes uncertainty and reluctance about SWI for householders. A critical analysis of the literature around SWI reveals that in most of the previous studies the effect of SWI was given in combination with other retrofit measures in a retrofit package, which makes it hard to understand the sole potential saving of SWI as a single retrofit measure. Furthermore, the reported results about the effects of SWI on its own were mainly for a single U-value, and in some cases reasons such as the occupant behaviour and weather variations interfered in acquiring the actual potential saving result of SWI. Also, there is a discrepancy and uncertainty about the selected U-values of walls in estimating the potential benefits in related studies which led to under- or over-estimation of SWI performance. As such, the current literature cannot clearly specify the potential of energy savings and $CO_2$ emissions reduction from using SWI. There is a need to develop more specific and clear information for SWI with minimum error and interference to provide a better picture of SWI energy benefits for a variety of solid brick walls in the UK solid wall homes for the Government, relevant retrofit industries and building users.

Beside this gap in knowledge about the energy performance of SWI, there is a need for an innovative approach to unlock the demand and increase the attractiveness of SWI (Hansford, 2015), however, a practical solution hasn't been recommended. Homeowners are not interested in energy renovation of their homes even if it is economically feasible and relevant technical means are available (Gram-Hanssen, 2014). On the other hand, renovations to increase the indoor aesthetic and functions were purported to be more attractive than renovations which might save energy (Gram-Hanssen, 2014). To solve this issue, aesthetic features are considered in this thesis for the first time as a trigger for energy renovation measures, particularly for SWI. Aesthetic features were used in different industries to promote their market and increase customer satisfaction. However, attractiveness and aesthetic aspects have been overlooked in the energy efficiency industry (Aydin et al., 2019; Hauge et al., 2011) and are entirely absent in SWI promotion. Therefore, this research will take an innovative approach to evaluate the role of aesthetic in improving the interest in ISWI retrofit among homeowners and for promoting its implementation in the UK.

The result of this research is going to contribute to an increase in the uptake of SWI in the UK by adding more clear information about the energy saving potentials of SWI into the existing literature as well as by evaluating the importance of the inclusion of aesthetics of SWI among the householders for the first time as a possible practical solution. Finally, the results from both energy and aesthetic analysis are integrated and used to provide recommendations for relevant stakeholders in support of the acceleration of ISWI in the UK stock.

## 1.4 Conceptual Framework and Outline of Thesis

Figure 1.2 presents the conceptual framework for this research. It follows a user-centred design approach in ISWI retrofit to contribute to fulfilling the two identified gaps from the literature. The research designed in two phases of energy assessment and aesthetic evaluation. In phase 1, the potential benefits of SWI for variety of U-values and AP identified from the literature are for solid wall houses will be assessed to provide clear information on saving benefits of ISWI as a single retrofit measure (discussed in Section 5.1). In phase 2, the aesthetic factors were studied in respect to other variables to investigate the importance of aesthetics in uptake of ISWI. These variables are householders' characteristics, criteria in internal renovation and negative concern of ISWI identified from the literature review (discussed in Section 5.2). Moreover, considering both non-energy and energy benefits, which was also suggested in the literature (Abreu et al., 2017; Risholt et al., 2013; Wilson et al., 2015), the findings from both phases of the research are inferred to provide recommendations and viable approaches for relevant stakeholders to increase the uptake of ISWI (discussed in Section 6.3).

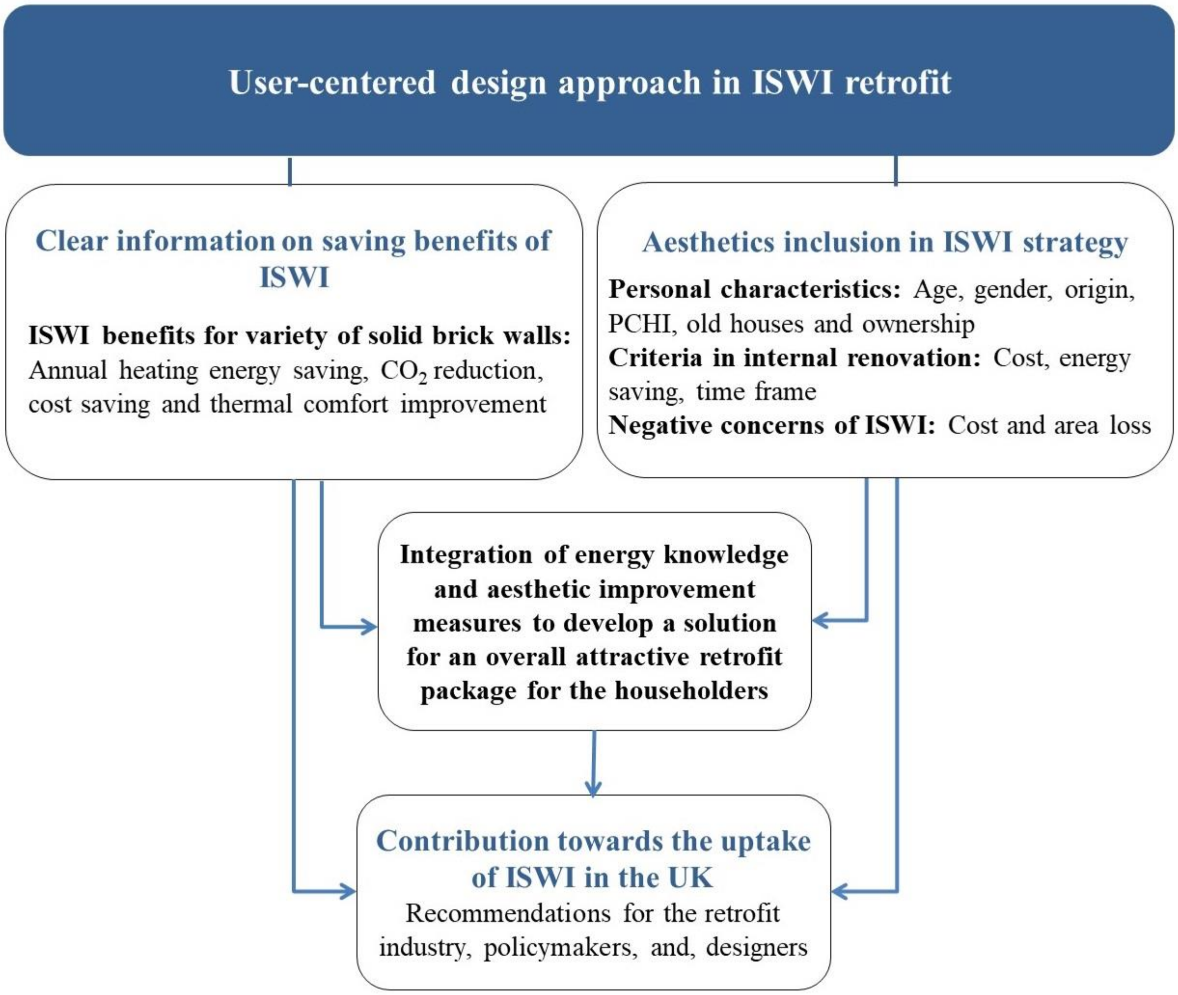


Figure 1.2. Conceptual framework of this research study.

This thesis consists of six chapters:

**Chapter 1-Introduction:** In this chapter, an overview of the current research subject is presented and research motivation and significance, aims and objectives and contribution to knowledge are discussed.

**Chapter 2-Current state of knowledge on energy retrofit in UK housing:** This chapter gives an extensive literature review and analysis of the current body of knowledge about the subject matters to identify the research background and the research gap. The main reviewed subjects are related to current energy use and emission level of domestic sector, solid wall dwellings and their potential energy saving by insulation as an effective retrofit measure.

**Chapter 3- Occupants' attitudes and aesthetics preferences for housing retrofit:** In this chapter occupant's attitudes for retrofitting and user-centred design approach are reviewed. Difficulties in energy efficient retrofit especially for the case of SWI reviewed from the literature. Aesthetic factor as one of the driving factors in renovation were reviewed to identify its potential contribution towards energy efficiency. Following the literature review, the demands of energy efficiency market are discussed.

**Chapter 4- Methodology:** This chapter explains the methodological approach to achieve the aim and objectives of this research. It introduces the research design, concept map, research tools and cumulative approach to presents the detailed methodology applied in this research. Experimental and numerical methods are used in the first phase to quantify the potential savings of IWI more realistically as a single retrofit measure in solid wall houses for different solid wall U-values and Air Permeabilities (AP). The survey approach is employed in the second phase to find out the role of aesthetics in the renovation and uptake of ISWI among householders in the UK. Besides, the summery of the methodology is presented in a concept map to show the different steps in development of this project.

**Chapter 5-Results and discussion:** In this chapter, the simulation, and experimental results from energy assessment phase as well as the results of the questionnaire analysis from the aesthetic evaluation phase, are presented and discussed. Also, the estimation of energy saving of housing stock using IAWI will be discussed.

**Chapter 6-Summary, conclusion, and recommendations:** In this chapter, the study is concluded by summarising the energy assessment and aesthetic evaluation main findings. It then follows by the recommendations for industry, designers, and policy makers. Furthermore, the research limitations and possible areas for future works are presented at the end of this chapter.

# Chapter 2: Current state of knowledge on energy retrofit in UK housing

This chapter reviews and analyses the current literature in relation to energy retrofit of UK dwellings in order to provide a detailed analysis of current research in the SWI field and identify the research gaps. A comprehensive review of research articles, dissertations, books, government reports and other online resources was conducted on the following topics. An overview of the UK energy map and environmental policies is presented in Section 2.1 and the domestic sector and energy consumption in the UK are reviewed in Section 2.2. Energy efficiency retrofit in UK houses and solid wall houses and their retrofit in the UK are discussed in Sections 2.3 and 2.4 respectively. SWI and its energy saving potential are addressed in Section 2.5, which is followed by the presentation of the numerical studies of SWI in Section 2.6. Cost analysis of SWI is conducted in Section 2.7 and finally, Section 2.8 provides a summary of the discussed literature and highlights the research gap leading to development of the adopted conceptual framework for this study and how it relates to the energy assessment phase of this research.

## 2.1 Overview of the UK Energy Map and Environmental Policies

Energy consumption in the UK has changed considerably since 1990. Figure 2.1 shows the breakdown of energy consumption by fuel type between 1990 and 2018. As shown in the figure, there was a great change in coal consumption, nearly 87.3% reduction, over the years. The contribution from bioenergy and waste developed as a new source of energy around 1990 and rose by around 78.3% by 2018 (Waters, 2019). There were also small changes in oil and primary electricity (consisting of nuclear, wind, solar and natural flow hydro) consumption, 11.27% decrease and 25.42% increase respectively. The use of natural gas increased from 51.2 Mtoe to 75.0 Mtoe around 46.511%, natural gas is becoming the major source of energy in the UK (BEIS, 2019c).

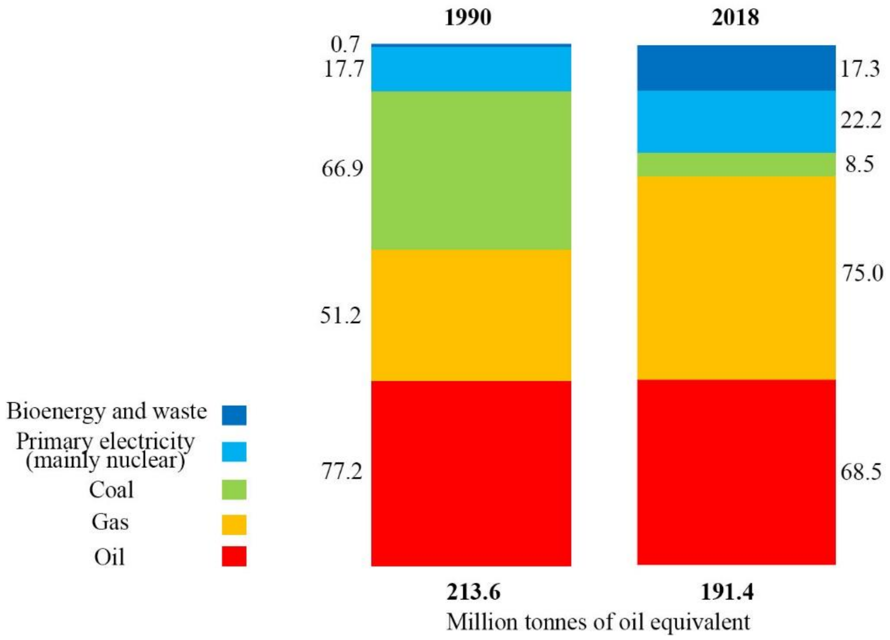


Figure 2.1. Overall energy-Inland energy consumption, 1990 and 2018 (BEIS, 2019c).

Figure 2.2 shows the energy consumption trend by sector from 1970. As can be seen, the most notable changes are in industry and transport with a dramatic fall and rise respectively. Services has the lowest percentage of energy use compared to the other sectors, and its trend remained almost stable with a slight increase over the years. As can be seen, the domestic sector is the second major energy consumer and the trend was upward in general since 1970, however, the energy consumption of this sector started to reduce over the last decade due to more efficient appliances, better home insulation and a warmer climate.

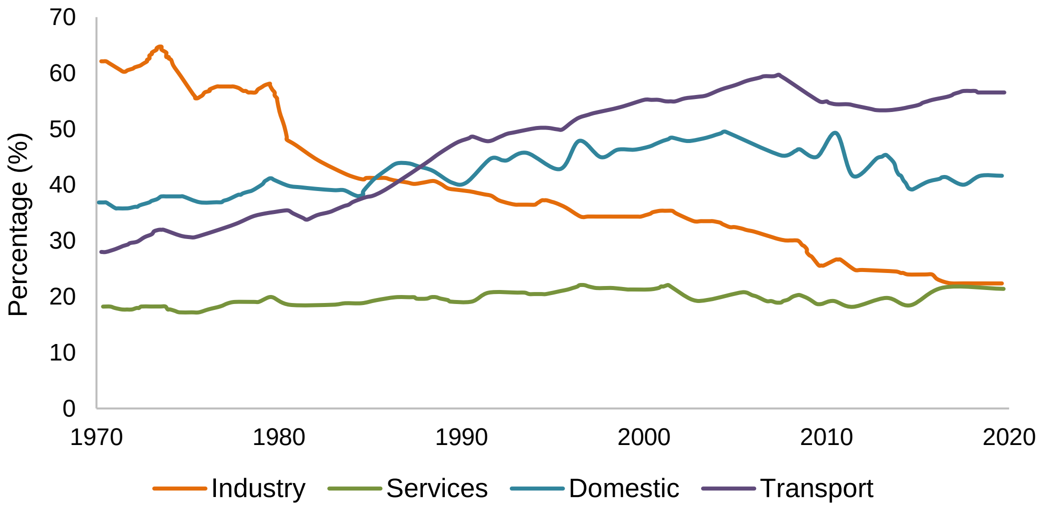


Figure 2.2. Change in energy consumption by sector 1970 to 2019 (Waters, 2020).

The total greenhouse gas (GHG) emissions in the UK were estimated to be 460.2 million tonnes of carbon dioxide equivalent ($MtCO_2e$) in 2017, this is 42.1% lower than the 1990 level. Changes in the electricity mix source led to a considerable decrease in energy supply by 59.5% since 1990 (BEIS, 2019c). According to Figure 2.3., between 1990 and 2017, the trends of GHG emissions for the transport and residential sectors were almost stable compared to other sectors with 1.7% and 16.47% decrease, respectively. The highest source of GHG in 2017 is from the transport sector, accounting for 27.4% of total emissions. Residential sector emissions accounted for about 14.5% of total emissions in 2017 (BEIS, 2019c).

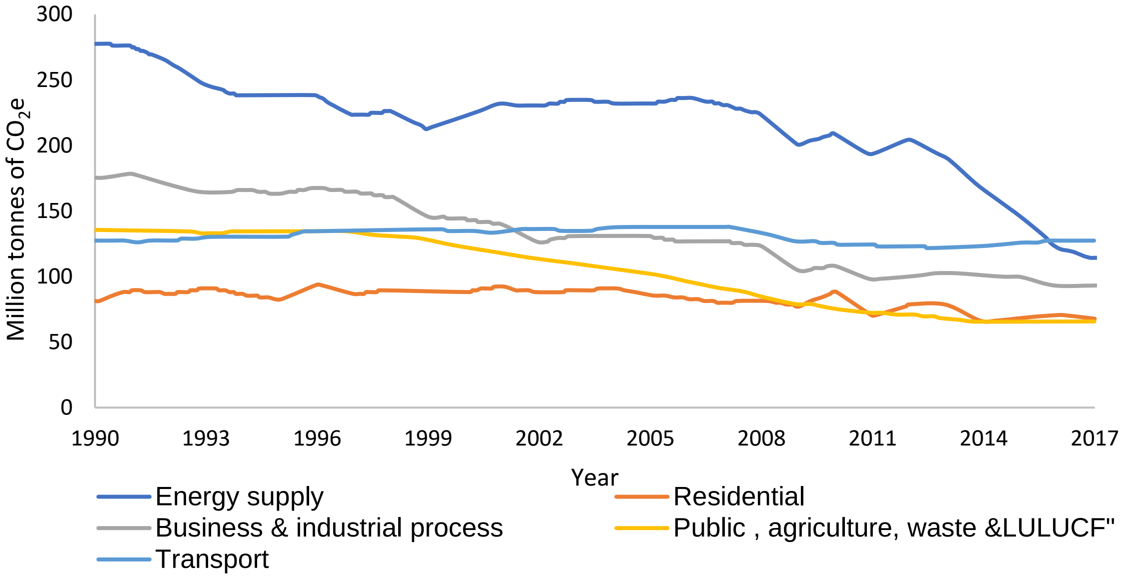
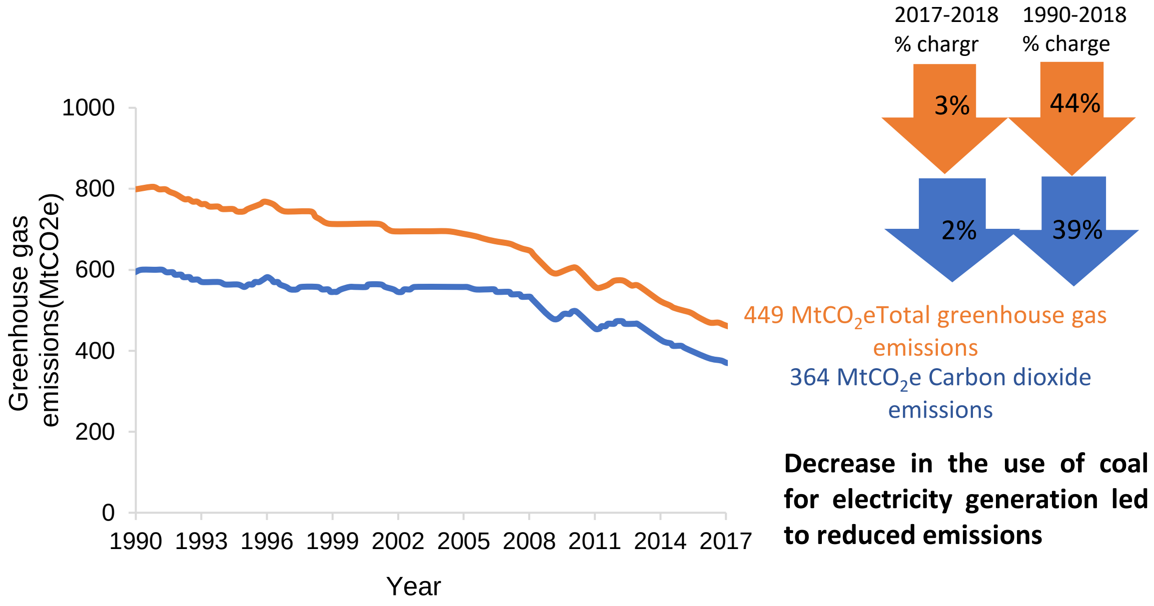


Figure 2.3. Greenhouse gas emissions by sector, 1990 to 2017 (BEIS, 2019c).

Based on provisional emissions estimation for 2018 (Figure 2.4), the level of GHG emissions is expected to reach to 449 $MtCO_2e$, 43.5% lower than 1990 level which is around a 2.5% decrease compared to its level in 2017. The UK net carbon dioxide ($CO_2$) emissions in 2018 are estimated to be 364.1 million tonnes (Mt) compared to the 2017 figure of 373.2 Mt, suggest a 2.4% reduction. Carbon dioxide ($CO_2$) accounts for 81% of the total GHG emissions and is the main source of the greenhouse gas. In the UK, total $CO_2$ emissions reduced by 9.9% from 2017 to 2018. However, this decrease should not be misunderstood as it is related to fuel shifts in power stations from coal towards renewables rather than the specific measures for reducing emissions in households, businesses, or other sectors (Penistone, 2019).



449 $\text{MtCO}_2\text{e}$Total greenhouse gas emissions

364 $\text{MtCO}_2\text{e}$ Carbon dioxide emissions

**Decrease in the use of coal for electricity generation led to reduced emissions**

Figure 2.4. Provisional estimation of 2018 UK greenhouse gas emissions compared to its level in 2017 (Penistone, 2019).

Regarding environmental policies and commitments, UK was part of the United Nations Framework Convention on Climate Change (UNFCCC) which was signed by 166 countries in 1992. However, it had not specified any timeframe and target for reducing greenhouse gas emissions at the time. A few years later in 1997, the developed countries agreed on emission targets for 2008-2012 known as the Kyoto Agreement. Based on this agreement, the contribution of the UK towards the European target was a 12.5% reduction in greenhouse gas emission between 2008 and 2012 (DETR, 2000; Johnston et al., 2005). In 2012, the second commitment for the Kyoto Protocol was adopted in Doha for the period of 2013-2020 (United Nations climate change, 2021). To maintain the international commitment for reducing greenhouse gas emissions for post 2020, another agreement was signed by 195 countries on 2015 known as the Paris Agreement (Nations., 2015). Based on this agreement, EU members including the UK, has established a goal of a 40% greenhouse gas reduction by 2030 compared to 1990 level climate (Waite, 2020a). In 2018, 65.9 $MtCO_2$ of the total carbon dioxide emissions belonged to the residential sector accounting for 18% of the total UK $CO_2$ emissions while $CO_2$ emissions from the residential sector decreased by 16% between 1990 and 2018 (Penistone, 2019). The UK government has recently established an ambitious emissions reduction target to achieve net zero emissions by 2050 and set five-yearly carbon budgets (BEIS, 2019b). The first three carbon budgets (2008 to 2022) were met, however, the fourth one (2023 to 2027) is not on track to meet the target (CCC (Committee on Climate Change), 2016b). At the recent UN Climate Change Conference (COP26) in the UK, 26 climate action initiatives were announced on ’Cities, Regions and Built Environment Day’. In addition to the 136 countries including buildings in their Nationally Determined Contributions, the UK and 11 other countries committed to Net Zero Carbon Buildings by 2030 (World Green Building Council, 2021). All this is showing that the domestic sector is one of the key players in both GHG emissions and energy consumption in the UK and will be discussed in more details in the next section.

## 2.2 Domestic Sector and Energy Consumption in the UK

The number of dwellings were estimated to be around 24.2 million in England in 2018, which includes both vacant and occupied stock. From this figure, 63% (15.3 million) were owner occupied, 20% (4.8 million) privately rented, 7% (1.6 million) local authority and 10% (2.5 million) housing associations homes (EHS (English Housing Survey), 2019a). Some households in Britain cannot afford their heating bills and are in *fuel poverty* (BBC, 2019; Newcastle City Council, 2019). In England, the fuel costs of a household above average means the household residual income is below the official poverty line. The most effective way to reduce the fuel poverty of dwellings is to ensure that homes are better insulated (BBC, 2019). Figure 2.5 shows the rates of UK households in fuel poverty and shows that England and Northern Ireland have the lowest and highest proportion of households in fuel poverty respectively. In Scotland, Wales and Northern Ireland, if a household spends 10% or more of its income for heating purposes it is considered fuel poor. The average expenditure on energy including road fuel in the UK is 5% of the household’s income while about one fifth of poorest households spend 10% of their income on energy (BBC, 2019). This highlights the necessity of improving insulation levels and the energy efficiency of homes to tackle fuel poverty in the UK, with a higher priority for Northern Ireland, Scotland, Wales, and England in order. Addressing fuel poverty initiatives is important not only to have a more equitable and healthy society, where all households can keep themselves warm and healthy, but also to contribute towards UK emission targets to create win-win solutions.

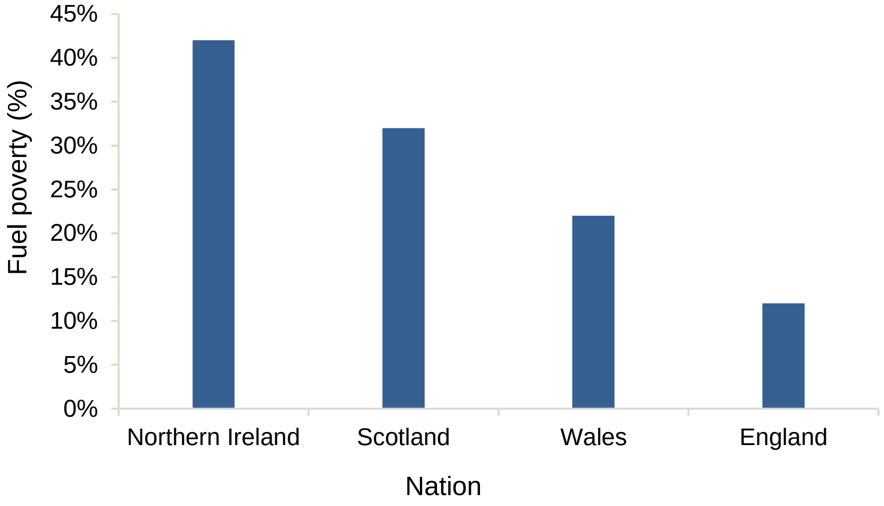


Figure 2.5. Percentage of households in fuel poverty by nation in the UK (BBC, 2019), based on (CCC (Committee on Climate Change), 2017).

Historically, the first requirement for a basic level of thermal insulation was introduced by the Building Regulations in 1965 (Billington et al., 2017; Lowe & Chiu, 2020). Later in 1991, and then followed by the edition in 1995, the UK started to introduce the regulation for the gradual change of the energy requirement in UK new built houses with the target of decarbonisation (Hardy et al., 2018; NBS, 1995). Figure 2.6 shows the dwelling age by tenure for the private and social sectors in 2018. As shown, the majority of the dwellings (13,267,000 dwellings) were built before 1965, some were built without basic insulation. The private sector has the higher rate of pre-1965 dwellings (when houses were constructed with no insulation) with 11,369,000 dwellings compared to the social sector with 1,898,000 dwellings (EHS (English Housing Survey), 2019b). This means that retrofitting these homes with energy efficient measures rely on the individual private owners' decision, which makes it more challenging to have control over the application of energy efficient measures. Also, the majority of very old houses built before 1919 are owned by the private sector (33% private rented and 20% owner occupied from the total 24,172,000 dwellings) (EHS (English Housing Survey), 2019a, 2019b).

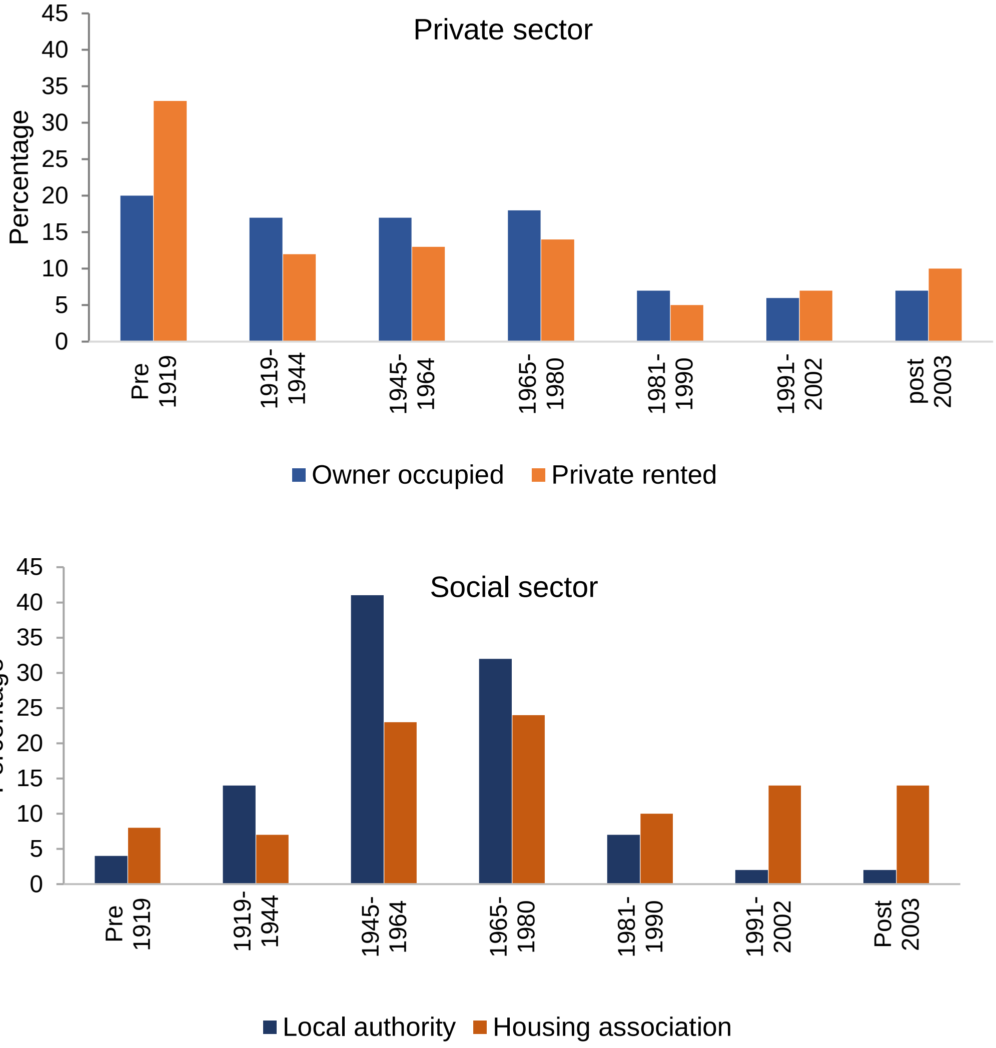


Figure 2.6. Dwelling age by tenure, 2018 (EHS (English Housing Survey), 2019a).

According to the Households Report of the English Housing Survey, around 18.4 million (80%) households live in houses in 2017-2018. People living in flats are around 4.7 million (20%) of which 3.3 million (14%) live in blocks up to three storeys, a smaller proportion of 908,000 (4%) live in blocks of four to five, 250,000 (1%) in six to nine and 193,000 (1%), in ten or more storey buildings (Rottier R, 2019). The UK has the least energy and carbon efficient housing stock in Europe (CCC (Committee on Climate Change), 2019; Chris, 2019; Lowe & Chiu, 2020; Palmer & Cooper, 2013). The new homes construction rate is less than 0.5% of the total stock annually while the demolition rate has been significantly low since 1991(Lowe & Chiu, 2020). Consequently, building new homes adds to the number of houses rather than replacing existing homes. Existing homes remain a challenge and the retrofit of current dwellings is inevitable as part of any energy efficiency improvement and carbon emission reduction strategy (CCC (Committee on Climate Change), 2019; HM Government, 2013, 2017; Lowe & Chiu, 2020).

The usable floor area of dwellings in England was in average 94 m$^2$ in 2018, with average usable floor area of 108 m$^2$ for owner occupied homes, and 66 m$^2$ for social sector and 76 m$^2$ for privately rented homes. Owner occupied homes are typically larger than social and privately rented homes with social sector homes usually the smallest (EHS (English Housing Survey), 2019a). Figure 2.7 shows the dwelling types classified on the basis of the surveyor's inspection in 2018. For purpose-built flats, low rise has the highest proportion of dwelling types in the social sector whereas less than 1% of them are detached houses. On the other hand, the detached and semi-detached house types are the highest typologies of owner occupied in the private sector.

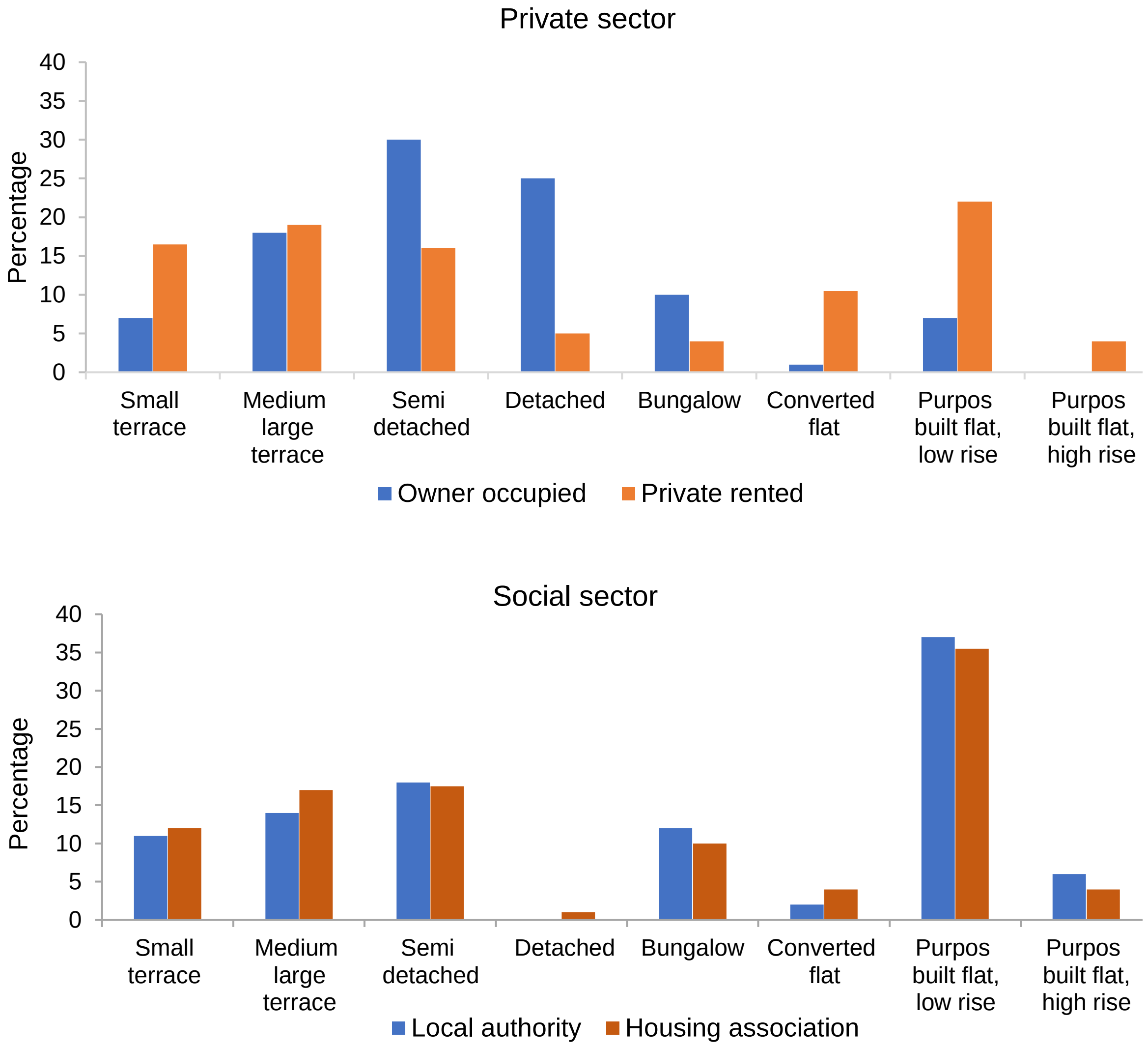


Figure 2.7. Dwelling type, by tenure, 2018 (EHS (English Housing Survey), 2019a).

The residential sector is the second highest energy consumer among all other sectors in the UK, slightly less than that consumed by the Transport sector. Energy use within this sector has been growing relatively slowly (see Figure 2.2). There are approximately 15.5 million homes in the UK, which accounts for the top 12 domestic property archetypes in the UK. They account for around 60% of the total UK housing stock which release 57% of the greenhouse gas emissions of the building sector (Hansford, 2015). The energy consumed by the residential sector includes the use of fuel and electricity in homes. Up to 80% of energy demand in the domestic sector is for space and water heating for which natural gas is the main source of energy. The external temperature directly influences the emissions produced from this sector, which means that the use of heating increases during the colder winter months (Waite, 2020a). For example, the energy consumption in the residential sector raised by 3.4% in 2018, that was the highest increase of all the sectors compared to 2017 level as shown in Figure 2.8. This increase was due to the severe weather caused by the so-called ‘Beast from the East’ in early 2018, resulting in the increase in gas consumption of the domestic sector which affected the annual demand despite the fact that the temperature in the rest of the year was moderately higher than usual (Waters, 2019).

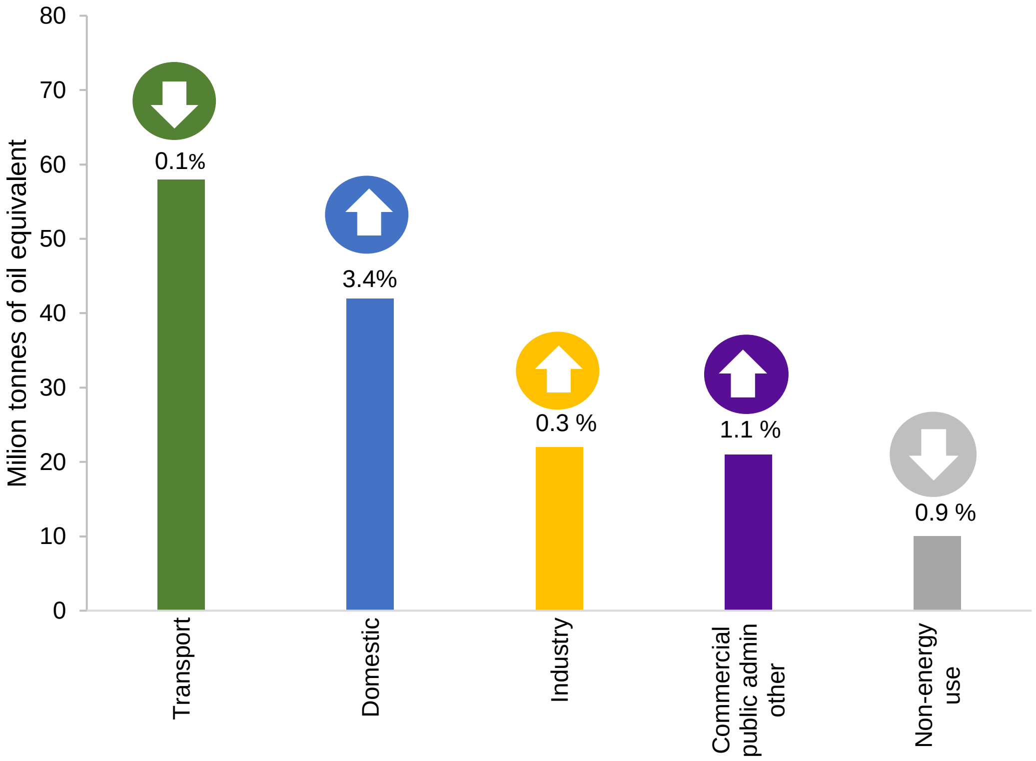


Figure 2.8. Final energy consumption by sector in 2018 compared to 2017 (Waters, 2019).

As previously discussed, 29 million existing homes across the UK must be upgraded or repaired with the use of energy efficiency measures, such as wall and loft insulation to meet the UK ground-breaking target of 100% carbon emission reduction (net zero emission) by 2050 (CCC (Committee on Climate Change), 2019). The existing homes remains a challenge as many of them are not compatible with energy efficiency standards. Around 65%-80% of the properties were built before 2000 (Boardman, 2007; Kelly, 2009; Ravetz, 2008; Simpson et al., 2019) and are anticipated to still be in use in 2050, which many of them not being energy efficient. Therefore, technical solutions in retrofitting these houses and boosting the energy efficiency potential of existing properties can lead to positive environmental consequences such as pollution reduction and lowering the carbon heat transition over the coming years (Gillich et al., 2019; Simpson et al., 2019).

## 2.3 Energy Efficiency Retrofit in UK Houses

There has been an argument in the literature whether it would be better from the environmental perspective to demolish and build a new house instead of renovating. Few case studies have been conducted previously and they were inconclusive and contradictory (Gram-Hanssen, 2014; Power, 2008; Thomsen & Van der Flier, 2009). Some arguments, such as cultural heritage and people's emotional dependencies to their homes, force the attention to energy retrofits of the existing buildings rather than demolishing. The UK intends to retrofit all the dwellings to EPC level C as standard as part of its clean growth strategy by 2035 to contribute towards its climate targets (BEIS, 2018). Only 29% of stock met this standard by 2019, which is nowhere near the UK ambitious plan to tackle the remaining 71%. On the other hand, householders find retrofits a major hassle, industry have not invested enough, and energy efficient measures are expensive which all led to energy efficient improvement having stalled (Chris, 2019). Without intervention and innovation, the long-term mitigation targets by using some key technologies such as SWI will not be achieved, most households will stay in fuel poverty, and they cannot contribute to decreasing the importing of fossil fuels into the UK and consequently the UK carbon budgets will not be met.

The Green Deal (GD) and the Energy Company Obligation (ECO) schemes are complementary policy mechanisms with the aim to address market failures and barriers which slow the uptake of energy efficiency measures such as SWI, cavity wall and loft insulation (Elderkin, 2011). The GD was an energy efficiency finance mechanism created by the British Government for homeowners as an innovative pay-as you-save scheme to help increase the installation of energy efficiency measures into their properties and pay back the costs of these measures through their energy bills over a period of time (Oxley, 2019). The large scale of retrofit was expected through this scheme with no need for public subsidies in an age of UK austerity. According to the estimation of Department for Energy and Climate Change (DECC) in 2011 with the GD support, 14 million homes should be retrofitted by 2020 and a further 12 million by 2030 (Department of Energy & Climate Change, 2011; Rosenow & Eyre, 2016). In reality, the GD was a failure as it only delivered about 6,000 homes per year since its launch in January 2013, a total of approximately 14,000 by the end of March 2016 (CCC (Committee on Climate Change), 2014).

In January 2013, the ECO was first initiated in Great Britain to enable Government to deliver the step-by-step aspirations to reduce carbon emission whilst providing critical support to low income and vulnerable households (Ofgem, 2020; Oxley, 2019). The (ECO) is a key policy which has been amended over time and some sub-obligations with different names were produced accordingly following the previous policy to complete each other. Table 2.1 lists the sub-obligations within the ECO. The Infographic presented in Figure 2.9 illustrates the distribution of the ECO measures installed across the Great Britain by region. From the 2.7 million ECO measures installed across the UK, the Northwest with 18% and Wales with only 5% have the highest and lowest rate of ECO measure installations up to end of December 2019. ECO3 is the latest policy commenced on 3rd of December 2018 and will run until March 2022, with the focus on low income and vulnerable households entirely, helping to meet the Government’s fuel poverty commitments (BEIS, 2018; Ofgem, 2020).

Table 2.1. Sub-obligations within the ECOs, based on (Oxley, 2019).

| ECO sub-obligations | Description |
|---|---|
| **Carbon Saving Target (CERO)** | This covered the installation of measures like solid wall and hard-to-treat cavity wall insulation, which ordinarily cannot be financed solely through GD Plans. From April 2017 this included a rural sub-obligation where at least 15 per cent of a supplier's CERO for Help-to-Heat must be achieved in rural areas. (Closed end September 2018) |
| **Carbon Saving Communities (CSCO)** | This provides insulation measures to households in specified areas of low income. It also makes sure that 15 per cent of each supplier's obligation is used to upgrade more hard-to-reach low-income households in rural areas. (Closed end March 2017) |
| **Affordable Warmth (HHCRO)** | This provides heating and insulation measures to consumers who receive means-tested benefits. Since April 2017 it enables those in social housing living in E, F and G rated properties to receive insulation measures, and some heating measures. This obligation supports low-income consumers who are vulnerable to the impact of living in cold homes, including the elderly, disabled and families. From October 2018 this included a rural sub-obligation where at least 15 per cent of a supplier's ECO3 must be achieved in rural areas. |
| **Flexible Eligibility** | Local Authorities can determine eligible homes under the new 'Flexible Eligibility' mechanism, introduced in 2017. Up to 25% of the Obligation can be delivered through Flexible Eligibility under ECO3, up from 10% under ECO Help-To-Heat. Households can be assessed by local authorities to be 'living in fuel poverty'; or assessed to be 'living on a low income and vulnerable to cold'. |
| **Innovation Measures** | Under ECO3, suppliers can meet up to 10% of their obligation to deliver innovation measures to eligible households. A further 10% can be used to monitor the actual energy performance of measures in homes. |

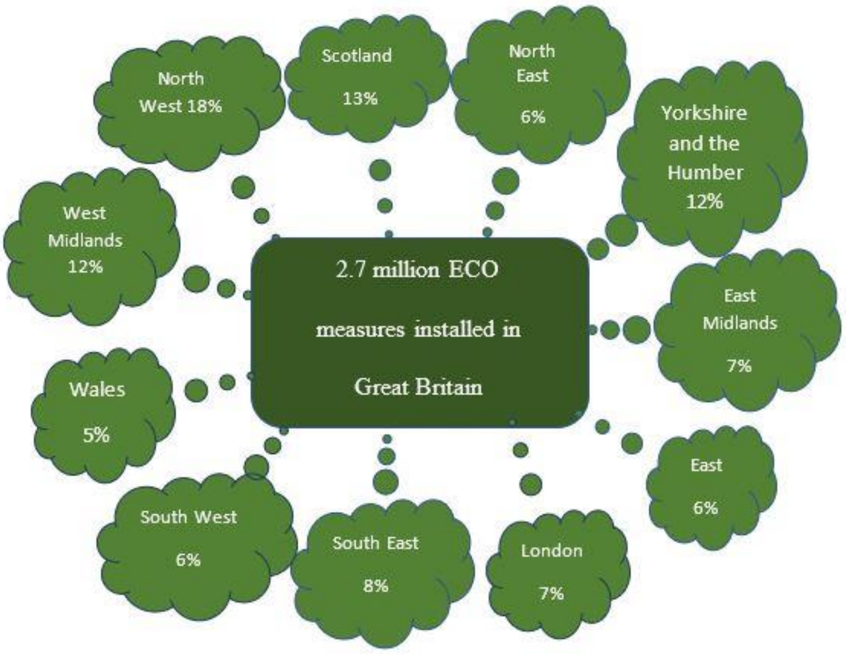


Figure 2.9. Infographic 3: ECO measures by region, up to end December 2019 (Oxley, 2020b).

In July 2015, the new Conservative government announced that it would no longer fund the GD because it was not providing value for money plus some concerns about standards. This scheme is still running but with very limited funds available through very few private firms which are prepared to offer the loans without government support (Rosenow & Eyre, 2016). The installation of measures distribution by different schemes including GD and ECO until December 2020 can be seen in Figure 2.10 below. As shown, in total about 3.1 million different measures were installed in 2.3 million dwellings under the GD framework and ECO until the end of December 2020. About 97% of these installed measures were delivered through ECO (Oxley, 2021).

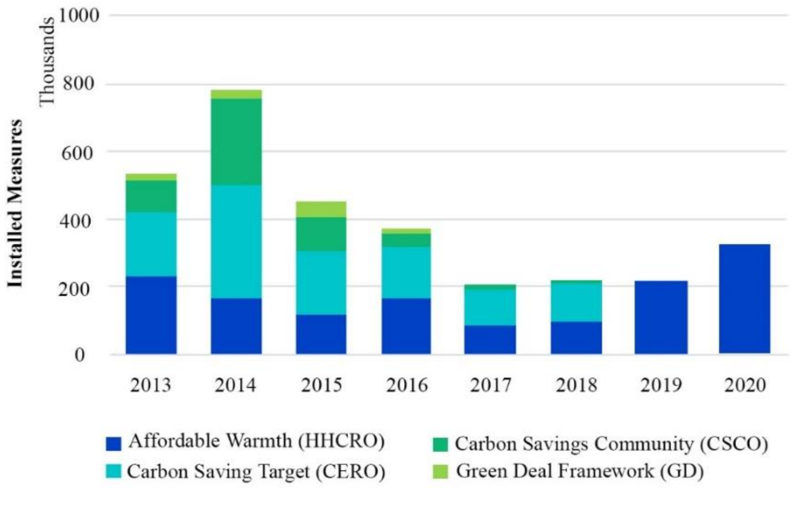


Figure 2.10. Measures installed by scheme and year (Oxley, 2021).

The ECO scheme options include energy saving measures such as heating measures and insulation because there is a lack of insulation and heating system measures in the majority of the existing stock to the standard level indicated in the UK strategy. These include cavity wall insulation, SWI, loft insulation, boiler installation or replacement and other heating or insulation measures (Oxley, 2019, 2020a). Figure 2.11 compares the weekly insulation requirement and their deployment rate in practice in England until 2035. As can be seen, the current installation of wall insulation is far behind the weekly target by 88%, requiring around 2,000 extra weekly deliveries. Among these measures, SWI and floor insulation have the lowest deliveries compared to the number of deliveries expected weekly.

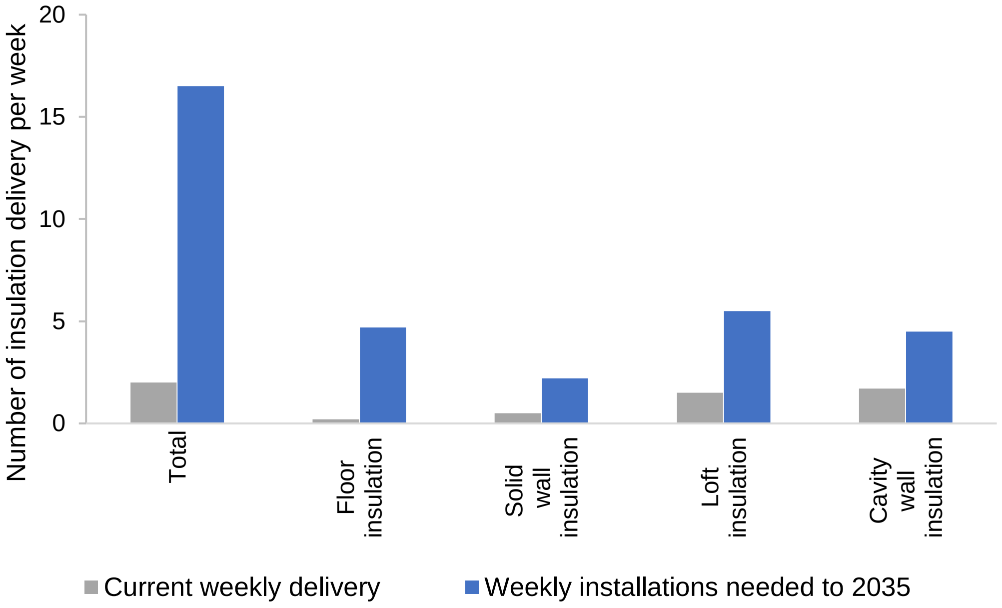


Figure 2.11. Weekly insulation installations required in England to 2035 compared to the current rate of weekly deployment (BEIS, 2019a).

The installation of ECO measures by measure types are shown in Figure 2.12. These measures are the ECO measures installed up to the end of January 2020. From the total measures installed in Great Britain, 66% of the measures belong to insulating the properties and 34% is for the heating measures. Amongst the ECO measures, SWI with only 7% is behind other measures such as cavity wall and loft insulation with 34% and 23% respectively. Even with the ECO plans to extending programmes such as ECO for energy efficiency or the Renewable Heat Incentive (RHI) for low carbon heat will not be enough to achieve the UK emission reduction targets in the built environment. The policy makers have few cost-effective options, and these schemes are not stimulatingly innovative with a minimal impact on bringing the cost down (Chris, 2019). Furthermore, the band C target as EPCs policy required, is not going to be cost effective for some measures such as SWI. It was suggested that the level be upgraded to band B or A which would make SWI be more cost effective in the long run (Eyre & Killip, 2019).

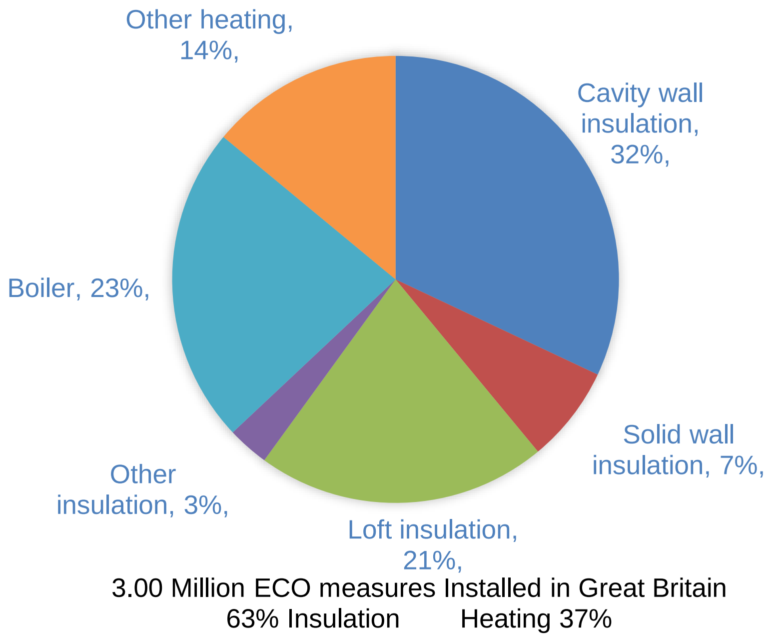
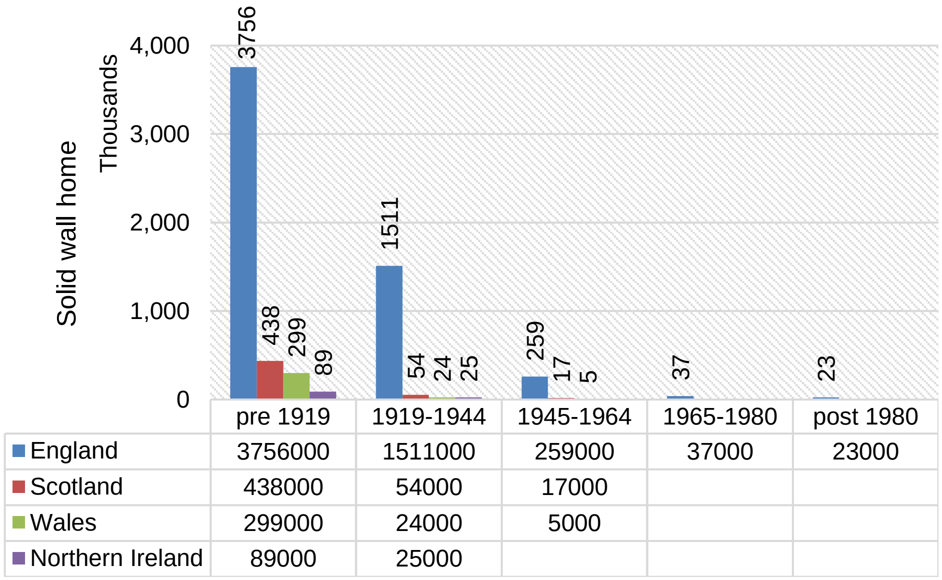


Figure 2.12. ECO measures by measure type, up to end December 2020 (Oxley, 2021).

Analysing the literature shows that applying energy efficient strategies to the acceptable level in existing stock, consisting of private and social sectors, are in the hands of house owners and government as the decision maker for their properties. Government can immediately affect the decarbonisation of the current old social sector stock which have the lower proportion of old houses (EHS (English Housing Survey), 2019a) compared to the private sector. The statistics also prove this; the social rented sector had the higher installation proportion of SWI with 27% compared to the private sector with 8% of the dwellings with solid walls from 2008 to 2018 (EHS (English Housing Survey), 2019a). While this statistic shows a big gap in the social sector, it also means that the major impact on energy efficiency of old houses relying on the private owners and individuals who live in these houses and the existing private houses apparently need to be the focus of the future policy (McGilligan et al., 2010). They are the key factor for decarbonisation of the current stock as the decision makers for improving the energy performance of their homes to the indicated standards. A plan or strategy for improving the energy efficiency within these houses seems unlikely to be successful unless they are designed to be stimulating and attractive enough for householders to consider it (Haines & Mitchell, 2014).

## 2.4 Solid Wall Houses and their Retrofit in the UK

According to BRE (2014), the history of construction methods in the UK reveals that in houses built prior to 1930s, the frameless structures were used in house construction, where the external façade acted as the load bearing wall. These solid walls consisted of regular and rectangular shape units (bricks, blocks, or slabs of natural stone, fired clay, concrete or calcium silicate) usually combining with a mortar; however large units were built without mortar. Most of the walls were typically one layer of material (solid walls) although cavity walls were also in existence prior to the 1930s. Nearly 70% of the dwellings built before 1918 have solid walls, and older properties are more likely to have solid masonry walls. Historically, around the late 1800s and early 1900s, a range of masonry materials and thicknesses were used in solid masonry walls, but the most used material were clay brickwork with a thickness of nominally 230 mm. The material used in solid walls need to be considered as some of these materials may present their own technical and buildability issues at the time of thermal upgrading (BRE (Building Research Establishment), 2014). Detailed breakdowns of the UK dwelling wall structure with various wall types can be found in Appendix 1.



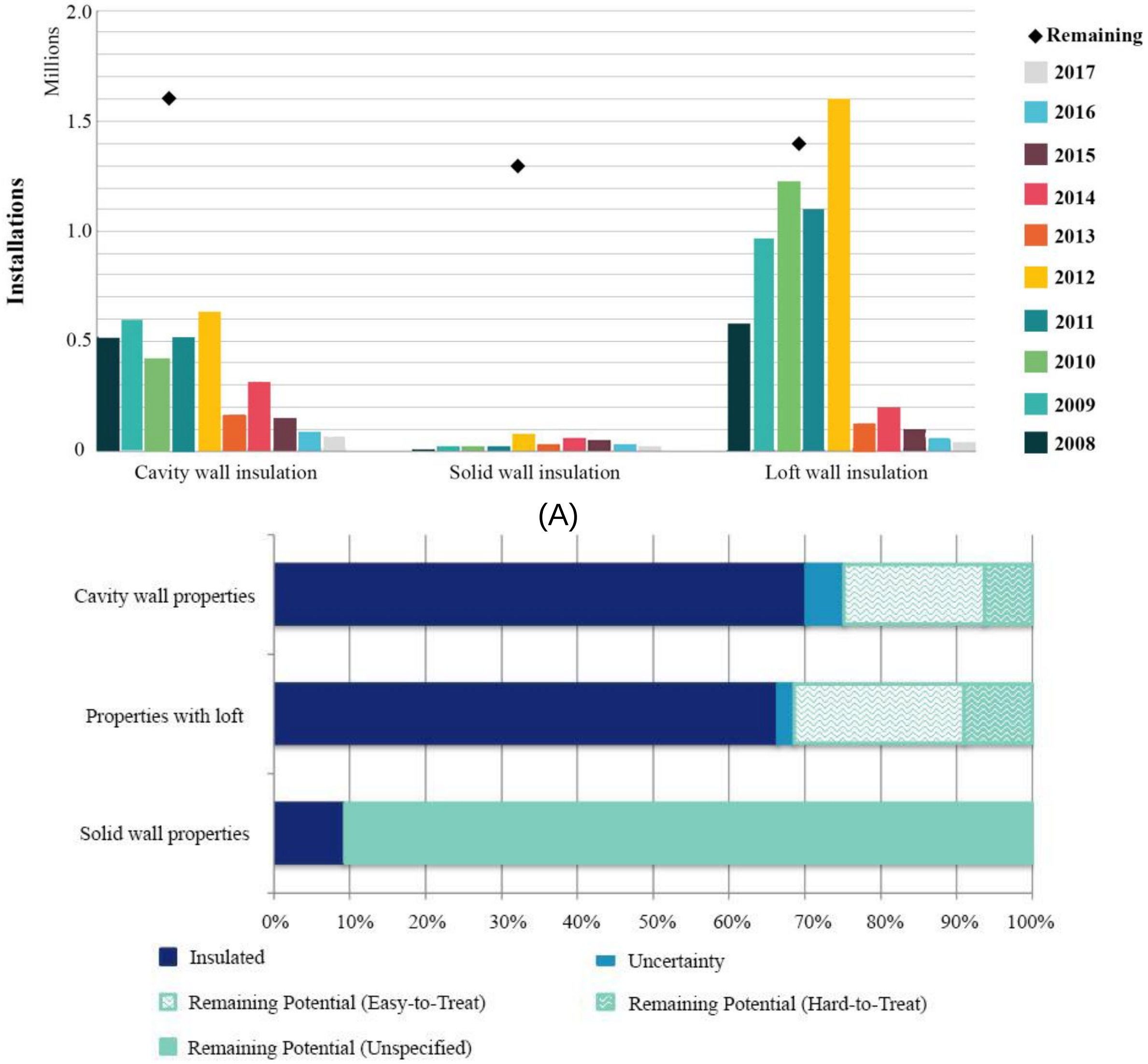
| | pre 1919 | 1919-1944 | 1945-1964 | 1965-1980 | post 1980 |
|---|---|---|---|---|---|
| 🟦 England | 3756000 | 1511000 | 259000 | 37000 | 23000 |
| 🟥 Scotland | 438000 | 54000 | 17000 | | |
| 🟩 Wales | 299000 | 24000 | 5000 | | |
| 🟪 Northern Ireland | 89000 | 25000 | | | |

Figure 2.13. UK solid wall by dwellings age (BRE (Building Research Establishment), 2014).

Figure 2.13 expresses the number of UK solid wall dwellings according to their build dates (for example, number of '9 inch solid' plus 'greater than 9 inch solid' for England, Wales and Northern Ireland – 'Up to 18 inch solid' plus 'More than 18 inch solid' for Scotland from Appendix 1). These data are extracted from the UK stock structure table presented in the Building Research Establishment report in 2014 (BRE (Building Research Establishment), 2014). As illustrated, the majority of solid wall dwellings are in England and built before 1919. Table 2.2 shows the progress of wall insulation in the regions of the UK until 2017. In all the regions the progress in SWI was very slow, especially in England and Northern Ireland (BRE Trust, 2017). However, the grants programmes and other financial support seems to be effectively working in driving the take-up of measures such as cavity wall insulation. Solid wall homes have the largest potential to reduce energy demand and $CO_2$ emission in various housing types (Kim, 2015). However, SWI is one of the greatest challenges for energy efficiency policies and the available support for SWI were not that effective (see Section 3.1) and other approaches will have to be sought for future savings from implementation of SWI (BRE Trust, 2017).

Table 2.2. Wall insulation, 2017 (BRE Trust, 2017).

| | **England** | | **Scotland** | | **Wales** | | **Northern Ireland** | |
|---|---|---|---|---|---|---|---|---|
| | Thousands | % | Thousands | % | Thousands | % | Thousands | % |
| **Cavity Insulated** | 11,157 | 68% | 1,363 | 75% | 636 | 68% | 570% | 90% |
| **Cavity Uninsulated** | 5,242 | 32% | 457 | 25% | 298 | 32% | 66 | 10% |
| **All cavity walls** | 16,399 | 100% | 1,820 | 100% | 934 | 100% | 636% | 100% |
| **Solid with insulation** | 694 | 10% | 115 | 18% | 71 | 19% | 11 | 9% |
| **Solid Uninsulated** | 6,301 | 90% | 529 | 82% | 307 | 81% | 107 | 91% |
| **All solid walls** | 6,996 | 100% | 644 | 100% | 378 | 100% | 118 | 100% |



(A)

(B)

Figure 2.14. Annual installation rate and remaining potential to insulate the housing stock A) in the UK until 2017 (Eyre & Killip, 2019), based on (CCC (Committee on Climate Change), 2015) and B) in GB by the end of December 2021, based on (Oxley, 2022).

Figure 2.14 illustrates the summary of installation rates of energy efficiency measures and the remaining installation potential for each measure in the UK and its progress in Great Britain. As shown, a huge potential is outstanding in solid wall houses to reduce the energy consumption and carbon emissions. The application of SWI with around 9% is far behind the levels of cavity wall and loft insulation with 70% and 66% respectively. It is estimated that by the end of December 2021, 7.7 million solid wall homes remained uninsulated (91% of homes with solid walls), with only around 794,000 insulated solid wall properties. There is a level of uncertainty in loft and cavity wall insulation where the possibility of applying the measures is not clear for example the insulation is hard, costly or impossible (Oxley, 2022). Retrofitting solid wall houses is still a challenge and needs to be promoted to achieve the decarbonisation target of the UK. According to the Department of Energy and Climate Change (DECC), the Government is keen to see the solution that enforces the energy efficient schemes considering the standards, and consumer protection to ensure that the system properly supports and protects consumers (Hansford, 2015).

It is commonly assumed that most of the traditional and historic buildings in the UK were built before 1919 and their walls are usually made of solid masonry (Marincioni & Altamirano-Medina, 2018). The highest proportion of UK homes that are historical buildings with pre-1919 buildings is approximately 21.5% of the total housing stock in the UK (Moran, 2014). Some of these solid wall properties have high values but are hard to treat for energy consumption and $CO_2$ emission reduction. Any minor alteration in a lot of these buildings, especially externally, can be impermissible. This needs to be considered in proposing retrofit plans for these buildings and seek help from experts with special knowledge of the domain to avoid unintended loss of aesthetic and historic value of the place and time (BRE (Building Research Establishment), 2014). Despite some benefits of External Wall Insulation (EWI) (such as reducing the risk of thermal bridging and minimising moisture issues) (Glew, Brooke-Peat, et al., 2017), in solid wall houses, especially for historical buildings, external insulation may raise some concerns due to the undesirable potential effects on the aesthetic features of the buildings (Moran, 2014). In such cases, ISWI is preferred as a retrofit option (Brannigan & Booth, 2013).

Solid wall buildings built between 1919 and1944 and traditional buildings account for almost 40% of the housing stock in the UK (Moran, 2014). Most of the solid wall stock are low-rise (two-storey) and include detached, semi-detached or terraced type homes (BRE (Building Research Establishment), 2014). London and the Northwest have the highest number of solid wall houses in the UK (Kim, 2015). The large number of solid wall buildings in UK necessitates consideration of both historic and traditional dwellings in energy improvement measures and $CO_2$ emission reduction which can lead to significant savings.

In the literature about solid wall energy assessment, *repair*, *renovation*, *improvement*, *maintenance*, and *refurbishment* are terms that are used interchangeably (Haines & Mitchell, 2014; Munro & Leather, 2000). However, *retrofit* specifically refers to the implementation of technologies resulting in energy saving and consequently $CO_2$ emission reduction (Haines & Mitchell, 2014; Moran, 2014). The UK government was committed to reduce carbon emissions by 80% compared to 1990 level before 2050 [3] and in 2019 this target was updated to net-zero by 2050 (BEIS, 2019b). Some analysis has been done in the literature to reflect the 80% reduction in housing stock across the UK as a whole and the following requirements have been standardised (Bothwell et al., 2011):

- Maximum $CO_2$ production: 17 kg/m$^2$ /yr
- Maximum primary energy use in the house (all energy consumption including the electronic appliances, such as white goods): 115 kWh/m$^2$ /yr

Recent feasibility studies show that a 50 to 60 percent $CO_2$ reduction is achievable at a reasonable cost, however, the 80% reduction is not an easy target because of both technical and aesthetic aspects in many retrofit programs (Bothwell et al., 2011). To achieve those targets solid wall retrofit needs more attention because of its great potential to save energy and reduce $CO_2$ emissions. Examples of poor detailing and inadequate installation of SWI can be improved for many archetypes with a proper evaluation framework, from a pattern book solution (manual) with appropriate training. For other types of buildings, when the case is more complicated, substantial work is needed to create proper methods appropriate for the delivery of the installation (Hansford, 2015).

There are potentially over 7 million properties remaining for SWI of which around 6.6 million are likely to be hard to treat according to the study on solid walls by the Building Research Establishment (BRE). However, under broad assumptions, 5.3 million homes can be treated when we assume all rendered and non-masonry dwellings are insulated externally, all masonry pointed properties with greater than 60 m$^2$ floor area are insulated internally and 50% of the properties with the mixed wall structure types can also be insulated (BRE (Building Research Establishment), 2008a, 2008b; Gillich et al., 2019).

There are some unintended consequences for solid wall retrofits documented in the literature. One of these consequences is the change in distribution of moisture in the building following an intervention. To avoid this, the probabilistic moisture risk assessment models for ISWI was discussed in literature (Marincioni & Altamirano-Medina, 2018; Marincioni et al., 2018). These predictive models can be used as a fast moisture risk assessment tool to support decision-making for the internal insulation of traditional solid brick walls. For example, one study indicates that the moisture buffering capacity of the materials can be greatly reduced by applying the surface finishes as these are less vapour permeable than insulation materials (Holcroft & Shea, 2013). In other studies, the effect of moisture was modelled numerically using WUFI software. Flood and Scott (2019) performed hygrothermal simulations to identify the value of discrepancies between simulated, calculated and measured properties. The findings of this research suggested that the moisture levels within insulated external wall increases gradually over five years and then reaches the moisture equilibrium before 10 years from its initial construction. In another study, O'Leary et.al (2015) designed a methodology to identify hygrothermal performance to develop the best retrofit intervention on rendered solid brick wall constructions. In this research the case study building was monitored for 12 months, and material properties and other specifications required for inputting in the model were measured to provide accurate data input for the model which then determined accurate results. This method was set out to establish best practice in creating a robust, appropriate experimental design for studying solid walled structures.

Some documented studies indicated that the moisture problem is the result of poor installation (BRE, 2016; Glew, Brooke-Peat, et al., 2017; Innovate UK, 2016; TSB (Technology Strategy Board), 2014). Glew et al. (2017) reported almost 1 out of 10 installations is not adequate enough to pass the quality check for the first time, however, this figure can change by several percent each year (Ofgem, 2015). "*Thermal bridging, non-contiguous insulation, infiltration pathways behind wall and floor coverings, interstitial condensation*" are also the consequences of poor performance installations (Glew, Smith, et al., 2017; Ofgem, 2015). Many installation issues are a consequence of not correctly implementing the guidance, and a change to enforcement of standards implies creating considerable changes in the quality of installation and control processes. Glew et. al (2017) in another study presents the findings from detailed surveys on 51 retrofitted properties to study the quality of retrofit appraisal in the domestic sector. Some failures were observed from this survey, which includes 72% pre-retrofit moisture issues and 68% post-retrofit moisture issues, 62% did not adopt a whole house approach, 16% inadequate quality assurance protocols, and insufficient design detailing in 64% of the dwellings. The retrofit was conducted by multiple installation organisation types and sizes delivering a range of retrofit solutions for Victorian and mid-twentieth century solid wall dwellings across the North of England. The sample studied in this research well represented proportion of UK homes, and it suggested that the quality of retrofit in many cases may not meet the required standards.

Global warming is expected to increase severe heat waves, therefore the possible overheating issue in hot seasons is another unintended consequence in buildings with SWI (Porritt et al., 2012).  Still, the energy saving benefits in colder seasons overweighs the possible heating penalties in the UK. However, occupant behaviour plays a significant role in overheating affects inside buildings (Mavrogianni et al., 2017). It is purported that while overheating may not happen until 2080s by using an annually adaptive approach, short term overheating (weekly or monthly) can occur before 2050 by 3%-5% number of hours being over the category upper limits which is the cause of concern for high expectation occupants but not for the normal expectation occupants (Ji et al., 2014). There are some studies showing that simple measures can be considered to reduce the overheating disadvantage. Gupta and Gregg (2013) assessed the risk of overheating in six suburban house archetypes in three cities of Bristol, Oxford and Stockport in the UK. All these case study homes were modelled in the Integrated Environmental Solutions-Virtual Environments (IES-VE) software and dynamic analysis was performed to evaluate the effect of adapted packages to prevent the possibility of overheating. There were four packages to limit overheating applied to the houses; 1) wall retrofit, 2) floor/roof retrofit with solar reflective (high albedo) coating added to the roof and louvered shutter shading applied to existing glazing, 3) Heating system retrofit by insulating the hot water tank and primary pipework and controlling the cylinder temperature, and 4) full retrofit which included all previous 3 packages. The results showed that combining all packages (package 4) was the most effective measure in overheating reduction in all the case studies. Package 1 was the best standalone package in most homes and package 3 was effective in smaller homes with a higher need to reduce overheating. The findings of this study suggest that any future retrofit programmes and any building regulation upgrades must include appropriate measures to tackle the overheating of homes due to the global warming climate. Moreover, to address the overheating concern in summertime in the UK, Tink et.al (2018) conducted an experiment in a research study on two solid wall houses in which one was retrofitted with ISWI. Night ventilation and shading using internal blinds were applied as a simple overheating mitigation strategy in the case study with ISWI. The internal temperature in both houses were similar by applying the mitigation strategy in the internally insulated house, confirming that overheating is not a major barrier for taking up ISWI. Based on the results, they suggested that shading by using internal blinds and secure noise attenuation become a requirement in building regulations for reducing the overheating risk in retrofitting existing solid wall homes.

## 2.5 Solid Wall Insulation and Energy Saving Potential

According to the Energy Saving Trust, a third of the heat loss is happening through the wall of a house (Pullen, 2009). Many solid wall properties have no wall insulation in the UK which puts them in more tricky position to waste energy. Wall insulation could be a very effective technology for energy saving, and it is commonly deployed in different countries (Rosenow et al., 2014). In SWI, the internal or external face of an exterior solid or *hard to treat* cavity wall will be insulated (Forman & Tweed, 2014). Several government policies are supporting SWI across the UK (Forman & Tweed, 2014). While the use of SWI has doubled between mid-2011 and mid-2013, only 3% of nearly 8 million houses with solid walls in the UK have been insulated by March 2014 (Walker M, 2013). This figure was improved in recent years and the number of solid wall insulated houses increased to 8.8% by 2016 (BEIS, 2017b). In general, the progress of SWI was very slow with insulated solid wall houses increasing to 9% of the total number of solid wall houses only at the end of December 2021, and still over 7 million solid wall houses remaining uninsulated (Oxley, 2022).

Furthermore, according to Building Research Establishment (BRE) (2014), around 1.75 million homes have cavity walls, but they cannot have cavity insulation due to construction issues, e.g., cavity is too narrow for the injection of insulation and so these are also suitable for SWI. This highlights the substantial potential for energy improvement remaining in SWI, which can contribute towards energy saving and emission reductions pledged by the UK Government, despite the challenges of SWI. However, there is a significant oversight in literature to undertake conclusive studies about the benefits of SWI in solid wall dwellings, which counts as 34% of UK housing stock, 92% of them still remaining uninsulated (BRE (Building Research Establishment), 2014).

The aim of installing SWI are energy use reduction, building market value increase (Ginevičius et al., 2008; Zavadskas et al., 2008), improving the building structure performance and building service life (increase up to 40 years) (Biekša et al., 2006; Ginevičius et al., 2008; Sasnauskaite et al., 2007), increasing the comfort level inside the building and improving the architectural appearance of the building (Ginevičius et al., 2008). SWI is more effective for detached houses (Loucari et al., 2016). This technique is more expensive (see Section 2.7) compared to some other retrofitting technologies (Rosenow et al., 2014). It could be the reason why the focus of the retrofitting programs was on cavity wall and loft insulations (Hansford, 2015), whereas the potential energy saving, and $CO_2$ reduction are significantly higher for SWI (as shown in Figure 2.15). In an individual study it was indicated that the SWI can result in higher energy savings compared to cavity wall insulation by more than 60% (Byrne et al., 2016), when SWI is part of a subtle renovation this saving can reach 80% (Innovate UK, 2016). In a recent study, it was shown that the SWI is beneficial even when considering whole life carbon analysis (Li & Tingley, 2021). From the results, the carbon reduction exceeded 1654 $kgCO_2e$ per $m^2$ over the whole life with a payback period of 1 to 23 years depending on the insulation material.

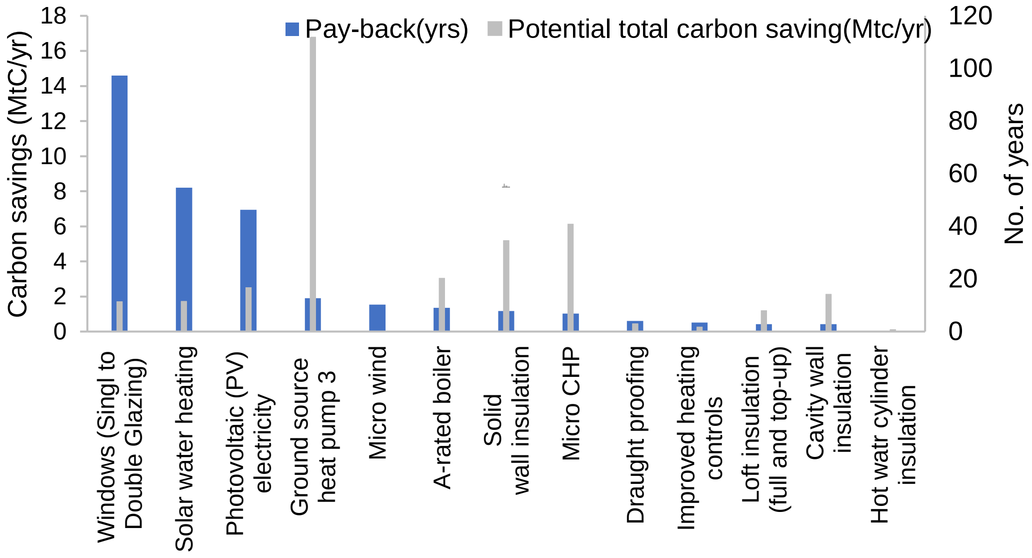


Figure 2.15. Pay-back period and $CO_2$ reduction potential for various retrofit technologies (Vadodaria et al., 2010), based on (DCLG, 2006).

The issues relating to wall insulation in existing properties were considered in Building Regulations that apply across England and Wales. There is clear guidance about the minimum thermal transmittance of 0.30 $W/m^2K$ to be achieved after SWI according to the standards, however, the rules are flexible and higher thermal transmittances can be accepted as SWI may not be feasible to be perfectly applied in some buildings (BEIS, 2017a). The direction of building regulations is to make sure the feasibility of the intervention technically, functionally and economically. They advise that SWI should have a payback period of up to 15 years and the space loss should not be more than 5% of the internal floor area (Marincioni & Altamirano-Medina, 2018). The Building Regulation Part L made it compulsory to improve the insulation level of walls when any wall renovation is taking place (BEIS, 2017a).

A minimum of 17,000 homes with solid wall will be treated yearly by the government in a flexible way to achieve the savings resulting from the use of SWI or energy saving equivalent from other insulation and renewable heating technologies (BEIS, 2018). The UK Government acknowledges that the market for SWI need to be supported as this market needs time to become wide-spread and extra funding is still required for such innovative measures (DECC, 2014). However, the number of properties that have received the government support was only about 23,000 (by June 2017) and the majority of them were supported by the Welsh and Scottish Governments (BEIS, 2017a). From ECO measures implemented by Government support to upgrade the existing stock, a total of 7% installed SWI reported up to the end of December 2021(Oxley, 2022).

SWI can be implemented externally or internally. Insulation boards or prefabricated stud walls containing insulating material (e.g., wool fibre) are fitted on interior wall surfaces in IWI while for EWI an insulation layer is placed on the exterior wall surface covered by render or cladding. There are advantages and disadvantages for both internal and external insulation that will be discussed in detail in the following subsection.

### 2.5.1 Internal versus external wall insulation

About 21.5% of the housing stock in the UK was built before 1919 and they have an external historic and architectural character. Therefore, IWI is the suitable retrofit option because the architectural quality and heritage value of the external building surface can be preserved (Bothwell et al., 2011; Brannigan & Booth, 2013; BRE (Building Research Establishment), 2014; Loucari et al., 2016; Marincioni & Altamirano-Medina, 2018; Moran, 2014). Furthermore, IWI is usually cheaper (about £4000 cheaper according to 2013 price rate) and the payback period is more than 30% shorter compared to EWI (CJ Morris, 2014). There is also a slightly higher potential for energy saving for IWI as reported in the literature compared to EWI (Loucari et al., 2016). For example, Moran (Moran, 2014), reported that his underfloor insulation program (Retrofit Package 1) had the potential to reduce energy consumption in the region 8-51%, however, adding IWI can improve the energy consumption reduction to about 70%.

Besides the benefits, there are some drawbacks to IWI. Depending on the wall porosity and water penetration, there is a risk of frost damage and condensation in internal insulation and natural ventilation will be reduced more than with EWI (Moran, 2014). In historic buildings, it can cause fabric decay and a minimum infiltration rate is needed to be considered (Loucari et al., 2016; Moran, 2014). Moreover, insulating the walls from the internal side reduces the floor areas to some extent. It also could be disturbing for the occupants since the internal spaces should be evacuated for a while. EWI would be more convenient to install for the occupants since the work will happen outside the building. It does not affect the internal floor area of the house, however, it could affect the area of the garden, passageway, and patio outside the house (Haines & Mitchell, 2014). It can hide the gaps on the bricks, reduce the damp, improve the life of the bricks and bring a better look for the house (Energy saving trust, 2021). However, if features and architectural character (such as mouldings) exist on the wall, they will be lost by wall insulation (Changework, 2012). Any form of wall insulation is likely to require consent or planning permission for buildings with historical value (Pickles, 2016).

The legislation and planning permission constraints are a challenge for EWI, while the legislation has been relaxed in recent years, the permission from local councils is still advisory for lawful development (Brannigan & Booth, 2013; The greenage, 2015). The uniformity of dwellings on the street itself provides an architectural value even if the buildings are not architecturally important (Vakhitova, 2013). For listed buildings, the legislation is even tighter and external insulation would be more challenging (HomeLogic, 2019). EWI may not be permitted for buildings with historical and architectural value. Even in houses without historical value, planning permission may be required for implementing the external insulation. It could be the main advantage of IWI against EWI. The advantages and disadvantages of external and IWI are presented in Table 2.3 which is extracted from the BRE report (BRE (Building Research Establishment), 2014).

In both IWI and EWI, there is a chance of overheating during the summer (Tink et al., 2018). However, some research undertaken to tackle the overheating resulted from SWI by the use of night ventilation and shading to tackle the issue (Gupta & Gregg, 2013; Tink et al., 2018) (see Section 2.4 for details).

Table 2.3. Summary of the advantages and disadvantages of EWI and IWI (BRE (Building Research Establishment), 2014), based on (Changework, 2012).

| | Internal wall insulation | External wall insulation |
|---|---|---|
| **Pros** | • Can be cheaper, particularly if done on DIY basis<br>• Can be applied room-by-room or just to certain rooms<br>• Heating has faster response<br>• Can improve interior décor of property<br>• Fewer restrictions on where in what types of properties it can be applied (e.g., can be applied more easily in high-rise blocks, conservation areas) | •Lower risk of moisture build-up and condensation<br>•Walls retain heat so lose heat less slowly<br>• Enhance structural integrity of building<br>• Less disruption to occupants/ no need for decanting<br>• Can enhance exterior appearance |
| **Cons** | • Potential problems with moisture build-up and condensation<br>• Leads to cold bridging<br>• Issues with accessing services<br>• Loss of room size (unless injection method or slimline products used)<br>• Complex cornicing or fittings can be an issue with fixings internally | • More expensive<br>• Not applicable in many properties: buildings where it is desirable to retain original appearance, multi-occupancy properties<br>• Restrictions on when work can be carried out (e.g., due to weather)<br>• Require neighbour's agreement if joined properties. Can be particularly difficult in blocks of flats |

Table 2.4 shows the total number of ECO measures for SWI including external and IWI until January 2020. The SWI was delivered by the Contribution of Carbon Saving Target (CERO), Carbon Savings Community (CSCO) and Affordable Warmth (HHCRO) obligations. As the data shows, EWI deliveries were significantly higher than IWI especially in ECO1-2 measures and ECO Help-To-Heat up to the end of September 2018. In recent years, in ECO3 measures, the deliveries of IWI (solid and cavity) level had an increase of 832 installations compared to EWI (solid, cavity and park home). ISWI deliveries in all the measure types are a total of 16,713 homes with solid walls and cavity walls which were suitable for SWI compared to 172,470 EWI deliveries. The installation of SWI internally is far lower (90% less) than externally although it is reported that IWI would potentially lead to more savings (Loucari et al., 2016). Therefore, it is important to promote the application of IWI in a satisfactory way for the householders to unlock the demand for wall insulation which potentially leads to a significant reduction in energy use and emission production in the domestic sector. Furthermore, the retrofit process can be faster for internal works as in most cases planning permission is required for external insulation (Brannigan & Booth, 2013; The

greenage, 2015). Also, IWI is cheaper (CJ Morris, 2014) and can lead to more heating energy savings compared to EWI (Loucari et al., 2016; Brannigan & Booth, 2013; Loucari et al., 2016).

Table 2.4. Solid wall insulation installed through the (CERO), (CSCO) and (HHCRO) obligations, up to end January 2020 (Oxley, 2020b).

| Measure type | Solid Wall Insulation | Total number of ECO measures delivered | Percentage of ECO Measures |
|---|---|---|---|
| **ECO 1-2**<br>**measures installed up to end March 2017** | External wall insulation: Solid Walls | 133,266 | 2.13 |
| | External wall insulation: Cavity Walls | 5,132 | 0.2 |
| | External wall insulation: Park home | 183 | 0 |
| | Internal wall insulation: Solid Walls | 6452 | 0.10 |
| | Internal wall insulation for Cavity Walls | 41 | 0.0 |
| **ECO Help-To-Heat measures installed up to end September 2018** | External wall insulation: Solid Walls | 25,170 | 2.56 |
| | External wall insulation: Cavity Walls | 1,832 | 0.6 |
| | External wall insulation: Park home | 205 | 0.1 |
| | Internal wall insulation: Solid Walls | 2,679 | 0.27 |
| | Internal wall insulation for Cavity Walls | 27 | 0.0 |
| **ECO3**<br>**measures installed, up to end January 2020** | External wall insulation: Solid Walls | 6,113 | 2.4 |
| | External wall insulation for Cavity Walls | 436 | 0.2 |
| | External wall insulation: Park home | 133 | 0.1 |
| | Internal wall insulation: Solid Walls | 6,870 | 2.7 |
| | Internal wall insulation for Cavity Walls | 644 | 0.3 |
| **Total** | **Solid Wall insulation** | **189,183** | **12** |

A summary of the literature on SWI potential concentrating on heritage buildings was published by BRE in 2014 (BRE (Building Research Establishment), 2014) (see Table 2.5). The report contains the aims of retrofit in several case studies while comparing the pre- and post-retrofit performance of the buildings. The major case studies reviewed in the report were Historic Scotland, Sustainable Traditional Buildings Alliance (STBA), Sustainable Energy Communities in Historic Urban Areas (SECHURBA) as summarised in the table below (BRE (Building Research Establishment), 2014).

The information provided acknowledges that there is a wide variation in improved performance for each heritage building after SWI, and different improvements for U-values and airtightness observed after insulation for each case with different insulation materials. The table does not provide information on possible saving benefits following the wall insulation. The exception is for Lena Garden, an 1870s Victorian house, with a reported 89% saving on metered energy use after implementing several retrofit measures in which one is SWI. Such studies, which report different retrofit scenarios and insulation materials, can provide a general picture about SWI benefits, however, they cannot deliver critical data for SWI benefits for the UK solid wall dwellings.

Table 2.5. Summaries of retrofit case studies with wall insulation, based on (BRE (Building Research Establishment), 2014).

| Case study | Description | Description of the retrofit works | Measure of improved performance |
|---|---|---|---|
| 16 Roxburgh St | Ground floor flat, within a three-storey and basement terrace circa 1840. Existing: Walls in living room and entrance hall: polished ashlar with chamfered rustication, masonry thickness 600mm; external wall (bedroom and kitchen): random rubble stone with broached ashlar window surrounds, masonry thickness 650mm | Rigid insulation: Pavaflex wood fibreboard. Wood fibreboard was specified; however, due to procurement issues, rigid phenolic insulation board was installed in some locations (Kooltherm K12); blown insulation; Warm fill insulation: an expanded polystyrene bead insulation with bonding agent | U-values (in situ measurement)<br>Wall U-value from 1.4 to 0.8 W/m2K in living room |
| 22 Drummond St, Flat 8 | Rear second floor flat, accessed from common stair, within five-storey, tenement block c 1790. Existing fabric: random rubble stone with broached ashlar window surrounds. Masonry thickness approx. 750mm | Open cavities packed with mineral wool and bonded polystyrene bead blown in behind the plasterboard to fully fill the cavity (approx. 100mm deep) | U-values (in situ measurement)<br>Wall U-value from 0.5 to 0.4 W/m2K in bedroom |
| 33 Marshall St, flat 1F2 | End of terrace first floor apartment, within four-storey plus attic, mid-19th century tenement. Upgrading works to a single room (bedroom) with two external walls and two windows. Existing fabric: stugged ashlar with fair-faced window surrounds. Overall masonry thickness approx. 750mm and 60mm respectively | Open cavities around window openings packed with mineral wool insulation. Expanded polystyrene bead insulation was blown into cavities through the mineral wool packing to fully fill the cavity (35-45mm deep) | U-values (in situ measurement)<br>Wall U-value from 1.3 to 0.3 W/m2K in bedroom |
| 2 Roxburgh St, flat 2F1 | North corner, second floor apartment accessed off common stair, with four-storeys plus basement, tenement c 1800. Upgrading works conducted to the two external walls and five windows. Existing fabric: Broached ashlar, with droved margins to window surrounds. Overall masonry thickness approx. 650mm | Open cavities below sill level packed with mineral wool insulation and any gaps around the perimeter of the window opening were also filled to form a continuous seal. Expanded polystyrene bonded bead insulation (warm fill white) blown into the wall cavity (40-50mm deep to NW wall and 20-30mm deep to the NE wall) through the holes in the plaster and timber grounds. | U-values (in situ measurement)<br>Wall U-value from 1.4 to 0.7 W/m2K in living room |

| | | | |
|---|---|---|---|
| Wells O'Wearie, Edinburgh | Single storey detached cottage from early 19th century with an addition to the east dating from c 1880, category B listed. Sandstone rubble, bound with lime and finished with ashlar quoins and margins | Blown cellulose; blown aerogel (bead type high performance silica product) trialled on the second wall; surface applied insulation (wind driven water penetration walls). 10mm layer of aerogel blanket used, secured to the wall behind an expanded mesh sheet and fastened with thermally decoupled fixings. | U-values from 1.3-1.4 to 0.61.0W/m2K after the insulation (U-values vary on walls) |
| Wee Causeway, Culross | Detached cottage house mid-18th century. Sandstone rubble masonry bound with lime, although repointed with cement in several areas | Aerogel blanket - 10mm thick aerogel blanket; calcium silicate board sand and lime treated; blown polystyrene bead | U-values walls: Ground floor from 1.5- 0.5 W/m2K and first floor 1.6- 0.9 W/m2K (U-values vary on walls) |
| Sword St, Glasgow * | Four-storey tenement property with a ground floor retail accommodation and upper three floor containing two flats each. Sandstone rubble masonry with brick internal partitions dated 1890. External walls U-v 1.1W/m2K | Six internal insulation measures trialled: Blown polystyrene bead; blown cellulose; hemp fibreboard; wood fibreboard; 40mm and 50mm thick aerogel board and synthetic porous material finished with skim plaster coat. | U-values from 1.1 to 0.190.37W/m2K (varies per insulation type); average humidity over 18-month monitoring period on probes at 50mm depth of the wall thickness (RH=14.3-66.6%) and at the interface between insulation and wall (RH=14.8-65.2%) (RH varies per insulation type) |
| Kildonan, South Uist | Mass masonry building c 1935 of cement mortar whinstone rubble | Wood fibreboard insulation (wall linings had decayed-so retention was impractical); calcium silicate board insulation. | U-values from 1.1 to 1.0 W/m2K (ground floor, wood fibreboard) and 0.4 W/m2K (first floor, calcium silicate board) |

| | | | |
|---|---|---|---|
| Scotstarvit cottage, Cupar | Cottage late 19th century detached cottage. Built of roughly squared sandstone rubble bonded with lime mortar. Internally it is lined with lath and lime plaster on timber battens with a timber suspended floor. In some areas the plasterboard had replaced the lath and plaster | Walls: perlite poured in between all the uprights; ceilings: Lath and traditional haired lime plaster finished with clay paint; floor: hempfibre batts and solum isolated using a geotextile breathable membrane | No U-values after the retrofit. (Before the retrofit 1.6W/m2K). Airtightness pre retrofit 16.9 and after 10.7m3hm2 at 50Pa |
| Garden Bothy, Cumnock | Two-storey building. Sandstone rubble masonry except for rear elevation lined on the outside with brick, forming part of the walled garden. Originally all internal walls were lined with lath and plaster. Not derelict but in need of repair (enabling works | Hemp insulation and clay board; 50mm hemp board between the timbers; 80mm wood fibre insulation finished with clay board, plaster, and paint; blown cellulose (26mm diameter holes every 20mm blown dry behind the wall lining on 3040mm depth of cavity | No results comparing pre- and post-performance of walls. Moisture monitoring to be published. |
| 116 Abbey Foregate, Shrewsbury ** | End terrace two storey house with attic, c 1820. Brick with plain tiled roof with elements of timber framing and modern single storey extension | Internal insulation of all external walls on the ground and first floor with woodfibre board (except for the rear single storey extension) and fitting of secondary double-glazing to ground and first floor sash windows on the front elevation. | U-value improvement from 1.48-0.48 W/m2K (in situ) |
| Firs, Riddlecombe ** | Two storey semi-detached 19th century cob cottage with an early 20th century single storey addition in cob, new timber double-glazed units | External cement render, repair, and re-render of walls with insulating lime render. Internal gypsum plasters were replaced with lime and limewash finishes. | U-value improvement from 0.76-0.72 W/m2K (in situ) |
| Mill House, Drewsteignton ** | Barn built in granite from the 19th century or earlier, converted to a dwelling in 1970s with a modern extension added on the southeast. UPVC double glazed windows. | No major refurbishment works have been applied in this building but in 2011 it was internally insulated with PIR insulation | U-value improvement from 1.2-0.16 W/m2K (in situ) |
| Albert St | Victorian terraced house situated in conservation area | 60mm of Diffutherm insulating board | U-values from 2.1 - 0.55 W/m2K |
| Cottage in Greyfriars, Shrewsbury | Listed cottage from the 14th century | The exposed stonework inside was originally rendered, it could be plastered again with an insulating plaster material such as Hemp or Lime or EcoRender Plus | Estimate reduction 1.89-1.56 W/m2K on wall if 20mm coat of Eco-render plus is applied. |

| | | | |
|---|---|---|---|
| Lena Gardens | 1870s Victorian terrace house in a conservation area in West London, 195m2 | n/a | Metered energy use (89% savings) after implementing several strategies including wall insulation |

* Compares the performance of different insulation measures resulting in different post-retrofit U-values

** Includes the estimation of U-value by simulation before and after the intervention and the monitoring of indoor environment parameters (case studies by SPAB Building Performance Survey)

### 2.5.2 Processes, impacts, and practicalities of solid wall insulation

Despite some government reports and review series, such as (BEIS, 2018; BRE (Building Research Establishment), 2014; Hansford, 2015; Oxley, 2021), the number of scientific publications is limited for SWI in the literature. One of the first publications about retrofit in solid wall houses was research conducted by Freund in 1983 (Freund, 1983). Two unoccupied 50-year-old semi-detached solid wall houses were selected as the case studies for retrofit using a number of energy efficiency measures, but with different techniques in each case study. The retrofit measures included loft and SWI, draught stripping, double glazing, heating controls and heat pumps. Different types of heating control in both houses were examined using the variation in daily mean house temperature with respect to the outside temperature. The insulation delivered the amount of saving that was expected, and heating analysis showed the 30% reduction of effective thermal capacity by internal insulation.

Hardy et. al (2018) studied the impact of SWI on the energy saving, thermal performance and the internal temperature of 14 dwellings. The electricity, gas and temperature readings were collected, and the results showed the reduction in gas and electricity usage in most of the case studies but with considerable variations. These dissimilarities strongly related to the changes in occupant behaviour which suggests that educating occupants for effective use of the retrofitted property can eradicate the waste of energy and the best potential of SWI in terms of both carbon and financial savings can be achieved.

Elsharkawy and Rutherford (2018) explored the effect of user pattern consumption influenced by occupant behaviour and awareness on policy initiative delivery. They assessed the survey results of 150 properties included in the Community Energy

Saving Programme (CESP) scheme in Nottingham before and after retrofit for home energy use. They found that the initiative was effective in home-improvement and energy use reduction, but the predicted financial saving could not be achieved due to occupant ingrained habits towards the energy use. This highlights the importance of giving information to residents for better managing their home energy use following the retrofit, which was suggested to be necessary in the delivery of future retrofit initiatives.

In another experimental research, the effect of retrofit in stages was studied on a pre-1919 UK solid wall house as a case study within the controlled condition chamber with a consistent temperature of 5◦C, the average UK winter temperature. The reduction of 63% in heat loss from the property was reported in the deep retrofitted case study with some thermal upgrades. The retrofit measures conducted one by one, and its effect were measured and compared to the previous step for effective comparison in the field which previously only was fully explored in models. The highest improvement in heat loss occurred by SWI with 72% and the savings for loft insulation and both the floor and glazing were 6% and 11% respectively. By using the Heat Transfer Coefficient (HTC) findings and some other assumptions, the annual heating was anticipated to see the impact of projected retrofit. The analyses revealed that heating energy saving of 45% for SWI, 7% for glazing, 7% for floors and 3.6% for loft insulation and the overall of 63% saving, can be achieved annually (W Swan et al., 2017). In a different study in controlled conditions, Farmer et. al (2017) chose the case study inside the controlled chamber and tested the effect of retrofit measures within a steady-state environment by measuring the building fabric thermal performance on site. The calculated and measured retrofit U-value for each stage of the retrofit suggest that the retrofit measures performed as expected. However, retrofit U value for internal and ESWI were slightly different from the target retrofit U value, with 10% lower and 8.3% higher figures respectively. This highlights that measuring before and after the retrofit is applied is important for assessing the fabric heat loss. The steady-state boundary conditions have strengths as well as weaknesses. It enables the measurements of heat loss following a retrofit measure on the house to a precise level which normally is unlikely to be achieved in the field. However, lack of wind in the enclosed environment would result in airtightness improvement and can underestimate the potential ventilation heat loss. They also note that the EWI is more effective than IWI. However, there is a chance of error because in their tabulated results the numbers were in favour of internal insulation and it contradicts other studies (Brannigan & Booth, 2013; Loucari et al., 2016) as well.

The importance of U-value was also highlighted by Li et.al (2015). In this study, the uncertainty of the energy performance estimation of properties was expressed due to the U-value assumptions of solid walls. Re-analysis of the U-value was performed on 40 brick solid walls and 18 stone walls using the technique of inverse parameter estimation and lumped thermal mass. The results indicated that the wall mean U-value was 1.3 ± 0.4 instead of 2.1 given by guidelines of the Chartered Institute of Building Services Engineers (CIBSE) (CIBSE, 2006) which is also used in the UK Standard Assessment Procedure (SAP) and reduced SAP (RdSAP) (BRE (Building Research Establishment), 2012). Solid walls seem to be more resistive thermally than was previously estimated which can have a significant effect on estimations of the energy savings and cost-effectiveness of SWI measures. Previously, poor alignment of modelled results with the actual data purported to be related to occupant behaviour, but such anomalies may also be related to wrong assumptions of the physical characteristics of the property. It is important to measure the key basic parameters of the UK domestic buildings in any national programme to support more precise estimation of energy performance of retrofit measures and remove the uncertainty. In another study (Loucari et al., 2016), again the uncertainties in the estimation of the thermal performance of solid walls and in the emission and energy saving reduction from the retrofit measures were assessed, and the consequences in meeting the UK housing retrofit target based on the doubtful estimations were raised. Five different dwelling archetypes were selected for this study. Three insulation retrofit scenarios were applied, including (1) the base line with no insulation, (2A) EWI by adding the 90mm of EPS and (2B) IWI by adding 90 mm of EPS. The results illustrate that internal or ESWI reduce the space heat demand considerably, however the IWI was found to be slightly more effective. The space heating demand reduction ranged from 60%-66% and 62%-68% when compared to the pre-insulation baseline condition for the external and the internal insulation scenarios consequently. Beside the improvement effect of SWI in wall thermal performance, the airtightness of the building also improved but the level of airtightness was still undetermined with great deal of uncertainty. The maximum savings as a result of IWI and EWI occurred in detached houses, and reduced constantly in order of semi-detached, end-terrace, bungalow and mid-terrace houses.

Gillich et.al (2019) anticipated that energy savings target in building sector would be achieved by 2035 with the help of SWI, cavity wall insulation and loft insulation using both sets of data from the fifth carbon budget (CB5) policy projections and updates on the in-use factors using measured data from the National Energy Efficiency Database (NEED). However, their results illustrated a 26% discrepancy in the anticipated energy savings resulted from these measures in 2035 compared to CB5 expected estimation level. This highlights the urgency and importance of accurate information about SWI performance for better anticipation of energy and carbon reductions of this energy efficient measure in the future.

In the retrofitting of three case studies of two-story-dwellings, the most appropriate retrofit options were performed according to the wall constructions of the case studies. The selected retrofit measures were cavity wall insulation for case study 1 with a cavity wall, IWI for case study 2 with solid stone walls, and EWI for case study 3 with a different structure of cavity wall. In all the retrofitted case studies, the significant saving in energy costs were observed but IWI offered the greatest reduction in heating cost with a saving of £36.79 per m$^2$ of wall based on the standard tariff rate of 4.65p/kWh. The main barrier of ISWI was the space reduction of 95mm from the internal face of all external walls which might be difficult around bathrooms, sinks, radiators and fitted kitchens. Also, despite the fact that great savings can be achieved from wall insulation, homeowner motivations to instigate the retrofit options to make their home energy efficient is highlighted as a significant barrier which requires research attention (Brannigan & Booth, 2013).

## 2.6 Building Simulation Approach for Energy Performance Assessment

Different Simulation software was used in developing the model to study the buildings energy performance. In this section information about the approved modelling methods and simulation software is provided. The U-Value is a critical factor in any energy retrofit analysis including SWI and is discussed in a sub section. Finally, the specific simulation studies about SWI are reviewed.

The Standard Assessment Procedure (SAP) is a method which assesses the energy performance of the buildings approved by UK government. The National Home Energy Rating (NHER) is one of the modelling software that works based on different occupancy type, house location, and appliances and creates SAP output data and it can be used to predict the energy consumption and $CO_2$ emissions (Bothwell et al., 2011). The Passive House Planning Package (PHPP) is another software package used for the study of SWI performance.

Dynamic thermal modelling software such as IES and TAS has shown good performance in building simulation applications, and they can be used for evaluation of SWI performance (Bothwell et al., 2011). However, there may be a gap between the predicted and actual performance of the building in thermal modelling; due to the inaccurate assumptions of the building envelope and temperature inside the building prior to installation, poor skills in installation of insulation, and occupant behaviour change following the insulation (BRE (Building Research Establishment), 2014). Among the primary reasons for possible differences between the building actual savings and what was estimated by modelling software, a discrepancy in U-values is the major one which will be discussed further in the following subsection.

### 2.6.1 Effect of U-value in Simulation TEST

The U-value is the key parameter for developing any building energy simulation. The common U-value assumption for solid walls were about 2.1 W/m$^2$ K in previous studies, however, there were some concerns about the overestimation; recent works proved that U-values of solid wall houses is lower than 2.1 W/m$^2$K which was generally assumed (BRE (Building Research Establishment), 2016b; Loucari et al., 2016). This overestimation can cause an unrealistic reduction in estimated $CO_2$ saving potential up to 65% (Loucari et al., 2016). It can easily mislead the government in carbon reduction targets. Further research in related topics to solid walls are needed to achieve more comparable and reliable results for the benefits of the Government, relevant retrofit industries and building users, which is important for the success and acceleration of SWI implementation.

In this concept, The Building Research Establishment (BRE) suggested a revised U-value for solid walls (BRE (Building Research Establishment), 2016b). They conducted some field works, experimental research as well as the theoretical work about thermal performance of solid walls. The research findings revealed that 2.1 W/m$^2$K for U-value of the uninsulated solid wall needs to be revised to 1.75 W/ m$^2$ K. There is also more evidence from other publications that support the reduction in U-value. For example, in another study the U value of 1.3±0.4 W/m$^2$K was recommended for both brick and stone solid walls (Li et al., 2015). This reduction in U-values could be related to the air cavities within the wall resulting from some damage to the bricks and broken bricks' mortar, lower moisture content (0.8% for brick and 2.8% for mortar instead of 5% by volume assumed for moisture content) and higher wall thicknesses than expected (BRE (Building Research Establishment), 2016b). Therefore, further research in related topics to solid walls needs to be conducted to achieve more accurate results for U-values since the current U-value recommended by Government's Reduced Data Standard Assessment Procedure (RdSAP) could be inaccurate and the difference in U-value can lead to significant over/under estimation of the saving benefits of SWI and mislead the potential of retrofit programs for solid wall houses (Loucari et al., 2016).

### 2.6.2 Current Simulation Studies about Solid Walls

Relevant simulation studies that used a numerical model to evaluate solid wall dwellings are analysed in this section. The modelling approach is advantageous from different perspectives for evaluating the effects of retrofit measures, such as SWI, on building performance as they provide detailed and timely information with a low cost before implementation. The simulation approach was therefore employed in previous studies and in general it showed that the SWI can have a substantial effect on energy consumption and $CO_2$ production (Jones et al., 2017; Moran, 2014). In a research study by Moran (2014), the predicted energy use results from different software were compared with actual energy consumption for three terraced Georgian dwellings as case study dwellings in Bath, UK. The results show that the three software of PHPP, IES and SAP software used in this study overestimate energy use compared to actual energy use. For assessing the potential of retrofit measures, PHPP was selected not based on comparison with other two software but to inform the software potential and develop architect's confidence in use of PHPP for historic buildings. The findings show that adding SWI into the underfloor insulation program (Retrofit Package 1) can increase the energy consumption reduction from 8-51% to about 44-81%. In another study called 'Retrofit for the Future', the effect of a comprehensive retrofit program including PV, LED light, efficient appliances etc. and SWI on a case study from social housing was considered. IES-VE was used to develop the simulation model and the behavioural parameters were studied. It was found that the retrofit program was very successful and provided a pleasurable thermal comfort with a low energy bill (Sunikka-Blank et al., 2012).

Banfill et al. (2012) simulated a Mechanical Ventilation with Heat Recovery (MVHR) system installed in a typical solid wall house built for research purposes. Using IES-VE software, their simulation was developed based on the survey of various household behaviours. They found that achieving a $CO_2$ emission reduction and energy savings required air permeability of below 5 $m^3/m^2h$. However, this level seems not to be pleasant for the occupant based on their survey results. In a recent study on the Salford Energy House (Ji et al., 2019a), IES-VE was used to model 3 different scenarios. At first, the model was developed by using the default and calculated infiltration rate and U-values, and a large discrepancy between simulation and experimental data was observed. A significant improvement in the model was achieved by inserting the measured specification from experiments, such as the measured U-value and infiltration rates instead of using the material default properties for one of the scenarios. However, in the other two scenarios some degree of discrepancy between the simulation and actual data was reported even when using the measured specifications in the model. This could be due to some inaccuracy in setting up the model and limitations of the software. The overall results prove that using the values from experimental measurement in setting up the model will significantly improve the accuracy of the simulation and minimise the performance gap. In the other study on the Salford Energy House (Marshall et al., 2017), the performance gap between the model and experiments and the validity of the assumptions within the model were assessed. In the electric co-heating test using the assumptions and defaults value in the model showed a difference of 18.5% representing a noticeable prediction gap between the modelled and measured data. Then the in-situ measured air permeability and U-values were input into the models and the simulation results showed a prediction gap of only 2.4% with the experimental data. Using the measured in-situ values leads to having a more accurate model for better understanding the building performance in different scenarios. In a literature review report by Building Research Establishment (BRE (Building Research Establishment), 2014), the identified difference between the predicted and actual savings of SWI can be as a result of 1) the inaccuracy of assumptions for the baseline performance of the building envelope and temperatures that the home are heated prior to the wall insulation, 2) poor workmanship in installation of the insulation and 3) occupants behaviour change following the insulation installation. In another publication by Ji et al. (2019b) the building retrofit and saving potentials on a UK typical end-terrace house (Salford Energy House) were assessed using IES-VE software. The predictions show the heating demand would reduce by more than 75% when the level of insulation improve to the similar level of Passivhaus standard requirements in the whole building. Also, assessing the future energy demand and overheating possibilities using the projected CIBSE climate data (2020 (high emission scenario), 2050 and 2080 (medium emission scenario) at 50 percentile probabilities), shows that the heating demand would be 27% less than the level currently needed as a result of global warming. Manon and Eames (2017) also used IES-VE to model a detached externally insulated solid wall house retrofitted according to the minimum 1995 building standard requirement. In this research, the IES-VE (Suncast shading data analysis) tool was employed to analyse the effectiveness of retrofitting with different glazing systems such as triple vacuum glazed windows. The predicted results based on the dynamic thermal modelling, showed better improvement for the space-heating energy and cost savings when the insulation level for the wall was upgraded to the 2010 UK Building Regulation level.

Parker et al. (2019) conducted the fabric performance tests on two ‘no fine concrete conjoined’ dwellings pre and post retrofit. The inputs and outputs of dynamic simulation models was compared with the calculated figures in SAP in the pragmatic calibration method. The results revealed a 45% improvement in HTC following the retrofits on this type of building. The method used in this research is specifically useful for retrofit programs on a large scale and could contribute towards developing an assessment method for building energy performance. In another research study (Tzortzopoulos et al., 2019), a Building Information Modelling (BIM) protocol was devised with the aim of supporting social housing owners in retrofit decision making. Three retrofit scenarios including energy efficient measures such as ESWI was proposed. Alternative technical solutions considering energy, disruption and cost were evaluated in an integrated method to identify the most effective retrofit scenario. The result of What-if analysis in S-IMPLER illustrate that scenario 1 has the best balance in all three aspects with energy saving of 49.3%, 4D disruption of 20 days and cost estimation of £12,356.

Jones et al., (2017) studied energy modelling using HTB2 linked with VirVil SketchUp software. Field measurements were used to analyse the performance of five houses retrofitted in a whole house approach. Each five retrofit plans applied to the in-use houses with different occupancy and pattern of use. Retrofit plans 1, 2, 4 and 5 included EWI in combination with other retrofit measures. The demand consumption for the house with retrofit 3 was the highest compared to the other 4 houses after the retrofit. The analysis of the five retrofitted houses illustrates the significant reductions in heating demand, imported electricity from the grid, $CO_2$, and costs with up to 56%, 84%, 50-75% and £402 to £621/year respectively. Also, the findings suggest that applying the energy measures into the building envelope at the time of the need for fabric refurbishment such as re-rendering, could lower the costs of energy improvement considerably.

In a parametric study conducted by Marincioni et. al (2015) the impact of thermal bridges on the total heat loss of a mid-terrace house with ISWI were assessed. The parameters were wall thickness, internal insulation thickness, insulation thermal conductivity and two levels of insulation at junctions. The highest total heat flux reduction of 107 $WK^{-1}$, occurred with the best combination of parameters but still similar to the results of other combinations. Overall, insulating the junctions in all cases was seen to be more effective than reducing the heat flux through thermal conductivity reduction by increasing the insulation thickness. Individual junctions and the jambs in particular, accounts for the most heat flux through junctions. The higher heat flux trough junctions were revealed in the thicker existing walls as well as the thicker wall insulation. Furthermore, it was found that the default value used in the UK for the total heat flux at junctions per unit of exposed area was smaller than the observed heat flux through junctions where it mainly occurred at reveals.

In a study conducted by Gupta and Gregg (2018), local energy use and resultant $CO_2e$ emissions were measured, modelled and mapped to understand the energy use and $CO_2$ emissions associated in communities to stimulate their reduction in a house-by house level. Their research was aiming to contribute to the prediction of existing energy demand in urban areas to enable proper future energy planning. They selected six communities of A to F to evaluate the effect of single retrofit measures or packages using the DECoRuM Mapping Tool. The results showed that the greatest reduction can be achieved through using SWI among other measures with around a 22% reduction in mean $CO_2$ emissions.

Glew et al. (2017) investigated the effectiveness of insulation coving products in reducing the risk of thermal bridging, mould growth and surface condensation in externally insulated historical solid wall properties. They assessed ten retrofit scenarios using thermal modelling software of Physibel TRISCO to find the optimum dimension for the coving. The results prove the effectiveness of insulated coving in externally insulated properties in reducing the moisture related problems in some solid walls situations and decreasing the thermal bridging in all the scenarios. The use of coving is a useful complementary product to the EWI in case of historical building with roof details and architectural features where the EWI cannot be extended fully to the roof.

Ji and Webster (2012) presented various retrofit options on a typical pre-1920s Victorian terrace house using dynamic thermal simulations. However, the model has not been validated against the experimental data and the material properties were assigned based on ‘local sources’ assumptions. The simulation results confirmed the great potential of SWIs either internally or externally in heating demand reduction. The higher amount of energy saving was related to the higher insulation thickness; However, this benefit is minor when the insulation thickness is increased to a certain level. Also, the overheating effect of EWI over the years of 2005 to 2080 using DSY weather year was assessed. The results showed that the uncomfortable internal temperatures increase as the weather gets warmer, which suggests that the dedicated space cooling methods should be utilised in the houses due to global warming.

From the simulation studies about solid walls, the importance of using the in-situ measurement for developing a reliable simulation model which perform closely with a real building was acknowledged. However, some shortcomings and limitations were also identified. In most cases, SWI was included in a retrofit package and there is a discrepancy in reported savings following the aggregated retrofit measures. Furthermore, the reported results are exclusive to the case study building and experimental conditions, and in some cases, they were not solid wall. Therefore, the current information cannot provide a clear insight about SWI benefits as a single retrofit measure. Also, it was identified that the necessity of using the in-situ measurement for developing a reliable simulation model which performs closely with a real building.

## 2.7 Cost Analysis of Solid Wall Insulation

The possible recourse of reimbursing the capital cost of SWI for householders should be through energy saving within a reasonable payback period. For any cost analysis, the amount of energy saving, and fuel costs are required. While all the cost-effectiveness estimations are subject to significant uncertainty due to the unknown future costs of the fuel, having accurate figures in potential energy savings can reduce some degree of uncertainty. The *Golden Rule*, a customer protection embedded in GD, indicates that “*the expected financial savings from the installation of energy saving measures must be equal to or greater than the costs attached to the energy bill*” (Department of Energy Climate Change, 2010). This rule is important as it ensures that the default rate balances between the expected GD customers and standard energy which helps to keep the finance costs low, and protects the GD costumers to have energy bills lower or equal to another household with no GD. In some retrofit measures such as SWI with a high capital cost, the repayment period would be around 15-25 years or longer. This means that retrofit programs require a very long payback period if the energy saving is the only way of recovering the cost (Bothwell et al., 2011). While the payback period for SWI is very long, the highest bill savings of (£200-300 pa) could be achieved compared to loft insulation and cavity wall insulation with £10-20 pa and £100-200 pa respectively (BEIS, 2017a). If all the measures of SWI, cavity wall insulation and loft insulation were applied in a dwelling, the average modelled fuel bill would potentially go down nearly 54% from an average £1,018 to £473 annually per dwelling at standard 2015 energy prices (BEIS, 2017a; Department for Communities and local Government, 2015).

SWI would not be viable under the Golden Rule, however, it is socially cost-effective with a lot of carbon reduction and energy saving potential, rather than financeable under the Golden Rule and GD. To meet the Golden Rule for SWI, subsidies from government are required in many cases (Elderkin, 2011). With the support from government, such as ECO which provides the upfront capital subsidy, and in combination with GD finance (the relative finance proportions may vary), the required funding and delivery of such measure on the large scale would be possible (Elderkin, 2011). However, there might be a behavioural mismatch in householders as not every householder prefers to have a GD loan; as they feel the loan is a barrier if they want to sell their house before finishing the finance repayment period (Weeks et al., 2015). Furthermore, it is purported that the GD was a failure (CCC (Committee on Climate Change), 2014) and other available Government finance support, such as the ECO scheme, did not enhance the installation of SWI notably so far (Oxley, 2022) as 91% of properties eligible for SWI still remained uninsulated by the end of 2021. In a study in 2015, some householders found the initial cost of some retrofitting measures such as SWI unaffordable even under the financial incentive provided through GD scheme (Weeks et al., 2015). In another study, householder participants felt reluctant to plan retrofit projects if the payback period was too long, especially in cases when they believed there was potential to move house (Massung et al., 2014).

The cost analysis of wall insulation was conducted in the literature to address the economic challenge. Ginevičius et al., (2008) considered nine main criteria for analysing the available wall insulation alternatives using multicriteria evaluation methods to find the most economical thermal insulation for their case study building.

The selected criteria have various dimensions and changes in direction meaning that when the value for some of these criteria are increasing, the situation is getting better while for some other criteria the higher values deteriorate the situation. Cost of wall insulation, warranty period, service life and time of completion were among those criteria. Possible approaches for reducing the cost of SWI over time are described in Table 2.6. This shows the key areas where the costs of the SWI market could fall, such as potential reduction of the installation cost. The cost of installation would reduce by more than half by deployment of SWI at scale (Chris, 2019; Elderkin, 2011). Offering finance packages with the lowest interest rate possible to be repaid over the time would ease meeting the Golden Rule for measures. There are also implications about future market demand and installers investment through the ECO scheme to facilitate increasing capacity and training more installers (Elderkin, 2011).

Table 2.6. Cost reduction possibilities in installing SWI, based on (Chris, 2019; Elderkin, 2011).

| | **Increasing Deployment of SWI** | **Product Innovation** |
|---|---|---|
| **External Solid Wall Insulation (ESWI)** | Installing SWI to multiple properties at the same time can reduce the costs associated with an individual property by up to 20% or more. Cost savings include sharing scaffolding and other equipment, better use of labour on site, developing solutions to common installation problems, etc. Procuring the energy components and the installation at scale could cut the costs even by half.<br>As the market for SWI grows, there would be more teams specialising in its installation throughout the country. This increased specialisation is likely to bring costs down as installers learn how to complete jobs more swiftly.<br>Economies of scale in producing and purchasing SWI would lower costs. | Currently the market supplies a variety of SWI systems for which installers need to be trained for each variant. Innovation that increases standardisation and de-skills installation would reduce training and installation costs.<br>Dry rendered panels cut installation time and are less susceptible to wet weather disruption than wet rendered panels |

| | | |
|---|---|---|
| **Internal Solid Wall Insulation (ISWI)** | Installing SWI to multiple properties at the same time can reduce the costs associated with an individual property by up to 20-25%. Cost savings include better use of labour on site, sharing equipment, developing solutions to common installation problems, etc. Procuring the energy components and the installation at scale could cut the costs even by half.<br>As the market for SWI grows, there would be more teams specialising in its installation throughout the country. This increased specialisation is likely to bring costs down as installers learn how to complete jobs more swiftly.<br>Economies of scale in producing and purchasing SWI would lower costs. | Currently the market supplies different SWI systems for which installers need to be trained. Greater standardisation/deskilling installation would reduce training and installation costs.<br>Innovations in surveying premises can reduce the time taken to install panels if they have been pre-cut to fit the required space. |

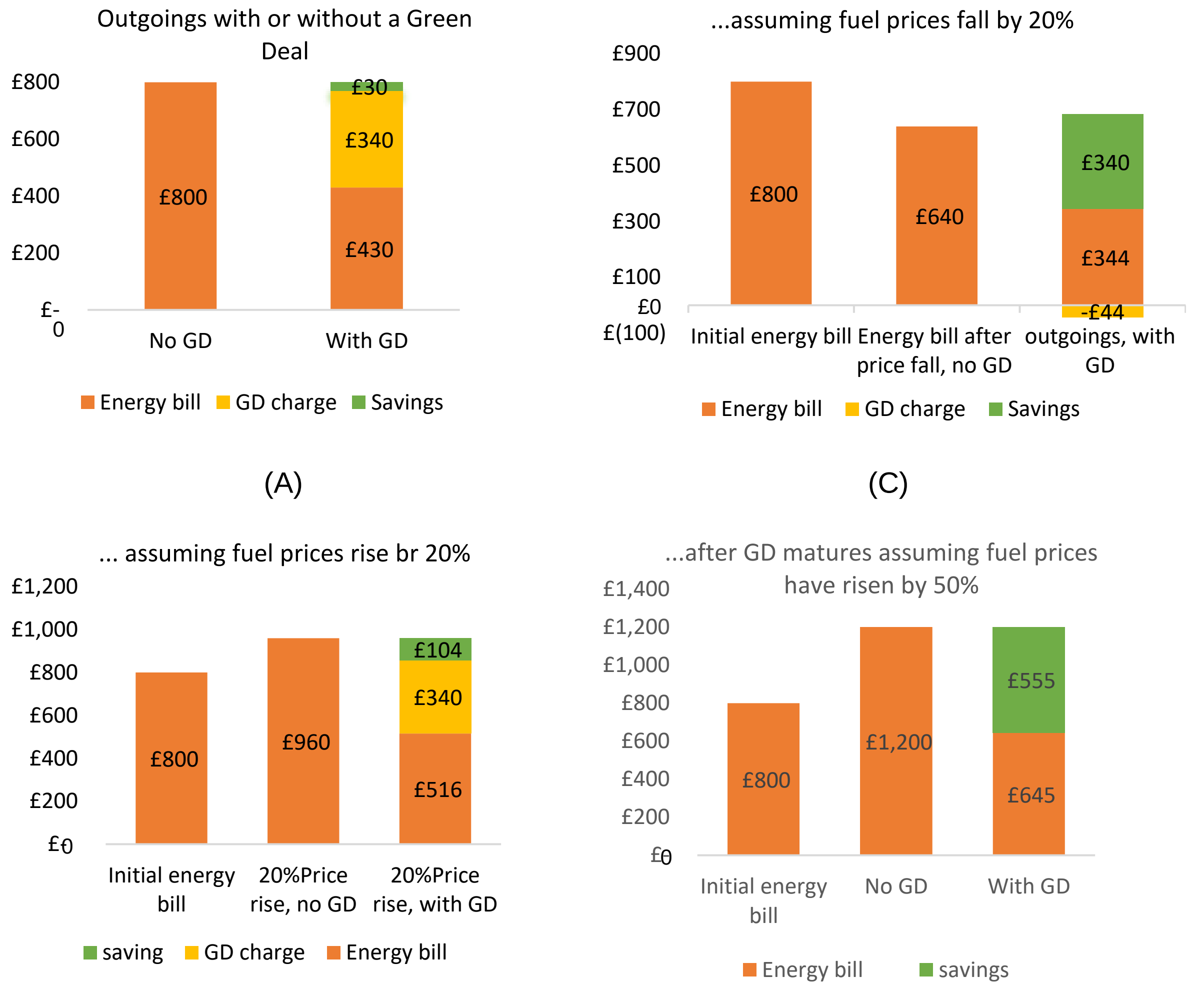
Besides cost implications, carbon reduction technologies should be aspirational and appealing for householders, who also need to feel their benefits. These aspects could become more important than the costs associated with disruption from the perspective of the householder. To achieve this, engagement of technologists and designers alongside marketing specialists for energy improvement measures is unavoidable (Vadodaria et al., 2010). Furthermore, it is essential to remember that SWI is beneficial, not only for reducing energy use and fabric heat loss, but also importantly to reduce condensation and mould incidences on internal surfaces and to improve ventilation heat loss. *Comfort* is the other benefit resulting from SWI yet there is no explicit economic value for the level of comfort from SWI (Li et al., 2015). The increased comfort is not reflected in current cost analyses and its benefit is not told in a simple quantitative method to householders (Weeks et al., 2015). Furthermore, the added value to the property following energy efficiency measures should be highlighted in the eyes of householders as a valid practical approach to minimise the resistance to energy retrofit measures (Aydin et al., 2019). Therefore, there are hidden benefits for SWI when evaluating the cost implication, and all these benefits should be considered when the cost-effectiveness of SWI is calculated.

Rosenow et al. (2014) estimated that the cost of insulating a 3-bed semi-detached solid wall house in 2014 is about £9000+5% VAT. They analysed the budgetary effects of energy efficiency programmes, focusing on the example of SWI in the UK using three subsidy options of low interest rate loans and two policies with variant degree of direct subsidy. The results show that increased revenue and savings can significantly balance the costs for schemes that fund SWI. They also studied the budgetary effects of SWI as an example of energy efficiency programmes in the UK. They recommended a two third non-repayable subsidy to be awarded to homeowners to encourage SWI in their model. Furthermore, they suggested that the fiscal impacts of energy efficiency programmes should be assessed by policy makers for better perception of energy efficiency programs, and to see the impact of such programmes on the public budget. They estimated that for each 1-million-pound investment for SWI, the NHS will save between 1% and 2% in treatment expenditures because of the better living environment provided by the retrofit program. In another study with a staged retrofit program undertaken for a solid wall dwelling located in an experimental environmental chamber (Salford Energy House), a reduction of 63% in heat loss were reported. The cost savings calculation suggested that the whole house deep retrofit would not be financially feasible if it is only supported by energy saving (W Swan et al., 2017).

Estimation of the total cost for wall insulation will depend on several factors such as the type of insulation being installed, access to wall cavities, and existing wall conditions which can affect labour pricing. However, it is estimated the maximum price of £1.90-£2.60 per square foot for 2-by-4 walls at r-13 and 2-by-6 walls at r-21 respectively in 2022. R-13 is a typical value for 2x4 stud walls. R-21 is a typical value for a 2x6 wall that has been blown with a dense packed fibreglass (Deane & Samantha, 2022). According to a Northern Ireland Government report about retrofitting dwellings (CJ Morris, 2014), ISWI and ESWI cost around £7000 and £11,200 on average, with a payback period of around 15 and 23 years respectively based on the 2013 price rate. It proves that ISWI is cheaper with a shorter payback period compared to ESWI.

McGilligan et. al (2010) studied the effect of subsidies in performance improvement of Energy Performance Certificates by decreasing the carbon emissions in the domestic sector. While subsidisation in various insulation measures such as loft insulation, cavity wall insulation and heat tank installation were found to be effective, it was found that a subsidy alone is unlikely to improve the unpopularity of other measures, especially for SWI. Opportunity cost (when there is opportunity forsaken in capital to be spent elsewhere) and long payback times (when large capital costs cannot be recouped for many years) are mentioned as possible reasons for the low uptake at low levels of subsidy. Some respondents did not like to lose internal living space by 70-120mm with

IWI. Also, inconvenience caused by some of the measures and ignoring the re-decoration costs in the subsidy and damage to new decoration already in place, were among the most important discouraging factors. In another study for the French market (Foda et al., 2020), a practical optimisation approach was performed on the range of most popular retrofit measures in France. A French family house made of solid bricks was selected as a case study and the range of retrofit measures modelled in energy plus software, including a ventilation strategy, glazing, EWI, loft insulation, ground slab construction, airtightness improvement, and heating system. A parametric analysis tool was used to calculate the costs associated with each retrofit measure in each simulation run. Optimisation was set to keep the delivered energy and costs of retrofit investment as low as possible while considering the energy saving minimum limit, payback criterion, and summer overheating-risk.



(A) (C)

(B) (D)

Figure 2.16. Energy bills and GD charges for a couple in a 3-bed semi-detached house. A) Expected outgoings immediately after taking out the GD package. B) Expected outgoings if during the GD period nominal energy prices have increased by 20%. C) Household's

combined outgoings for energy bills and the GD with 20% fall in energy prices. D) Expected savings after repayment of the GD, by nominal energy price rise of 50%, based on (Elderkin, 2011).

In a report by the UK Department of Energy and Climate Change (DECC) (Elderkin, 2011), The energy bills and GD charges for a couple in a three-bedroom semi-detached house was compared during the 10 years repayment term for both situations where they did and did not use the subsidised GD for the installation of SWI. Figure 2.16 presents the energy bills and GD charges for a couple in the 3-bed semi-detached house in four scenarios of A, B, C and D. The charts representing the couple's expenditure for energy bills and the GD charge over time depending on the rise or fall of energy prices. The nominal increases in energy price scenarios considered according to the DECC central energy price were under which the increases of 48% and 45% in prices for gas and electricity respectively in nominal domestic energy retail prices between 2011 and 2020. As the results indicated during the GD repayment period, more saving can be obtained with higher energy prices, however, negative saving was gained when the energy price falls. The great saving will be achieved upon the repayment of the GD, especially when the energy price was assumed to increase by 50%.

## 2.8 Summary, Shortcomings, and Limitations of the Literature

This chapter has presented the current state of the knowledge and analysis of the most relevant literature of SWI in the context of the UK housing energy retrofit. The primary UK Government carbon emissions target was to reduce carbon emission by at least 80% below the level of 1990 baseline with the recent amendment in the UK commitment in June 2019 to achieve the net zero emission (Waite, 2020a) in all sectors, including the building sector, by 2050 (Dowson et al., 2012; Loucari et al., 2016; UK Parliament, 2008). The UK faces a major challenge to improve the thermal performance of its existing housing stock in which currently 7.7 million of dwellings have solid walls and a further 1.75 million houses with hard-to-treat cavity wall have the highest energy consumption and emissions compared to other dwellings (Dowson et al., 2012). Controlling the heat transfer through walls can have a significant effect on energy saving and consequently $CO_2$ reduction in UK dwellings considering the large number of poor insulated houses.

As discussed, there are some advantages and disadvantages of both internal and ESWI. There are many solid wall houses with heritage value and the main concern is aesthetic preservation in those old properties that limits the application of ESWI (Moran, 2014). Cost is also a major barrier for the uptake of SWI. Government incentives and subsidies are very important since the payback period of SWI through the energy bills is very long (Weeks et al., 2015). The GD and ECO measures are in place for the financial support of energy efficiency measures, especially SWIs with a high capital cost. Although these measures have been in place from January 2013, the uptake of SWI is very slow with nearly 9% of solid wall houses insulated before the start of 2022 (Oxley, 2022). The progress of ISWI is far lower than ESWI (Oxley, 2020b), although it is cheaper to implement (CJ Morris, 2014), have shorter payback period and can lead to more saving benefits compared to ESWI (Loucari et al., 2016), (Brannigan & Booth, 2013; Loucari et al., 2016).) This could be because of space reduction of ISWI and difficulties around redecorating the home following wall insulation (Brannigan & Booth, 2013). Therefore, motivation is needed to encourage householders to engage in energy retrofit and minimise the existing barriers to improve efficiency of their homes.

These benefits should be the householder's aspirations to perform SWI. The alarming reality shows that the measures currently in place have not worked properly, and this area needs rethinking and reviewing. Novel solutions are required to compensate the cost of SWI. To realise the full benefits of SWI, engagement of technologists and designers alongside marketing specialists for energy improvement measures are unavoidable (Vadodaria et al., 2010). Regardless of cost implications, there are other beneficial aspects of SWI such as a reduction of energy consumption, emissions, fabric heat loss and an improvement in ventilation heat loss all in favour of the climate emergency. Also, there are some indirect cost benefits which are neglected by the cost calculations of SWI, such as added value to the property following the energy retrofit. Moreover, the economic value of condensation and mould reduction on internal surfaces and improving the thermal comfort are not recognised, which can result in health care treatment savings due to the improvement of occupants' living condition.

There is a contradiction in the literature about the actual potential of energy saving mainly because of the U-value estimations. SWI was proved to be the most effective solution to reduce energy use and emissions from these houses and the resultant energy saving of 60%-80% was reported for energy retrofit packages including SWI in the literature (Byrne et al., 2016; Innovate, 2016; Loucari et al., 2016; W Swan et al., 2017). U-value is the key parameter for developing energy saving estimations, and there are uncertainties about the U-values of solid wall properties in the literature which can cause the under/over estimation of SWI performance (BRE (Building Research Establishment), 2016b; Loucari et al., 2016). This discrepancy can easily lead to a miscalculation of the carbon reduction potential and mislead the zero-emission target. The common U-value assumption for solid wall houses were about 2.1 W/m$^2$K in previous studies, however, there were some concerns about the overestimation. Recent work has proved that U-values of solid wall houses should be lower than 2.1 W/m$^2$K, which was generally assumed (BRE (Building Research Establishment), 2016b; Loucari et al., 2016). This overestimation can cause a significant unrealistic estimation in the energy saving and $CO_2$ saving potential (Loucari et al., 2016). The Building Research Establishment (BRE) suggested a revised U-value for solid walls (BRE (Building Research Establishment), 2016b). They conducted field works, experimental research as well as the theoretical work about thermal performance of solid walls. Their results revealed that 2.1 W/m$^2$K for U-values of the uninsulated solid wall needs to be revised to 1.75 W/ m2 K. However, this revised U-value still contradicts some studies in the literature. For example, in one of the studies about the importance of U-value (Li et al., 2015), the uncertainty of the energy performance estimation was observed due to the variation in U-value assumption for solid walls. The results of this study for 40 brick solid walls and 18 stone dwellings revealed that the wall mean U-values were in the range of 1.3 ± 0.4 W/m$^2$K, which was significantly different from 2.1 W/m$^2$K given initially in the guidelines (BRE (Building Research Establishment), 2012; CIBSE, 2006) as well as the revised value of 1.75 W/m2K suggested by BRE. This variation in U-values was the other driving force for developing the energy assessment phase of this study to quantify the potential energy savings and $CO_2$ reduction of SWI more clearly for a range of U-values obtained from literature

Furthermore, it was identified from the literature review that using the in-situ measured building specifications required in the modelling helps in developing a reliable model which operates with a minimum performance gap compared to actual case study buildings (Ji et al., 2019a; Marshall et al., 2017). Therefore, using the in-situ measurement in the simulation modelling provides reliable simulation results and this was the motivation to choose the Salford Energy House (SEH) as a case study building where the required data of the case study for accurate modelling is partly available within previous published journal papers and/or can be accessible to be measured on site.

The energy renovation has been evaluated to understand the effectiveness of energy measures in terms of energy saving, emissions reduction and financial savings when the existing building envelope were properly upgraded. However, the accurate energy saving potential of SWI still needs to be addressed by experiments and in-situ measures for a better understanding of the achievable energy saving in practice (Gillich et al., 2019). Furthermore, providing the instructions for energy use for occupants is necessary to achieve expected savings after applying energy retrofit measures (Hardy et al., 2018). The number of scientific journal and conference publications are limited in this area in the literature and the majority of data are specific to a single wall U-value (Brannigan & Booth, 2013; Loucari et al., 2016; Marshall et al., 2017). Also, the results presented in the existing studies related to energy improvements are mainly the aggregated effects of different measures in which wall insulation was included in the retrofit package (Byrne et al., 2016; Innovate, 2016; Loucari et al., 2016; Sunikka-Blank et al., 2012; W Swan et al., 2017), and most didn’t look at the solid wall properties. Furthermore, the potential saving result of SWI are sometimes influenced by the experimental conditions such as occupant behaviour and weather variations. Therefore, the developed results can provide a general picture of SWI benefits. They cannot deliver comparable critical data for SWI benefits as a reference for the UK government, relevant industries, and building users. This is the identified gap and shortcoming of current undertaken studies in the field. This can be due to the complexity and cost of experiments as well as challenges for running accurate models which need reliable experimental data under controlled conditions. Therefore, there is a need to quantify the energy saving potential attributed to the installation of SWI alone. Achieving such accurate quantitative analysis will present the expected potential benefits of SWI more realistically. This study intends to contribute towards covering this gap by contributing to highlight more realistic saving benefits of SWI as a single retrofit measure, which can be referred to and used by relevant stakeholders. Therefore, the first phase of this research will focus on addressing this gap by delivering a precise analysis of potential energy savings by SWI for variety of solid brick walls.

# Chapter 3: Occupants’ attitudes and aesthetics preferences for housing retrofit

Householders play a critical role in the uptake of SWI, as alteration to the property is made only with the householder’s desire or decision. Therefore, in this chapter, the current literature on retrofit from occupants’ point of view is discussed and critically analysed in order to identify the shortcomings and a viable strategy to promote SWI installations in uninsulated properties. A critical review of current literature is conducted for the relevant topics. The difficulties in energy efficient retrofit of solid wall dwellings are discussed in Section 3.1. The occupant attitude for retrofitting programs is reviewed in detail in Section 3.2. The demand of the energy retrofit market derived from the literature for this research is presented in Section 3.3. Finally, Section 3.4, summarises the current state of knowledge discussed in this chapter and provides recommendations for relevant stakeholders.

## 3.1 Difficulties in Energy Efficient Retrofit of Solid Wall Dwellings

There are a variety of policies and technical reasons which discourages the demand for SWI. Therefore, to encourage the retrofit solution of SWI, the barriers for its application need to be resolved urgently (Hansford, 2015). As was previously discussed, overheating is one of the concerns of SWI. However, there are unintended consequences of SWI, such as moisture related risks including mould, damp, rot, and air quality which was highlighted in some publications (BRE (Building Research Establishment), 2014, 2016a; William Swan et al., 2017). They can happen in some cases where the building fabric has not been appropriately assessed prior to deployment of SWI. There are several examples of poor and inadequate installation of SWI with incorrect installation methods affecting SWI reputation and performance (Fylan & Glew, 2021; Hansford, 2015). The effect of poor installation was consistently highlighted in the literature which indicated that the actual savings achieved were far less than what was predicted (BRE (Building Research Establishment), 2014). Large capital costs and long payback period, disruption and inconvenience of implementation, indeterminate time frame of renovation work, efforts for obtaining planning permission in case of external insulation, space reduction and wall redecorating (fixtures or fittings) within the property in case of IWI and the psychological aspects of human motivation are viewed as significant hurdles for SWI (Brannigan & Booth, 2013). All these issues were highlighted in the market in a way that the positive effect of SWI is likely to be neglected.

Government policy in terms of SWI seems to have some inconsistencies, which results in misunderstandings and confusion for homeowners (Hansford, 2015; Putnam & Brown, 2021). Because of the rent cap formula in England, some social landlords faced restrictions to adjust rents to see an acceptable financial return to invest in SWI measures. However, this is not the case for Wales as different rent formulae have been used (Hansford, 2015). Planning authorities by facilitating the development rights can impact on selecting the right solution for the right type of property for consistency of their application across the UK. This can help to avoid delays in retrofit procedures and frustration for landlords and homeowners (Moran, 2014). Likewise, there is a lack of investment of industries in this area resulting from the start-stop nature of policies and funding schemes (Hansford, 2015). There are different types of properties consisting of so many archetypes with no clear consistent retrofit solution that can be applied to each property type. This will add to the complexity of the subject and confusion of householders to decide which solution is the best for their individual dwelling (Hansford, 2015). For example, the historic and listed buildings in conservation areas have limited potential for improving the energy consumption and carbon reduction technologies because of aesthetic considerations (Moorhouse & Littlewood, 2012).

The market failures and barriers to energy efficiency measures such as SWI result in reducing the take up of measures. There is more motivation in deployment of heating and energy efficiency measures for households classed as low income and vulnerable (BEIS, 2018; Elderkin, 2011). Government intervention based on these rationales is necessary to meet the carbon budgets cost-effectively, deploy the key technologies such as SWI for long term mitigation targets and have fewer households in fuel poverty which would reduce the dependency of the UK on importing fossil fuel (Elderkin, 2011). Homeowners may hesitate to choose SWI as they are uncertain about the cost and benefit implications. To reassure the customers about performance, some measures such as a helpline, Home Performance Labelling and/or installing smart meters displaying the benefits to occupants can be considered (Hansford, 2015). There are limited performance data for retrofitted SWI properties to report the real performance of its application with the correct technical measures. Performance data increases the awareness of customers about SWI benefits as well as industry motivation to provide product systems with the optimum performance rather than relying on laboratory test results (Hansford, 2015).

Another imperceptible challenge in energy improvement, which is less documented but seems to be fundamental is that of users of solid wall dwellings as decision-makers for renovation of their own homes. The barriers that seem to discourage householders from retrofitting their premises could be summarised under three main themes of finance, information, and decision making (Massung et al., 2014; Weeks et al., 2015; Wilson et al., 2014). The breakdown of core barriers that householders face for retrofitting are shown in Table 3.1. In the persona-driven study by Haines et al. (Haines & Mitchell, 2014), seven evidenced personas for solid wall dwelling occupants were identified, with each type having varying behaviours and attitudes that drive motivations for home improvement. The results suggest that the design of energy retrofit measures for such properties should meet everyday requirements and personal preferences. Very little categorisation of UK home energy improvers was identified in the literature (Zhang et al., 2012) despite the diversity of the population with a variety of motivations and barriers to home improvement. Further studies are needed to provide more insights about occupants' personalities and their desires for home energy improvement which can direct developers and designers toward solutions that meet individual needs.

In a consumer survey published by DECC (Elderkin, 2011), the results indicate that if assessors and installers were skilled and regulated, a high proportion of consumers (70%) would be more likely to choose GD. Convincing information about the effectiveness of energy efficiency measures was another factor, which 45% of the respondents indicated to be important to make their home energy efficient. This is due to the small market for SWI which leads to having a smaller network of trusted advice for consumers to get information and raise their awareness. However, this barrier will be less important once the take-up of SWI grows. As an interim solution, offering consumer protection measures alongside government plans, such as GD and ECO, should help some reluctant householders to better engage in energy efficiency plans (Elderkin, 2011).

Table 3.1. The energy efficiency gap: Barriers to energy efficient renovations, partially based on (Weeks et al., 2015) and other relevant studies (Aydin et al., 2019; Brannigan & Booth, 2013; BRE (Building Research Establishment), 2014; Elsharkawy & Rutherford, 2018; Hansford, 2015; Hardy et al., 2018; Li et al., 2015; Moran, 2014; Putnam & Brown, 2021; Rosenow et al., 2014).

| | **Barrier** | **Description of Barrier** |
|---|---|---|
| **Finance** | Upfront cost & capital availability | High capital cost<br>Aversion to delayed gains (high implicit discount rates) |
| | Split incentives | Investor & beneficiary are different (e.g., owner-tenant) |
| | Neglecting indirect cost benefits | No explicit economic value still assigned to<br>• Added value to the property<br>• Health care treatment savings due to improvement of living conditions following energy retrofit |
| **Information** | Less emphasised positive awareness | Ignoring the beneficial aspects following energy measure such as:<br>• Thermal comfort improvement<br>• Tackle climate emergency by reduction of emissions, energy consumption, fabric heat loss |
| | Lack of information | Imperfect or biased knowledge of energy costs<br>Lack of awareness of potential energy savings<br>Lack of instruction for energy use after applying energy measures to achieve expected saving |
| | Low or misperceived salience | Invisibility of energy use and/ or efficiency measures (e.g., cavity wall insulation)<br>Low % cost of household budget<br>Misperceptions of high and low energy using appliances |
| | Social invisibility | Weakly supporting social norms<br>Weak social signalling / comparison |
| | Uncertainty (trust)/ Contractor risk | Contractor credibility<br>Unknown quality of work<br>Unknown performance outcomes |
| | Uncertainty (outcomes) | Unknown future energy savings or energy prices<br>Unknown comfort or health effects<br>(Related to high implicit discount rates-see under finance) |

| | | |
|---|---|---|
| **Decision making** | Opportunity costs | Crowding out of higher quality decisions (e.g., amenity renovations) |
| | Cognitive burden | High transaction cost of information search<br>Complexity of decision (information processing) |
| | Hassle factor | Anticipated disruption to domestic life from renovation work and time frame uncertainty<br>Perceived stress, hassle inconvenience of renovation work |
| | Irreversibility | Irreversible investments, cannot be trailed<br>Loss of option value |
| | Aesthetic concerns especially for SWI | Losing the aesthetical and historical features of the property<br>Damage to fixtures, fittings and decorations exists or invested by tenants<br>Lack of aesthetic features in energy retrofit |
| **Lack of user-centred Policies** | Householders' confusion | Ambiguity on selecting the correct path for energy renovation, i.e., using companies, contractors, DIY, etc.<br>Uncertainty in achieving the expected savings |
| | Policies awareness | lack of effective publicising the policies and supports<br>Complexity of policies that are not easily understood by the public |
| | Lack of support for householders | Building usage instructions after renovation<br>Absence of support for individual for identifying, understanding, and applying the available financial supports |

As discussed, the decision-making process for SWI can be complex. The householders' path towards doing energy renovation should be clear. The majority of householders directly contact the craftsmen who are not professionals for the renovation task. They feel it is an unnecessary service to pay for seeking information or advice from an energy adviser or energy-related architect. There are different reports about inadequate suggestions or installation quality that come from such interventions (Abreu et al., 2017; Hansford, 2015). With this view, craftsmen can be a barrier for energy retrofit because they lack knowledge when they suggest building renovation solutions, while intermediaries who are up to date with information related to energy efficiency technology can have a positive influence on the diffusion of energy retrofit measures (Zaunbrecher et al., 2021). Selecting the wrong path in decision making towards energy retrofit, i.e., employing the craftsmen instead of professionals, results in depressing the effectiveness and reputation of energy measures and stopping the uptake of some energy measures (Abreu et al., 2017). This section shows that barriers still exist for energy efficiency renovation. Those barriers should be addressed in any future retrofit strategies and policies to ensure their success.

## 3.2 The Occupant’s Attitude about Retrofitting

### 3.2.1 Renovation from the user’s perspective

The adoption of renovation measures is dependent on some social and individual variables such as aesthetics, convenience, comfort, social support and comparison, heritage values, time and money among others (Gram-Hanssen et al., 2007; Sunikka-Blank & Galvin, 2016). Householders motivated to renovation by a combination of personal and circumstantial reasons find their satisfaction in giving a new look to the old living space, in statues or by changing the lifestyle, and even emulate their neighbours, friends or family for the same solutions they have. Householders influence renovation uptake as they are responsible for their homes, and any renovation can be done only with their desire or decision (Abreu et al., 2017). However, their decision depends on both quantitative basis and qualitative preferences (Risholt & Berker, 2013) not only to know the cost implications or saving benefits but also to be satisfied with how their home looks after renovation.

Apart from cost and energy consumption reduction, Gram-Hanssen (2014) presented other driving parameters for renovation, such as comfort improvement, wear and tear maintenance, and having more fashionable spaces. Peng (2013) generalised the concept and categorised the reason for retrofit to *functional needs* and *lifestyle pursuits*. Homeowners require specific personal capacity before starting a retrofit project since the idea of renovation is exciting for some people while it is the source of anxiety for others (Earl & Peng, 2011; Haines & Mitchell, 2014). Although it is impractical to provide bespoke solutions for retrofitting programmes for the whole population, identification of needs for groups of similar people does provide a valuable approach and a possible way forward (Haines & Mitchell, 2014).

Figure 3.1 shows the four main reasons for renovating by occupants (Gram-Hanssen, 2014). As can be seen, homeowners may be interested in the actual renovation job (project) or the renovation result (product), or they may do the renovation for necessity for repair (wear and tear) or to have something new (lifestyle). A comprehensive renovation may not be possible in a single renovation job and it is not the source of concern for many householders (Abreu et al., 2017). Homeowners often have a to-do-dream-renovations list, but due to availability of time, money or other resources, and difficulties of renovation while they are living in the house, some renovations are carried out due to the priorities and others are postponed. The energy efficient renovation rate so far is too slow compared to indoor renovations with no energy related benefit as this seems to be a higher priority for householders (Gram-Hanssen, 2014). Looking at the renovation from the householder's perspective helps to understand and implement the drivers to enhance energy related renovations (Ebrahimigharehbaghi et al., 2019; Judson & Maller, 2014; Killip et al., 2014).

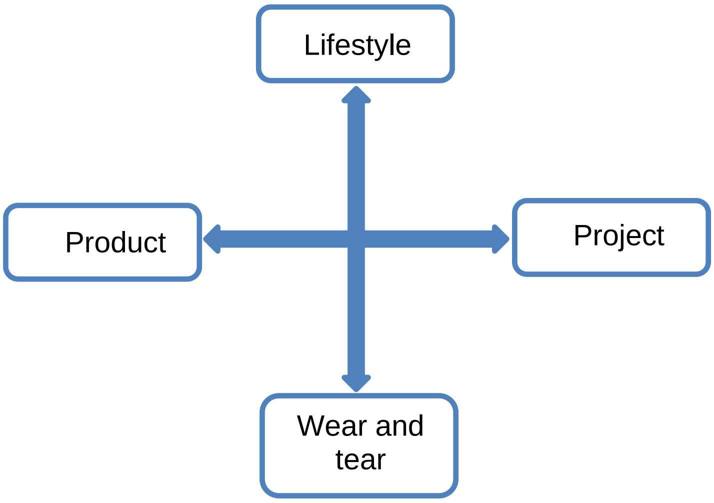


Figure 3.1. Reasons for renovating (Gram-Hanssen, 2014).

Energy efficient renovations should be considered as part of the home improvement as households engage with it routinely during their lifetime occupancy (Wilson et al., 2015). Householders' quality improvement priorities in home renovation assists in developing successful energy renovation policies in a human based approach to include the qualitative preference of the households which controls their renovation choices (Abreu et al., 2017; Risholt et al., 2013). In fact, it seems vital to consider the non-energy benefits as well as the energy benefits in future research (Abreu et al., 2017). Social context and technical expert solutions should be explored more to be the focus of energy related renovation in developing policies (Gram-Hanssen, 2014). Whilst regulatory control is commonly used to compel or induce greater effort, encouraging voluntary commitments is believed to be more cost effective in dealing with environmental problems and building energy efficiency (Lee & Yik, 2004). In Lee and Yik (2004) study, the voluntary-based approaches proved to be more effective compared to mandatory approaches because they offer flexible, practical and more cost-effective solutions leading to more investment on energy efficient buildings by the private sector. Therefore, both the energy efficiency renovation and home improvement should be considered in renovations of UK homes in the future.

There are factors (e.g., cost, payback times, aesthetics, and comfort) influencing the participants' willingness to adopt each of the specific renovation technologies. Any technological intervention should be acceptable to occupants and aligned with their lifestyle expectations (Hewitt, 2012). Non-energy benefits were found to be motivating and promote the decisions to take up energy efficient retrofit from a consumer perspective (Mills & Rosenfeld, 1996). Greater recognition of non-energy benefits and intelligent use of them in energy-efficient technologies would help the retrofit market by increasing the householders' interest in retrofit. The user-centred design concept and importance of the occupant as the key player can bring the idea of making the house homely and not only a warmer place to live for planning any SWI retrofit. This means that the methods that reflect the occupants' taste, such as aesthetic needs, can promote and encourage the use of SWI and contribute to energy reduction strategies.

Abreu et al. (2017) studied householders' motivations, needs, attitudes, and daily routines to investigate how these can influence the decision-making process for energy building renovation. The results show that renovation works are usually done step by step along the building occupancy lifetime by householders. Normally, the indoors is the first priority in renovation activities, which was a strong motivation by occupant desire as some of their preferred renovation works do not pay back. Also, improving the aesthetic and functionality of the home and building repair are priorities in renovation activities compared with solutions that save energy, even when there is no payback or potential savings to be achieved. The non-energy renovation desires, for improving indoor space for example, could be integrated with energy efficient technologies to trigger and further motivate householders to engage in energy renovation more effectively.

### 3.2.2 User-centred Design Approach to Energy Demand Reduction

Energy consumption reduction in buildings is not only a technical and economical challenge but it is a social problem (Chang & Zhao, 2019). Building users play a critical role in the decision-making process for both energy renovation and energy use during the building life-time occupancy and the important role of the occupants, for example in Portugal, has not been considered in the policies (Abreu et al., 2017). Occupant attitude and their concerns about energy consumption are playing a key factor in developing any retrofit programme (Moran, 2014; Moran et al., 2012). Except for financial support for the cost of energy efficiency measures, occupants as users of the buildings in the domestic sector and their needs were rarely considered in energy demand reduction strategies and policies (Haines, 2014). Increasing the new policies with a focus on the social dimension of renovation is essential, and policy measures should respect the role of householders in renovation processes (Abreu et al., 2017). It is important to understand the effect of qualitative information about users' experiences, values, and practices related to UK domestic energy demand reduction, and incorporate them into engineering-focused energy research (Haines, 2014). This involves a socio-technical approach to identify the occupant preferences and satisfaction. It can also provide additional insight and understanding of the users' needs in designing energy reduction strategies by engineers.

The changing nature of society is affecting energy demand. In some studies, the user requirements in energy demand were investigated and it was demonstrated that design, technology, and energy management systems can help each other to control the increasing demand (Loveday et al., 2008). To meet the requirements of users, a proper plan focusing on the user during the design process is required, which needs to be revised and followed iteratively (Haines & Mitchell, 2013). User-centred design is a process, which includes the context of user and user requirements. In this approach, the user should be considered before, during, and after the design process by consultation about the product or service that is going to be delivered (Haines & Mitchell, 2014; Kujala & Kauppinen, 2004). It is challenging for designers and technology developers considering the diverse market these days since it requires research about users and their needs and provides continues feedback for the designers based on user demand. In the user-centred design concept, the creative design considering the technical and economic constraints is not everything because the focus of the design is on the people for whom the design is intended (Giacomin, 2014). In this method, understanding the motivations, values, and attitudes of the user is essential. The principal of involving users in the design process for user-centred design is defined based on BS EN ISO 9241-210: 2010 standard, recommending six main features (Giacomin, 2014):

- The adoption of multidisciplinary skills and perspectives
- Explicit understanding of users, tasks, and environments
- User-centred evaluation driven/refined design
- Consideration of the whole user experience
- Involvement of users throughout design and development
- Iterative process

The user-centred designed concept for SWI was highlighted in the CALEBRE project, (2008-2013) funded by both the Research Councils UK Energy Programme and E.ON (Vadodaria et al., 2010). The aim of this project was to establish a validated comprehensive mechanism for reducing UK domestic carbon emissions within solid walled housing that is acceptable and appealing to users. This focus on user acceptability and appeal required a specific user-centred approach, which can integrate user requirements into an otherwise largely engineering-driven project. However, this includes barriers for technology developers for the adoption of energy-saving measures, which demonstrates the range of non-technical challenges. There are the range of social barriers to the adoption of domestic energy demand reduction, and it is vital to understand these barriers in detail if future technology development and implementation are to be successful (Eames et al., 2014). It is important to engage the occupants as the key players in any energy retrofit programme (Vadodaria et al., 2010). As part of CALEBRE project, interview-based research was developed to understand the motivation factors for home improvement (Haines et al., 2012). Most of the reasons for home alteration by participants were related to cost reduction and achieving more pleasant living conditions, while they rarely declared energy as a motivator for their home improvements.

In a study conducted by the Energy Saving Trust (Prince, 2014) and the Scottish Government’s ISM (individual, social and material) behaviour change was investigated to understand why limited households installed SWI despite its proven effectiveness in energy savings and $CO_2$ reduction. The ISM behaviour change tool examined various factors (such as beliefs, cost and benefits, emotions, agency, and habit) may influence the householders’ attitudes to SWI. It helps to understand the required changes for desired behaviour of householders to a situation where they are more likely to install insulation. The households’ key motivations, perceptions of barriers, and experience of installation was extracted to promote SWI. It was found that positive messages and information about SWI would help to spark more interest towards its application. Deploying community groups as trusted sources in the local communities were recommended for promoting SWI. Offering good communication, quality of workmanship, clear timetables for the installation process was emphasised in enhancing the customers’ positive experiences. Furthermore, financial benefits and financial support should be advertised as the cost is deemed the biggest barrier in SWI application. However, warmth was more important than energy and bill savings, especially during retirement and increasing warmth is an opportunity to benefit.

As demonstrated, decision making by householders is an important process in taking up the energy retrofit which happens over time. Any ambitious retrofit plan requires a major decision, and it can be successful only if the right advice is available for the householder (Economidou et al., 2011). Weeks et. al (2015) evaluated how Information Communication Technology (ICT) can be used to help remove the barriers and enhance the drivers during the householder’s critical decision period of having energy efficiency measures installed. The findings suggest that ICT can help to encourage retrofitting in some recommended areas such as comfort, renovation, initial cost of high price items, and resignation. Zaunbrecher et al. (2021) studied the effect of intermediaries on the diffusion of energy retrofit measures and householders retrofit decisions. Craftspeople, architects, and energy advisors were interviewed about their personal views and experiences on retrofitting process. The results showed the positive influence of intermediaries on the diffusion of energy efficiency measures as their advice was almost always followed by their clients. This confirms their importance in increasing energy efficiency implementation, but there is a risk that intermediaries personal convictions hinder certain energy retrofit measures and they need continuous training to keep up with recent developments and innovations in the energy efficiency market.

Moreover, the public’s positive actions in enhancing the thermal performance and energy and carbon emission reduction are undeniable. Hawas and Al-Habaibeh (2020) studied the effect of the training process, with low-cost infrared thermal cameras to enable thermal performance evaluations of homes by users in order to encourage them to take corrective actions. Their studies involved 50 people surveying their homes to find technical issues and feedback on their personal experience of this approach. Their results showed that thermal imaging was a convincing tool for about 84% of the participants to think more seriously about improving the heat losses from their homes. Also, 88% of the participants stated that the educational sessions were helpful to understand the infrared thermography and 92% of participants believed that the thermal camera was an effective tool to identify the location of insulation defects and helped about 90% of participants to find them in their homes.

Many efforts were made to encourage and improve the occupants' role in the retrofitting of their buildings. Massung et al. (2014), for example, developed a smartphone application to help householders in decision-making process about retrofitting. This app was a technology as part of a supporting framework and was designed to work in conjunction with an open home event to help overcome the barriers and encourage the householders to adopt the energy retrofitting measures, while also helping the organisation track the event's impact. Also, they interviewed environmentally motivated participants who have not retrofitted their home to understand the barriers to the uptake of retrofitting. The findings of this research suggested that having the retrofitting smartphone app, not only may help retrofitting to seem like a normal home improvement, but also provides a platform for retrofitting to make it visible in the local community. This app harnesses the power of technology to put intention into action, while it did not make changes to the householder's behaviour, which most ICT technologies aimed for. In other research, Oliveira et al. (2019) studied the expected benefits and anticipated challenges of introducing smart home technology as a key opportunity to reduce the levels of energy demand into housing stock. The users' experiences of using the technology after a year was compared with pre-use experience. It was found that some of the users had concerns regarding the reliability, usability, and the way the new system would fit in their existing routines. The users' experience after a year showed some of the concerns and challenges had disappeared, while other issues arose. Understanding the user experience would help the technology development for existing homes to improve the functional, instrumental, and socio-technical benefits.

### 3.2.3 Aesthetic Features and its Potential Contribution towards Energy Efficiency

Aesthetics can be defined as the philosophical concept of beauty linked to emotion (Yaran, 2016). It can be perceived even by infants, which proves the existence of a common instinctual aesthetic appreciation. Experimental studies were conducted and validate these statements (Langlois et al., 1991; Langlois et al., 1990) in which infants' preferences to attractiveness were observed. Although aesthetic preference is a subjective matter some studies showed that aesthetic preferences can change gradually through learning based on the cultural transmission, (Langlois et al., 1991; Langlois et al., 1990) and aesthetic decisions may be contingent on social or cultural factors (Stamps III, 1999). The existence of a common aesthetic appreciation among adults in different demographic categories was reported in 107 relevant references (Stamps III, 1999). A psychological framework of aesthetic experience, including a five-stage perceptual process analyses for the object of aesthetic interest, implicit memory integration, explicit classification, cognitive mastering, and evaluation, was proposed by Leder et al. (2004). Aesthetic judgement happens following the understanding of object ambiguity, while aesthetic emotion may be observed as a result of continuous and satisfactory affective evaluation through the five process stages (Reimann, Zaichkowsky, et al., 2010).

Aesthetic features as a hedonic motivational influence on individuals and society. It affects the level of satisfaction and happiness (da Luz Reis & Dias Lay, 2010; Parkinson et al., 2013) in individuals, which has the ability to improve the market (Hauge et al., 2011; Parkinson et al., 2013). Aesthetic was considered in the industry in different fields, and it is important especially for marketing purposes. Industrial designers, car manufacturers, building designers, product developers and jewellery designers are paying exceptional attention to aesthetics (Chang et al., 2007; Chapman & Larkham, 1992; Wannarumon et al., 2008). Nevertheless, this aspect seems to be neglected in energy efficient material production and marketing. To enhance the energy efficiency measures application in society and to combat the barriers, this issue should be looked at from a different perspective. Energy efficiency measures, being a high-priced item and one-off decision, should follow the purchase of *big-ticket* items, such as car manufacture, jewellery, or luxury holidays. These industries provide the possibility for their clients to customise, visualise, and read information about different features and combinations and even save the customised product online so when they visit the local branch store, they already know the customer preferences (BMW; Massung et al., 2014). Positive aesthetics, novelty, and overall user experience for the new technology, such as the hedonic aspects in smartphones, were reported to be high in initial user's experiences (Karapanos et al., 2009; Kujala et al., 2011; Oliveira et al., 2019).

In this study, aesthetics is considered in terms of its influence on the occupants' preference, and whether this can persuade people to apply and invest in IWI in their houses. Aesthetics is therefore a term used in reference to the provision of interior materials and finishes that would possibly be included in an overall product or strategy for IWI. It is therefore not the aim of this study to include personal taste or cultural related preferences or choices.

In some energy building research studies, aesthetics was highlighted as an important factor in the design elements of the buildings. The aesthetical features were considered in enhancing the products for rooftop, facade and windows in building integrated photovoltaic (BIPV) technology to give the aesthetical modern appearance to the building (Shukla et al., 2017). Aesthetical impact of such solar energy system installations, due to the positive landscape transmission, was leading to growing the interest for this technology (Sánchez-Pantoja et al., 2018). Aesthetics was considered as a signature of the building when it comes to building facades (Bueno & Özceylan, 2019). In a publication about building façades (Pahlavan et al., 2019), aesthetical patterns of high-rise residential buildings were studied and the effect of building facades on urban aesthetics was evaluated. In another study (Mondini et al., 2020), three roof types of green, reverse, and waterproofed roofs were assessed according to their effects on the aesthetic, economic, and social aspects using the Life Cycle Assessment (LCA) and Multi-Criteria Decision Analysis (MCDA) tools. In this study, the green roof showed overall high performance compared to other roofs, especially in aesthetic performance and social issues.

Recently, the user-centred approach with the goal of energy consumption and $CO_2$ reductions started to look at the energy efficiency technologies from users' point of view and considering their needs. As highlighted by Haines and Mitchell (2014), achieving aesthetic was indicated as a factor to apply ESWI by some of the persona categories in their research. Therefore, achieving aesthetic after ESWI is expected by some of persona categories, and meeting their aesthetic desire can stimulate people to engage in the SWI process (see Table 3.2). In another study (Weeks et al., 2015) semi structured interviews were carried out with participants in the decision process to deploy energy efficient retrofit to their households. It was found that improving the aesthetic features of the property is a motive for retrofitting for participants (Pelenur, 2014; Weeks et al., 2015), while concerns about losing the existing aesthetic feature was understood to be one of the barriers to retrofitting.

Table 3.2. Possible impacts on aesthetic requirements of EWI as a renovation measure (Haines & Mitchell, 2014).

| Persona type | Implications for Policy and technology design acording to persona requirements from EWI |
|---|---|
| **The Idealist Restorer** | It must be possible for EWI to be ftted without losing architectural or aesthetic features of the property |
| **TheAffluent Service Seeker** | EWI must be available in a range of quality fnishes to ensure the look of the property is not compromised |
| **The Pragmatist: Subtype Functional** | Appeal to this type of persona, EWI will need to be provided as a complete package, perhaps including redecoration to complete the job, under a project manager who guarantees the quality and time completion of the work |
| **The Pragmatist: Subtype Aesthetic** | The Aesthetic Pragmatist will want EWI that looks smart and performs well, but will focus more on value for money than the traditional appearance of the finish |

Aesthetics is a powerful desire in householders to start the renovation (Hauge et al., 2011). Improving the aesthetics, trusted company or brand, social influences, increased comfort, subsidies, discounts and potential financial savings are among the retrofitting drivers mentioned in the literature (Mills & Rosenfeld, 1996; Pelenur, 2014; Weeks et al., 2015). In the literature, non-energy benefits such as aesthetics and lifestyle were the main reasons for building renovation work during the occupancy lifetime (Abreu et al., 2017; Haines et al., 2012; Mills & Rosenfeld, 1996). Householders are motivated to non-energy retrofit by aspiration, related to aesthetics, a new lifestyle, status, or prestige, to achieve pleasant living conditions. They may do non-energy related renovation several times during their occupancy to keep the living spaces condition up to their desired individual and social needs. Such interventions are driven only by desire as there is no payback or savings achievable (Abreu et al., 2017). In some renovations, the aesthetics aspect is pre-eminent for the process to begin, and it may lead to an additional benefit of energy related interventions while it was not included in the main initial goal for renovation (Abreu et al., 2017; Gram-Hanssen, 2014). It was stated in another study that some renovations are happening because of aesthetical desire when householders compare their house with what is in catalogues or what their friends and family have (Gram-Hanssen & Bech-Danielsen, 2004). Some householders report that doing the renovation was because their neighbours were motivating them, and such desired interventions happen without any argument related to financial factors (Abreu et al., 2017). The result of a survey by Gram-Hanseen (2014) showed that the number of renovations which included indoor aesthetics and functions improvement were higher than renovations which might save energy.

Aesthetic features have not been given enough consideration in the design of energy efficient buildings, despite its important role in renovation motivation. It was reported broadly in the literature that most of the technological energy efficient measures are not aesthetically pleasing (Buckley & Logan, 2016; Hoffman & Henn, 2008; Ryghaug & Sørensen, 2009). The unappealing aesthetic of energy efficient building products are due to applicability problem of integrated design approach. Current strategies are engineering discipline dominant, which mainly focusses on the energy efficiency of the products. However, current efforts of a single discipline are insufficient, and a balance and harmony between different disciplines to contribute to the integrated design approach and to reduce the building sector's energy demand is needed (Aydin et al., 2019). In a study by Buckley and Logan (2016), 86% of the 1000 participants from 13 different countries believed that energy efficient buildings are not appealing aesthetically. In other study architects from Norway indicated that energy efficient technologies are aesthetically ugly (Ryghaug & Sørensen, 2009). The term of "*unappealing aesthetic*" was indicated by buyers of energy efficient buildings in the US (Hoffman & Henn, 2008). Aesthetics has been noted in very limited research studies about building energy efficiency. Similarly, the lack of research in this area was highlighted in previous publications (Aydin et al., 2019; Hauge et al., 2011). However, some research studies advised the necessity of demonstrating both non-energy benefits and energy benefits together in future related research (Abreu et al., 2017; Gram-Hanssen, 2014). The few documented studies related to both aesthetic and energy efficiency (but not on SWI or using aesthetic for triggering the building energy retrofit) are reviewed below:

- In the CALEBRE project, a four-year study about efficient technologies for improving the energy performance of solid wall houses, it was recommended that the soft factors, such as aesthetics, lifestyle and life events should be considered to make energy efficient measures appealing to house owners (Haines et al., 2012). An example of replacing or repairing windows as part of the home improvement was selected and the detailed findings from householder interviews was reported. The finding revealed that 'appealing to customers' was one of the characteristics and 'consumer appealing vacuum glazing system' have to be aesthetically pleasing to the householders. In this study, a requirement tree of Consumer Appealing Windows was developed based on the information extracted from the interviews using the Microsoft Visio.

- In another study (Sunikka-Blank & Galvin, 2016) to address the reluctancy of home owners to compromise traditional or aesthetically pleasing features for the sake of thermal efficiency, the qualitative interviews was carried out about retrofitting from householders of such homes in Cambridge, UK. The results revealed that it was challenging for homeowners to balance between the aesthetic concerns and thermal issues, as they have their own logic in what happens in retrofitting. Aesthetic convictions influenced significantly the retrofitting decision, as well as the heritage embodied in these houses, which is among the reasons that current retrofitting policies are not always effective.
- Corrao (2018) represented an advantage for both the aesthetic and energy features of translucent façades by introducing a patented innovative Integrated Photovoltaic (BIPV) component. The main peculiarities of this innovative product are aesthetic, efficiency, safety, $CO_2$ reduction, maintenance, and assembly costs. It enables the designers and builders involved in renovation or building construction to optimise the building component's energy performance by enhancing their aesthetics at competitive costs. The mechanical tests carried out on prototypes confirmed its functionality and the possibility of using this product in the safe and efficient construction of the building envelope in high-rise buildings.
- Habibi et al. (2019) developed a new concept for re-roofing, addressing thermal insulation, waterproofing and electricity generation while considering the aesthetic features. They concluded that the roof systems should be properly detailed and designed for any refurbishment programme for energy improvement purposes. Their proposed roof system with PV panels was claimed to have significant impact in terms of cost, energy, environment, and social benefits.
- A novel approach of increasing the energy efficiency market in buildings through enhancement of their aesthetical features for reducing the energy demand in the building sector was investigated by Aydin et al. (2019). Real-estate agencies across 26 cities in the UK participated in a comprehensive survey to contribute to the development of more effective strategies and policies related to energy efficient buildings. As part of this research and proposed multidisciplinary approach in the

UK, they investigated the aesthetic enhancement effect on better marketability. Their survey was related to the external attractive appearance of the building, window properties and the energy efficiency of the building, and the results were analysed using the statistical model via IBM SPSS. The results show that the added value to the property by aesthetics was around 7% added value for a property worth £200,000, three times more than energy efficiency measures and almost two times more than window properties. Also, there was strong agreement between participants in different levels that aesthetical appearance and house price are similarly the most significant influential parameter in the buyer decision-making process by 99.6% and 100% response rate.

- Kermanshahi et al. (2020) developed a survey study using the Likert Scale from a range of 0 for ‘not considered’ to 5 for ‘very important’ to understand the household priorities and preferences in terms of the retrofit measures and materials. They found that windows and doors were the top priority for energy performance improvements among the participants. Moreover, they found that aesthetics, payback cost period, and energy-efficiency are the most important reasons for the energy retrofit, while aesthetics was ranked slightly higher at the top.
- Tsirigoti et al. (2021) proposed an intervention strategy at the urban block scale in order to achieve both energy efficiency and improvement of the aesthetic quality in the city in Greece. They examined two different urban blocks’ typologies with four scenarios for renovation interventions based on energy and aesthetic criteria. The findings of the research proved that passive solar and shading strategies are important on improvement of both energy efficiency and the city aesthetic.
- Olusoga and Adegun (2022) developed a survey study to understand the perception of built environment professionals about the benefits as well as the limiting factors of Vertical Greening Systems (VGSs) in Nigeria. An online questionnaire was used to evaluate the socio-demographic variables, knowledge of VGSs, its benefits (including aesthetics) and impediments to the use of VGS. From their results of their five-point Likert scale questionnaire, there was general agreement among the professionals about the aesthetic benefits of the Vertical Greening Systems.
- Ke et al. (2022) designed the first tetra-fish-mimetic window to meet both energy-saving and aesthetic demands. The glasses are coated with photonic co-doped

vanadium dioxides to resemble the beautiful skin of tetra fishes that display vivid colours with changes in their appearances when being viewed from different angles. The results show acceptable solar modulation properties with decent energy performance of up to ~ 35.9 kWh/m$^2$ annual energy savings for a typical office building in representative cities in the Asia Pacific.

Comparing between building internal and external aesthetic features, research indicated that internal aesthetics is more important than external (da Luz Reis & Dias Lay, 2010). The internal and external aesthetics investigations on 12 houses sold to low-income people in Brazil, showed that 70% of participants found their building's external aesthetics was unappealing, while only 10% were dissatisfied with their property's internal aesthetics (Aydin et al., 2019). These results well demonstrate that people paid more attention to internal aesthetics compared to external aesthetics as inside is the space that they are living with, and it might be the reason for the majority of people who did not invest on their building exterior because it is the second priority. Also, as the time passes, more and more internal structural alterations happen inside the old homes such as stripping of floorboards or changing the fireplace, however, some of these would change the historical value of the internal space following this modernisation activity (Bridge, 2001).

The aesthetic solutions were confirmed to be an ambition of people in renovation without any expectations for financial support or savings (Abreu et al., 2017). As discussed in the literature, considering the aesthetic can help the stakeholders to make rational decisions about using low and zero carbon technologies such as SWI in retrofitting programs (Moran, 2014). The policy measures should be adjusted considering the realities in renovation, and new and innovative approaches should be employed to include aesthetic features within the refurbishment policies for UK existing homes. The role of architects and designers to apply their professional expertise towards improving the energy efficiency of buildings seems vital to help develop the industry in conjunction with user's desires, such as aesthetical requirements.

### 3.2.4 Economic Justifications of Aesthetics in the Energy Efficiency Market

Aesthetic sensibility applications are significantly configured across all of the different social and economic activities in modern societies (Miele & Murdoch, 2002). 'Aestheticisation' refers to reshaping the postmodern world where in reality is furnished by aesthetic elements (Welsch, 1996). To some extent, aesthetic values and concerns have become intrinsic to '*lifestyle creation'* in aestheticisation as a new cultural component (Miele & Murdoch, 2002). An "*aesthetic judgment",* introduced by Kant (Ginsborg, 2005), is a feeling-based judgment, and in particular relates to pleasure or displeasure feelings. He was especially aiming to define those feeling-based judgments in which an object is found to be beautiful, and then to show that we are entitled to make such judgments despite being unable to verify them (Ginsborg, 2005). *'Aesthetic experience'* can be objective or subjective. The difference is that the subjective sense of beautiful refers to the subjective experience alone while the objective sense of beautiful refers to the property itself in the object that causes the experience (Neil Van, 2006). The aesthetic component of everyday activity was called "*practical aesthetics"* by Gagnier (2000) and he distinguished a zone of economic life which retains a non-instrumental or intrinsic value of its own and cannot be included within economic modes of calculation or evaluation (Miele & Murdoch, 2002).

'*Utility*' has been the fundamental concept in economics theory for a long time to include desire. Utility is broadly synonymous with 'satisfaction,' 'well-being,' 'welfare,' 'happiness,' 'pleasure,' etc. Generally, people can increase their utility by doing enjoyable activities or purchasing things that they desire (Kapteyn, 1985). One would expect that, in making decisions, an individual will try to enhance his utility. In economic models of behaviour, it is invariably assumed that an individual behaves in such a way that his utility is maximised (Kapteyn, 1985). Thus, an individual's behaviour is completely determined by two things in economic models: his preferences, represented by an ordinal utility function, and the constraints that limit his behaviour (Kapteyn, 1985). If a researcher knows these constraints, he can employ observations on the individual's behaviour to draw conclusions about the individual's preferences (Kapteyn, 1985). According to consumer theory proposed by Lancaster, it is not a commodity itself but its attributes that determine its utility. Utility is therefore a function of attributes of the goods (Lancaster, 1966). Tradition of the political economy of art, known as "*culture and society*" tradition, assumes that if only aesthetics and economics could be harmonised, the world would have to be or would become an ethically better place (Gagnier, 2000).

It is purported that design and aesthetics are the two main differentiating attributes that significantly influence customers' preferences and choice of goods (Reimann, Zaichkowsky, et al., 2010; Zolli, 2004). Aesthetic importance is therefore growing in the market and aesthetic products are designed and marketed to satisfy the most basic needs of consumers. Quality and functionality as core product attributes, are getting increasingly similar and would require distinctiveness for marketing purpose (Reimann, Schilke, et al., 2010). Firms are moving towards less tangible features such as aesthetics from their differentiation efforts in concrete product characteristics (Brunner et al., 2008). For effective promotion of the products, the aesthetic attributes are important for sustainability of the developed products (Zafarmand et al., 2003). Aesthetic products are "*public or mixed goods of specific interest";* they are seen as 'different' by non-active consumers. Specific aesthetic natures in cultural goods market result in production, consumption, and collective decision-making functions (Mossetto, 2013).

Also, in the building sector market, the aesthetic preferences are the basis of decision making. Hedonic stimuli were seen to have a priority in marketing strategies compared to utilitarian motivations. Hedonic and utilitarian motivations are both the main driver of a client when purchasing a dwelling (Aydin et al., 2019). However, the hedonic stimuli trigger the crucial positive reactions in consumers, such as tendencies and willingness to pay the higher price, to attribute more emotional value to the product and create an irresistible urge to rushed possession (Reimann, Zaichkowsky, et al., 2010). More importantly, products may lose their appeal when functional utility is the only feature to be considered in the purchasing, while products with aesthetic qualities are still appreciated long after the functional value fades (Martin, 1998). Aesthetic features as a hedonic motivation play a crucial role on the marketability of products and especially should benefit the energy efficiency technology market (Aydin et al., 2019). Aesthetics affects the marketability of the energy efficient buildings highlighted among the market success in the literature (Haavik & Aabrekk, 2007).

Added value to the property or estate is another economic benefit of aesthetic features in buildings. It was confirmed in the literature that potential added value to the property through the aesthetics feature is very high compared to other alterations (Aydin et al., 2019). In another example, the UK rental value of an energy efficient workplace is associated more with aesthetics features rather than energy efficiency features (Parkinson et al., 2013). The US office buildings were reported to have rented and sold by 7% and 17% higher respectively as a result of having better aesthetical features (Fuerst et al., 2011). Aesthetics quality of the exterior increases the value of neighbouring buildings, and it was confirmed in an empirical analysis on 5000 homes prices in New Zealand, showing that more than one third additional value can be achieved from attractive neighbouring buildings (Bourassa et al., 2004).

Also, there are some economic benefits for energy efficiency of buildings in the market. In a study by Adan and Fuerst (2018), it was highlighted that there is a negative relationship between energy efficiency rating and time-on-market for properties. There was some evidence to show that more energy efficient dwellings are, the more quickly they tend to be leased. In another study (Aydin et al., 2019), it was reported that energy efficiency measures can increase the value of properties worth £200,000 by around 3%, however, this figure was higher for aesthetic features with around a 7% increase in property’s value. Most importantly, a reduction of energy consumption and fuel poverty in dwellings leads to lower energy bills and financial savings beside the benefit of achieving comfort and emission reduction.

A practical and economical approach is to have both aesthetic and energy features in buildings to not only maximise the economical added value to the building following a renovation (Aydin et al., 2019), but also, for more householders to be motivated to have the energy measures installed in their dwellings which helps towards the UK decarbonisation target. The energy efficiency technology market should move towards developing aesthetic products to enhance the energy performance of buildings, provide more added value to the properties and possibly provide the time and cost-efficient approach in a single renovation process as two features of energy efficiency and aesthetics are integrated in a product. This approach would unlock the demand and flourish the market following the investment in this promising strategy which leads to a significant economic value in the society (see Section 3.3). Furthermore, this approach helps to lift the negative barriers of energy efficient measures in dwellings, such as high initial costs compared to the low market added value, and not being the householder’s priority renovation. This should be possible by achieving higher market value with aesthetic features included, leading to raise the worth of energy efficient building in eyes of owners to bring forward the energy efficiency measures in their renovation priority list, and to have energy efficient measures installed in more and more homes in the UK. As a building does not use energy but people do, designers should work closely with people to deliver attractive energy reduction for building users (Janda, 2011). Despite the vital role of aesthetics and design in this process, this area was less addressed in the literature and this concept could be used to resolve the economic concerns of SWI and unlock the energy saving benefits.

## 3.3 Demand of Energy Efficiency Market

A question that arose from the presented literature review was how to increase SWI applications in people's homes when energy efficiency seems not to be their priority? According to the literature, the most powerful solution to reduce energy consumption in the existing UK stock, especially in solid wall houses, is SWI with a very high remaining potential, i.e., around 91% of the total houses eligible for SWI are yet to be insulated. However, it is essential to unlock the demand for SWI to improve the energy efficiency of existing housing stock. There is a need to make things easy for retrofitting where householders face less frustration and complexity (Massung et al., 2014). The cost of SWI is one of the important factors in energy efficiency retrofit, in which some financial support was provided through the Government for homeowners. However, IWI may be financially more feasible because it is cheaper than EWI by about 37% as reported in the literature (CJ Morris, 2014). From the user's point of view, retrofitting a house is only do-able when they just purchased a property and where they are renovating it (Massung et al., 2014) and people usually do non-energy renovation in their houses a couple of times during their residency. Internal home improvement was purported to have the priority in the householder's renovation list, and in most cases, they are happy to invest for aesthetical reasons. Home improvement is a voluntary approach taking place by householders, where they redecorate the walls, floors or change the furniture to raise the internal aesthetic features and cleanliness to achieve more pleasant living conditions (Haines et al., 2012). Currently, energy retrofit is seen as a separate matter from home improvement (Wilson et al., 2014) and this leads to the lack of uptake in retrofitting (Massung et al., 2014). There is a need for non-energy renovation measures driven by an aesthetics desire to include energy efficiency in their measures; or vice versa, the energy efficiency technology should include the aesthetical preferences of the householders in their products to encourage the uptake of energy renovation.

There is a lack of research on aesthetic aspects of the energy efficient buildings (Abreu et al., 2017; Hauge et al., 2011) and both energy benefits and non-energy benefits should be considered in renovations (Abreu et al., 2017). The cases of poor installations of SWIs by unprofessional craftsmen decreased the effectiveness of SWI and depressed the market (Abreu et al., 2017). The solutions in energy efficiency technology should include comprehensive packages for quality, delivering the measure into the customers home to remove or minimise the problems currently associated with the way energy efficiency is serving the market.

To address all the points above, the aesthetic feature can be included in SWI products to make energy efficient measures appealing to house owners (Haines et al., 2012), specifically in internal insulation as internal aesthetic is more of the priority for householders compared to building exterior (Aydin et al., 2019). The aesthetic aspects of IWI can be the customer’s favourite pattern from the variety of available decorative material such as wallpaper, paint with aesthetical effects or even more complicated decorative designs for a specific wall based on functionality. The aesthetic features could also be embedded onto the wall insulation material to have an integrated product in large or small panels for the use in modular design, or it can be applied after installation of the insulation by the same installers when they have all the finishes with aesthetic patterns ready for quick fixing. Creating an Internal Aesthetic Wall Insulation (IAWI) product can be a promising approach to flourish the energy efficiency technology market and overcome some of the existing barriers for SWI (see Section 3.1). If such products can be used and publicised in the market, householders are more likely to be encouraged to use them in their mainstream/routine home improvement to not only achieve the main renovation goal of the new aesthetical look in their living spaces, but also enhance the energy efficiency of their houses. In fact, with buying one product, they benefit from two characteristics of aesthetic and energy efficiency which can be achieved in a single renovation task. Also, improving the aesthetic and energy efficiency of property can lead to higher added value to the property (Aydin et al., 2019). This is currently seeming missing according to the literature review and building energy market as the current energy efficient product are ugly and unappealing (Ryghaug & Sørensen, 2009; Hoffman & Henn, 2008). This would be an effective and beneficial solution to reduce energy use in the housing stock, achieve more added value to the property following the renovation, improve the living space with aesthetical features for constant householder’s ambitions and save time and money for renovation by embedding the home improvement and retrofit in one single process.

Successful policies should be strongly consumer focused in their design and implementation (CCC (Committee on Climate Change), 2016a). Policy stability and sustained funding, targeting policies at times when consumers are considering renovation, gaining consumer trust, minimising the hassle and complexity for consumers, and having effective communication and marketing, are among the common success factors in policy design and implementation (CCC (Committee on Climate Change), 2016a). However, the policies in support of SWI have not been very successful so far, as is evident by the slow progress of SWI implementation (see Section 2.3) and a revolution in retrofit policies is needed to become successful for solid wall houses. Furthermore, the decision-making process for retrofit is a complicated task for householders. This process can be simplified through innovative collaboration and centralising the retrofit with an OSS (one-stop-shop) business model to provide an integrated retrofit co-ordinated by a single actor, as suggested for energy efficiency renovation in Swedish houses (Pardalis, 2021). This strategy can also be employed in SWI, where both energy goals and householders' preferences are addressed by one professional organisation. Such organisations should deal with customers from the starting point, when they are in the decision process, up to the end of the renovation. It would help to gain customers trust to perform the energy renovation professionally and remove the depressed reputation of SWI. The poor installation of SWI by unprofessional craftsmen was one of the barriers which decreases the effectiveness of SWI, and depresses the market (Abreu et al., 2017). A solution in energy efficiency technology should include a comprehensive package delivered by professional organisations to minimise the challenges currently associated with energy retrofit for customers. The organisations could possibly even provide a warranty or maintenance service over a time frame for customers to feel supported even after the renovation and to increase the appeal of the whole house retrofit (Brown et al., 2018). This idea would make the process easy and clear with less complexity for consumers to deal with a trusted licenced organisation to do their renovation task with the ability to increase the energy efficiency of their homes. Such renovation organisations can offer a comprehensive package to the customers in the ideal scenario. The package services should include the following services for householders:

- The relevant information about the energy enhancement and renovation process increase householders awareness about renovation (Hawas & Al-Habaibeh, 2020).
- Service and maintenance offer for their products as an incentive where possible to gain customers' trust (CCC (Committee on Climate Change), 2016a).

- The clear time frame and costs associated with the renovation job and expected added value (Aydin et al., 2019).
- The guidance for government financial subsidies or other incentives for the renovation if the householders are interested (Hansford, 2015; Putnam & Brown, 2021).
- The professional installers who have the relevant qualifications for the renovation job or provide training for installers to obtain the standard qualification for installation (Fylan & Glew, 2021; Zaunbrecher et al., 2021).
- Firm commitment and responsibility for the renovation job by providing high-quality customer service in all stages of the process, warranty and maintenance for quality of the job (Brown et al., 2018).

It is recommended that Government related bodies also review the performance of these organisations routinely, for continuous improvement and ensuring that the progress targets are met. Providing financial support for such organisations by the Government would be significantly beneficial to IAWI implementation progress. In a recent study by Putnam and Brown (Putnam & Brown, 2021), the community-led business model is found to be more effective than the government retrofit approach, it is also suggested that large scale retrofit would not be possible without government involvement and financial support. It can help the IAWI to be implemented exclusively with reasonable prices in a comprehensive package leading to achieving customer satisfaction and the UK carbon target for SWI. Performing wall insulation mainly through such organisations can help to reduce the installation costs considerably and improve the reputation of SWI. It is highlighted in the literature that procuring the energy components for each house and the installation at scale could cut the costs by half (Chris, 2019; Elderkin, 2011). Further cost reductions can be achieved because wall decorating installation will take place at the same time of insulation with the same organisation. Implementing the SWI and aesthetic wall improvements through relevant organisations can be efficient in terms of time and cost practicably with mass installation of renovation tasks by trained installers and with less hidden costs (Chris, 2019; Elderkin, 2011).

One of the greatest challenges in product development is creating a form that is aesthetically attractive to the intended market audience (Orsborn et al., 2009). The consumer aesthetic preferences should be well communicated with the product designer to make sure the final product is satisfying for the consumer. This can be more successful when the communication between the designer and consumers takes place effectively (Stevens, 2013) to understand the gaps in the existing products and consumers' wills leading to improvement. The engineering culture should support these changes to embed such strategies in practice (Petre, 2004). Besides the aesthetically appealing prefabricated products, to attract the customers during the design process the organisation can offer appropriate re-decoration aesthetic packages based on customer desire for the internal space where the insulation installation process leads to dismissing the existing aesthetic feature of the space. The feasibility of including the post service offer such as warranty and maintenance can also be considered and offered to support the householders (Brown et al., 2018). While some research has already started to look at the design process and its important effect on decision making (Stevens, 2013), more research is still required to find the best approach in understanding the customers' aesthetic preferences and implement them in the production market. There is a need for evaluating the novel idea of IAWI, as employing the aesthetic features for promoting SWI has not been studied in literature.

## 3.4 Summary, Shortcomings, and Limitations of the Literature

This chapter has presented a detailed literature survey to propose the theory of aesthetic inclusion for the uptake of ISWI in the UK. Different studies and reports were analysed to establish an overall conceptual framework for the importance of user centred design in retrofit. Also, the research background about the role of aesthetics on users' renovation preferences was established, and the theory of aesthetic inclusion in SWI to increase its popularity was brought forward.

Reviewing the literature showed that apart from cost, there are other barriers in the energy efficient retrofit of solid wall dwellings which slowed down the uptake of SWI, influenced the reputation of SWI and caused uncertainty for householders. Some of the barriers indicated as negative aspects of SWI in the literature are: poor installation with unprofessional installers resulting in not achieving the expected saving benefits and affected the SWI reputation (BRE (Building Research Establishment), 2014; Fylan & Glew, 2021), living space reduction in the case of IWI (Brannigan & Booth, 2013), lack of awareness of SWI saving benefits and householders confusion, lack of householder awareness of policies and available grants or incentives due to the inconsistency and complexity of the Government policies (Hansford, 2015; Putnam & Brown, 2021), the small market of SWI, and lack of support for householders in decision making for SWI and finding the correct path for energy renovation and lack of instruction for energy use after retrofit to achieve expected saving (Hardy et al., 2018). Moreover, losing aesthetical and historical features of property especially following EWI (Moorhouse & Littlewood, 2012), and damage to aesthetic features of internal space in case of IWI, such as fixtures, fittings and decorations (Brannigan & Booth, 2013), householders' low interest in SWI and lack of aesthetic features in energy retrofit measures in general (Buckley & Logan, 2016; Hoffman & Henn, 2008), lack of user-cantered policies to support householders for SWI and neglecting the positive consequences of SWI such as improving thermal comfort, added value to the property (Aydin et al., 2019) (see Table 3.1).

Building users are the key players in undertaking any energy retrofit programme, while they have been mostly neglected in the past. The user-centred design should be reflected in the policies to reduce the concerns and challenges of renovation for householders and to facilitate their renovation decision making. Moreover, in some studies (Abreu et al., 2017; Haines et al., 2012; Mills & Rosenfeld, 1996) non-energy benefits such as aesthetic and lifestyle improvement were the main reasons for building renovation work during the occupancy lifetime (Abreu et al., 2017; Mills & Rosenfeld, 1996). The householders do these non-energy renovations voluntarily at their own cost without any financial subsidy or incentives (Haines et al., 2012). Homeowners are more engaged in renovations to achieve aesthetic improvements rather than renovations to upgrade energy efficiency (Bravo et al., 2019). Householders participate in non-energy renovation work to achieve pleasant living conditions and sometimes they carry out non-energy benefit renovations a number of times during the building's lifetime. However, when it comes to energy renovations, the adoption of energy measures faces massive challenges and the uptake of some of these energy measures, such as SWI, has been very slow. On the other hand, for energy renovation the common argument is about the potential financial savings and payback period for householders (Weeks et al., 2015), whereas their desire motivated non-energy renovations are carried out without grants or possible savings (Haines et al., 2012). This opportunity can be extended to energy retrofitting, as in most cases householders are reluctant to do renovation only because of the energy improvement and behave as if energy efficiency is not the priority in their homes. It should be evaluated to understand if they are ready to improve the energy efficiency of their homes at the time that normal (non-energy) renovation work is taking place (CCC (Committee on Climate Change), 2016a; Massung et al., 2014). Understanding the householders' motivations for self-oriented non-energy renovation work and smart use of it may improve the energy efficient technology market and integrate the energy and non-energy renovation as one comprehensive package which not only meets the quantitative energy benefits but also the householders' qualitative preferences.

SWI is currently more important to scientists and government rather than the householders. The reluctance among householders has resulted in a failure of exploiting the potential of SWI and new motivations are needed to encourage the householders towards SWI in a way that match with their desire. There are several documented studies to investigate the behaviour of householders and finding the barriers to suggest the drivers to energy retrofit renovations to increase the uptake of energy efficiency measures. The literature suggests that there is a need for an innovative approach to increase the uptake and attractiveness of SWI (Hansford, 2015), however, a practical solution wasn't recommended. Aesthetic features were seen to be an important renovation driver for householders and the need for considering this subject for energy retrofit was highlighted in literature (Aydin et al., 2019; Hauge et al., 2011) but there are few studies related to both aesthetic and energy efficiency on subjects other than SWI. Furthermore, people pay more attention to internal aesthetics compared to external aesthetics (Aydin et al., 2019). Therefore, this research is going to evaluate aesthetic effect on people's perceptions and behaviour towards ISWI as a solution to promote the energy efficiency of existing houses in the second phase of this research. Nonetheless, to date, there is no study to evaluate the impact of aesthetics on ISWI and its promotion and this gap will be the focus of the second part of this research.

# Chapter 4: Methodology

This chapter outlines the research design (Section 4.1), concept map (Section 4.2), research tools (Section 4.3) and combination of energy assessment and aesthetic evaluation (Section 4.4).

## 4.1 Research Design

Design Science Research (DSR) aims at developing solutions that solve practical problems and provides a contribution to the associated theoretical knowledge (Holmström et al., 2009). The innovative solution, called *artefact*, is usually developed in cycles of evaluation and redesign (van Aken et al., 2016). The artefact may include constructs, models, methods, and instantiations (March & Smith, 1995). This research adopts DSR to evaluate the integration of aesthetic aspects in ISWI as a solution to promote its uptake in improving the energy efficiency of existing stock in the UK. Following the literature review, a suite of study tools was developed to achieve the aims and objectives of this research. The body of the works that have been published to date in the literature cannot clearly reveal the actual potential of energy savings and $CO_2$ emission reduction of wall insulation. An accurate energy analysis was developed first to establish the position of SWI from an energy perspective. Then, the aesthetic role in the promotion of SWI is evaluated.

This research is quantitative research, in which the first phase includes an analysis of energy benefits with a case study building, a typical Victorian solid wall house in the UK, the Salford Energy House (SEH), using experimental and simulation approaches. The experimental data was acquired, and IES-VE software was used to develop a validated model for the first phase of this research. The results from this part of the research provides a decent estimation of energy consumption of typical solid wall houses in the UK, and potential energy savings that can be achieved by SWI measures. Following on, in the second phase of this research, a quantitative (multiple choice question) survey is employed using an online questionnaire tool to evaluate the role of aesthetic features and its potential to enhance the application of IWI in solid wall houses in the UK. The findings from the second part of the research would support the initial part as this investigates the potential for aesthetic features to trigger the promotion of SWI implementation in the UK. These two parts form the basis of this study.

The methodology of this research is summarised in two main phases in the following consequent steps:

Phase 1-Energy assessment:

- Reviewing the literature about SWI and its energy performance to identify the criteria for selecting the case study building, obtain the relevant parameters required for modelling and development of a reliable simulation model.
- Identifying a solid wall house as a case study building (SEH).
- Obtaining suitable performance experimental data for SEH.
- Evaluating the energy performance of the SEH experimentally for the duration of experiments.
- Data preparation for inputting into the IES-VE model, such as U-values and AP, heating profile and construction specifications, weather file and other required information for developing the model from experimental data.
- Developing a simulated model of SEH using the input data in IES-VE software.
- Preparing the experimental data of temperature and energy consumption in comparable format of IES-VE output results.
- Validating the IES-VE model against experimental data.
- Assessing the energy performance of the SEH case study (with baseline uninsulated solid wall U-value of 1.56 W/m²K) for a period of one year through the simulation of validated model of SEH with Manchester weather file input.
- Alteration of the baseline uninsulated solid wall U-values between 0.64 W/m²K to 2.48 W/m²K for uninsulated solid brick walls as suggested in the literature (Caroline Rye and Cameron Scott, 2012).

- Running the simulation to obtain energy consumption and $CO_2$ emission from the model for each baseline wall U-value ranging from 0.64 W/m²K to 2.48 W/m²K.
- Selecting the ISWI material and input its specifications for all IES-VE models with different baseline wall U-values as above.
- Running the model simulation for improved AP of 10 $m^3/m^2h$ and 6 $m^3/m^2h$ after wall insulation as reported in the literature (Stevens et al., 2013).
- Analysing the energy improvement and $CO_2$ emission reduction and cost savings for insulated solid brick walls by comparing the insulated and non-insulated models in each case.
- Evaluating inside temperature changes for the range of below 18°C, thermal comfort range (18 °C to 23 °C) and above 23°C following the ISWI.

Phase 2-Aesthetic evaluation:

- Review the literature relevant to this study to extract the information required for developing the questionnaire.
- Develop the questionnaire required for the survey study to assess the participants' view on the aesthetics features of the internal living spaces and its potential effect on motivating the participants toward ISWI.
- Select the target group of respondents who are suitable and approachable for participating in this study.
- Piloting the developed questionnaire and improve the questionnaire based on received feedback.
- Obtain the ethics approval for the research.
- Conduct the survey using Bristol Online Survey tool.
- Analyse the results of the survey by using SPSS software.
- Understand the role of aesthetic features and its potential in promoting SWI.

## 4.2 Concept Map of the Methodology

Figure 4.1 below shows the schematic diagram for the methodology of this work which will be discussed in more detail in the following sections.

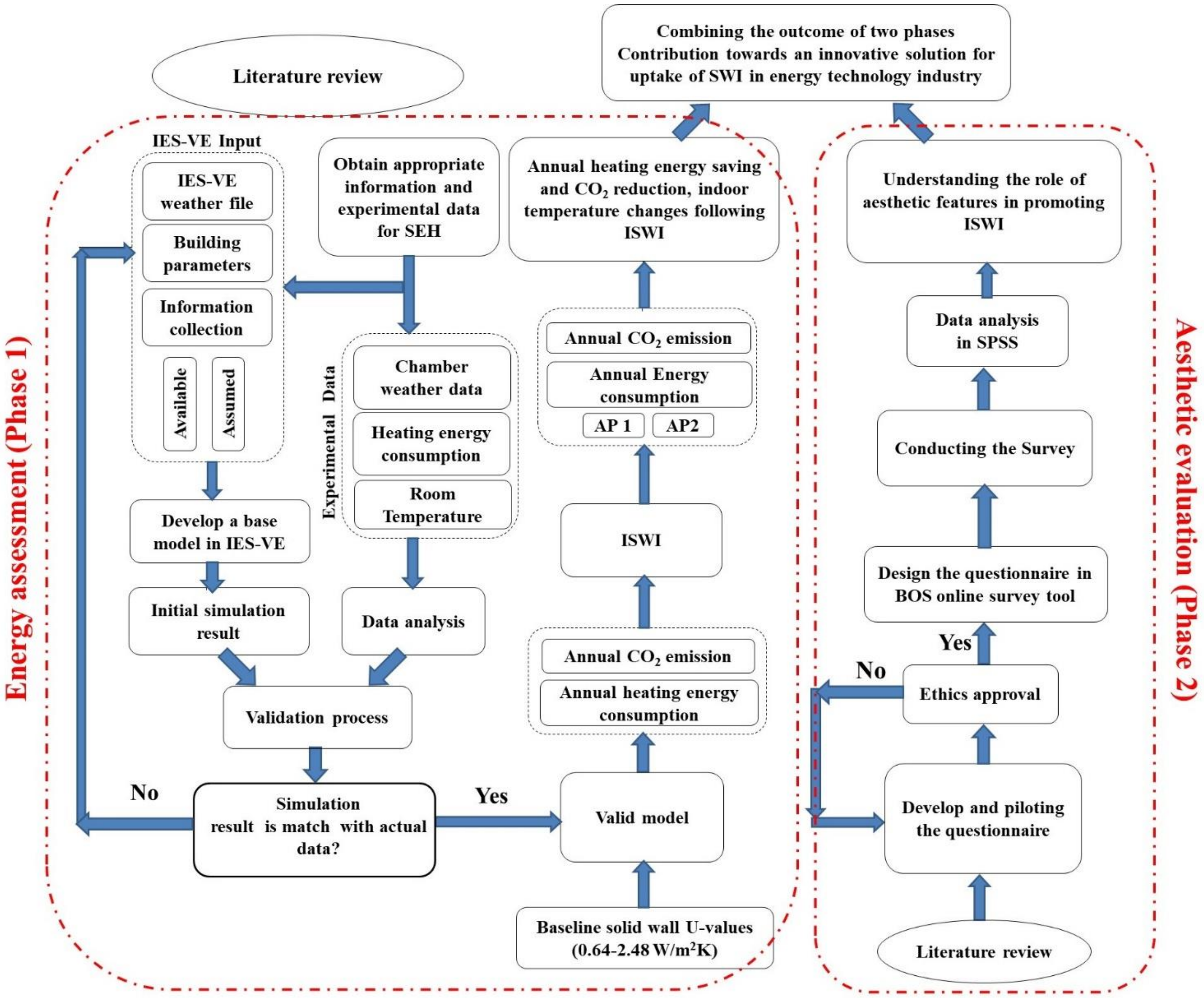


Figure 4.1. Schematic diagram of the research methodology.

## 4.3 Research Tools

### 4.3.1 Case Study

Some criteria for selecting the case study were set after reviewing the numerical studies of solid wall properties. Firstly, the property should be a typical solid wall property to better generalise the results. Second, the availability of the case study for experiments to be aligned with the time constraints of this research. Third, to be able to collect precise data without any interference from occupants. Fourth, to be able to access the in-situ measurements of the building for accurate modelling purposes. Fifth, to collect weather data on site for modelling purposes. These last three criteria are specifically important in developing a reliable model with minimum performance gap.

SEH was selected as a case study; this is a solid wall house located within an environmentally controlled chamber at the University of Salford. It is a typical end terrace house built similar to a pre-1919 Victorian house. The SEH was constructed by using reclaimed materials and traditional methods of the time, such as lime mortar and lath and plaster ceilings. Such properties are in considerable need to improve their energy efficiency due to their high AP and lack of insulation. Since the building is located in a controlled environment, the collected data can offer extremely precise information to validate the model and analyse the actual performance of solid wall houses and energy retrofit measures. SEH is a useful facility to test the thermal fabric retrofit effect for similar solid wall houses (Farmer et al., 2017). This type of house constitutes around 30% of the residential building stock in the UK (Hansford, 2015). In experimental studies, when the case study building is located in a real environment, the weather will change from day to day which affects the collected data, and it is hard to reflect the actual performance of the building precisely. Having SEH in the controlled environment facilitates the tests to be performed under steady-state conditions. This allows the building performance to be measured accurately with no intervening effects from occupants or weather changes. Usually, the effects of implementing any solution for improving energy performance in the SEH can be assessed precisely in a very short time, such as a week, where the in-situ measurements process could take much longer i.e., in some cases, up to a few months. The experiment was performed for the purpose of model validation under controlled conditions. The idea of the SEH test facility is to reduce the time of experiments significantly by removing the noise factors, so that the duration of the experiment is not a factor, and a short time is enough for validating the model for the purpose of this study. Therefore, SEH have all the criteria for being selected as the case study for this research.

Figure 4.2. Salford University Energy house (case study building).

### 4.3.2 Experiment

The experiment was performed under steady state conditions where the chamber temperature was kept at about 5 ºC constantly, the mean temperature value for UK winter (Lockwood et al., 2011; W Swan et al., 2017), during the data collection representing an average temperature for winter. The heating set-points were assigned to the lounge and other spaces with different heating profiles. The heating system of the SEH is a condensing combi boiler with heating unit capacity of 32 kW and efficiency of 93%. There was no occupant in the SEH and no electrical equipment was in use during the experiments. Having no occupant during the experiment was to identify the building performance with no interference to obtain more accurate results. Taking out the occupant factor in the SEH facility for the purpose of this study will help to avoid the gap between the model and real building performance data since occupant behaviour was seen to be one of the main sources of the disagreement between predicted and real building performance (Gupta & Gregg, 2015; Housez et al., 2014). When occupant behaviour is not the objective of the study, their behaviour could be a source of discrepancy between projected and actual energy performance (Wagner et al., 2018), and it is helpful to not have occupants in the building. Their behaviour can affect the accuracy of the data collection and the validation. After validation, the heating profile was imported into the model which is representing the occupant temperature preferences inside the house.

The Energy House team collected the experimental data, including heating energy consumption (gas), room temperatures and chamber conditions, such as temperature and humidity for the purpose and requirements of this study and the collected data was used for validating the model developed for SEH as a solid wall case study house. The experimental data and other data measured in previous research studies for SEH, such as AP and U-values, alongside building specifications and the precise floorplan with accurate building measurements were used in developing and validating the IES-VE simulation model to extend the analysis in the interest of this research.

The experimental data of room temperatures and heating energy consumption (gas) were used for validation of the model. The temperature ($^{o}$C) and gas consumption ($m^3$) were collected per minute during the 7 days of the experiment for the purpose of this study. The experimental data was then converted to Kwh for daily gas consumption and hourly for temperature to be comparable with IES-VE output results for the validation process. To create the hourly temperature data, the average of all the temperature readings for every minute in one hour was calculated. Also, the data for gas consumption in $m^3$ is converted to daily energy consumption in kWh, using the following formula:

Natural gas calorific value =40, Natural gas density= 1.02264

Daily gas consumption (kWh)=Daily gas consumption (m3) ×Density (kg/m3) ×Calorific value (MJ/kg) ×1h/3600s × $10^3$ (Eq. 1)

### 4.3.3 IES-VE

The Integrated Environmental Solution (IES-VE) software is a dynamic thermal simulation tool. It is well-established and widely used in analysing the dynamic response of buildings based on the hourly input of weather data (Ji et al., 2019a). IESVE is an in-depth suite of integrated analysis tools for the design and retrofit of buildings. It is an essential digital construction tool for top architects, engineers and contractors, which is utilised globally (IES Virtual Environment, 2011). This software is a 3D performance analysis software and has a variety of applications to create a reliable model. IES-VE software was used commonly as a thermal analysis tool for studying building energy performance in similar fields, and its accuracy and validity has been proven in several publications in the literature (Jannat et al., 2020; Ji et al., 2019a; Oleiwi et al., 2019). This tool is suitable for the first part of this research to study the energy performance of solid wall houses and determine the potential savings of SWI. Therefore, this software was selected due to its suitability and availability to develop the model of SEH and run the related energy analysis simulations for the purpose of this research. The accuracy and validity of the results from IES-VE software is confirmed in literature and it has been used by different academics and industries for energy performance analysis (Banfill et al., 2012; Ji et al., 2019a; Ji et al., 2019b; Sunikka-Blank et al., 2012).

The IES-VE software uses the default calculated U-values based on national and international standards. As indicated in the literature, better representations of building physics using the measured specifications such as U-values can help thermal models perform better with less discrepancy from the actual building performance. However, some level of discrepancies is inevitable in any modelling approach due to various underlying uncertainties (Marshall et al., 2017). Prediction results from the thermal model in relative terms, such as variations in percentage, tend to be more reliable than reporting the absolute numbers (Ji et al., 2019a). Percentage change is considered in reporting different results in many parts of this report.

### Input data for IES-VE model

#### *Weather file*

The weather file was created by Elements software in epw format based on the available data from chamber and assumed information. This customised file then was input into the IES-VE model to run the simulations with the customised weather file.

#### *Building parameters and information*

The building floor plan was designed in AutoCAD to match with IES-VE guidance before importing into the IES-VE software. According to the IES-VE ModelIT tutorial model, the inner wall line of external walls and the midpoint line for internal walls and partitions should be considered for developing the model (IES Virtual Environment Tutorial ModelIT, (Version 6.0)). Based on this approach, an accurate geometry model was built in IES-VE software using the adjusted AutoCAD floor plans. Figure 4.3 shows the adjusted floor plan of the SEH which was imported into IES-VE software.

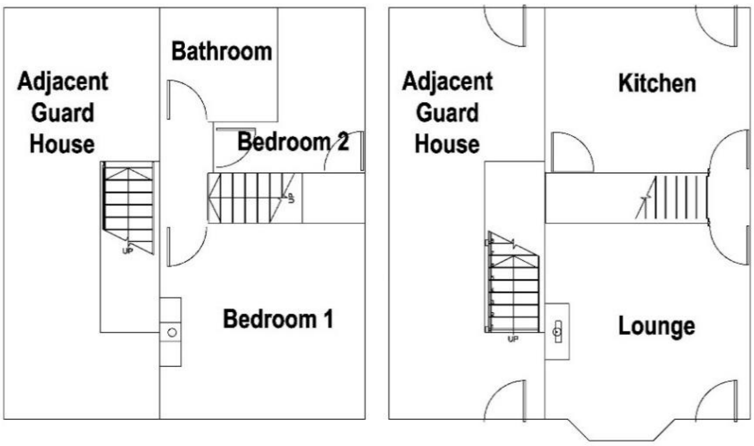


Figure 4.3. The adjusted SEH floor plans for developing the IES-VE model.

The building construction materials of the SEH (see Table 4.1) was modelled accurately to achieve reliable U-values for the SEH fabric elements. Then the default U-values were checked and matched with available SEH measured U-values to develop the model as precisely as possible. Also, the heating profile in the model was designed to reflect the set-points for the specified hours during the experiment and assigned to the related rooms. The other required data to develop the model, was obtained from the collected experimental data (e.g. chamber temperature and humidity data to create the weather file), previous studies of the SEH (e.g. AP and some U-values) (Fitton, 2016; Marshall et al., 2017) and assumed closely to software default values (e.g. a few U-values) to create a precise *standard model* performing as closely as possible to the reality. The building construction details of the SEH that were used in the IES-VE model are presented in Table 4.1. Various types of sensors were used in the SEH to log the data for this study, and they were calibrated for accurate measurements before the experiments. Table 4.2 presents the type of sensors with their accuracy levels that were used in the experiment.

Table 4.1. Construction details of the SHE.

| **Parts** | **Construction details** | **U-Values (W/m$^2$K)** |
|---|---|---|
| External walls | 225mm brickwork + internal plastering | 1.56 |
| Partition walls | Internal – 13mm plastering + 115mm brickwork + 13mm plastering | 1.88 |
| | Party wall – Plastering + 225mm brickwork | 1.56 |
| Ceiling | Suspended timber frame + lath & plaster | 0.46 |
| Roof | Stone chipping + Felt/Bitumen Layers + Slate Tiles | 5.03 |
| Floor | Synthetic Carpet + timber flooring + Plaster (lightweight) Gypsum Plastering | 1.97 |
| Glazing | 6mm Pilkington single glazing | 3.6 |

Table 4.2. Sensor specifications used in the experiment, based on (DMS, 2019; Ji et al., 2019a; Marshall et al., 2017; Papouch, 2018).

| Sensors | Model | Accuracy |
|---|---|---|
| Temperature sensor | Shielded 4-wire PT100 RTD | ±0.1ºC |
| Heat Flux Plate | Hukseflux HFP-01 | ±3% |
| Pressure gauge | Energy Conservatory DG-700 | ±1% |
| Data Logger | DataTaker DT80 | ±0.1% |
| Papouch sensor | TH2E | ±2% |
| Gas diaphragm meter | BK-G4 | ±1.5% |

### *Validation process*

The input parameters, such as building parameters and the customised weather file was imported in the standard IES-VE model. The measured input data of the she, such as U-values and the average measured AP of 13.95 m3/m2h, measured in a previous study using this facility by (Marshall et al., 2017) were imported into the IES-VE model to develop the valid model. The heating profile was also modelled to reflect the settings of the thermostatic heating controllers inside the house during the experiment. Using the in-situ measured data, such as U-values and APs for developing the model, provided us with a more reliable simulation and validation results compared to other related modelling studies that did not use in-situ measured specifications in the model (Marshall et al., 2017). This approach was also emphasised in literature to minimise the performance gap between the model and reality (Ji et al., 2019a; Marshall et al., 2017).

The experimental data were compared with simulation results for hourly room temperatures and daily gas consumption for heating to validate the SEH model, ensuring a highly reliable computational model was developed for this study; with the minimum performance gap between simulated and measured energy results in acceptable ranges (5-15% error) as expressed in the literature (Kaplan et al., 1990; Liu & Claridge, 1998; Pratt, 1990; Seifhashemi, 2015; Yoon et al., 2003). See Section 5.1.1 Section for more details.

### *Analysing the energy saving and $CO_2$ reduction of ISWI*

The valid model was used to simulate annual heating energy and house temperature for the SEH in the real situation by using the weather file for an example weather year in Manchester (ManchesterEWY). To develop our sensitivity analysis, the U-value was changed between 0.64 W/m²K to 2.48 W/m²K for baseline solid walls without insulation, as reported by the Society for the Protection Ancient Buildings (SPAB) for the solid brick walls (Caroline Rye and Cameron Scott, 2012). Such variations in wall U-values provides a better picture of possible energy saving and $CO_2$ emission improvement by SWI for solid wall houses with different brick fabric characteristics.

Furthermore, the model was insulated by an IWI material of high-quality polyisocyanurate which was offered by a reputable company as the best insulation material claiming to be "*an excellent thermal resistance and cost-effective option*" (Knaufdrywall, 2012). Insulation laminate board should be fixed to the 25 mm batten fixed on the internal wall surface to prevent the risk of cold bridging (Pullen, 2020). This instruction was followed in IES-VE software to model the wall insulation. The specifications of the insulation material are given in Table 4.3.

Table 4.3. Insulation Laminate board specifications (Knaufdrywall, 2012).

| P'board thickness (mm) | Insulation board thickness (mm) | Thermal conductivity (W/mK) | R-value ($m^2K/W$) |
|---|---|---|---|
| 9.5 | 65.5 | 0.022 | 3 |

Following the wall insulation, ventilation heat loss through the fabric reduces with higher effect for the IWI compared to the external as a result of more AP reduction (Moran, 2014). The AP determined in the Building Regulations is suggested by SAP as less than 10 $m^3/m^2h$ 50pa (Stevens et al., 2013). The AP improvement of up to 57% was reported in a study by the Energy Saving Trust as a result of IWI in solid wall properties (Stevens et al., 2013). Hence, two values for APs were selected for developing the analysis, in which one is the standard level of $AP_1$=10 $m^3/m^2h$ and the other is the more optimistic value of $AP_2$=6 $m^3/m^2h$ assuming a 57% improvement compared to a pre-insulation value of 13.95 $m^3/m^2h$ can be achieved. The models with previously mentioned range of U-values for both $AP_1$ and $AP_2$ were simulated and the results, including the heating energy, were extracted and the cost savings and $CO_2$ emission reduction for insulated solid brick walls were calculated. Also, temperature variations within the building following wall insulation were studied. Thermal comfort ranges may vary between individuals and depend on factors such as activity level, clothing, and humidity (Wang et al., 2018). The World Health Organisation (WHO) recommends the minimum room temperature of around 18 °C for UK households in winter and the Energy Saving Trust recommends the lowest comfortable temperature range of 18°C -21°C to aid the battle with climate change (Look After My Bills, 2021). Also, the most productive indoor temperature for occupants was reported to be between 21°C and 23°C in the literature (Tim Dwyer, 2020). Therefore, in this study, the neutral thermal comfort range of 18 °C to 23 °C, as used in some studies (Ghaffarianhoseini et al., 2019; Krüger et al., 2013), was considered to assess the internal temperature changes following SWI. The number of hours the temperature was below 18°C, thermal comfort range (18 °C to 23 °C) and above 23°C for baseline models and insulated models were compared to identify the effect of IWI on the inside temperature and possible overheating.

### 4.3.4 Questionnaire

In addition to the energy assessment phase, a professional survey was developed for the second phase of this project in respect to the reviewed literature (see Sections 3.1 and 3.2.3) and the author’s professional background. The purpose of survey was to address the third, fourth and fifth objectives of this research and respond to the research questions of 4 -7 (see Section 1.2).

The questionnaire is a research tool for gathering data from target participants. It enables the gathering of large amounts of data in an inexpensive, efficient and fast way (Pollfish, 2021b). The more structured the questions are, the easier the interpretation of the results for the researcher, as the quantitative data will be produced (Marshall, 2005). Therefore, a questionnaire is the survey instrument for aesthetic evaluation in the second phase of this study, and it was used in the studies in the field in the past (Blijlevens et al., 2014; Brimblecombe & Grossi, 2005; Moran, 2014). Aesthetic is important for every individual, but to be able to measure and report the level of its importance with statistics, a quantitative survey, which are a popular research method, used to collect data from participants by closed-ended questions. Quantitative surveys are seen as more scientific and easier to analyse compared to qualitative surveys as the numeric values are assigned to the answers so researchers can measure and analyse the survey data (Geer, 1988; Pollfish, 2021b). To achieve the higher response data, closed ended questions were only included in the questionnaire, as open-ended questions can produce non-responses or missing data, for example, respondents provide more than one answer or answers that cannot be coded. Also, open ended questions are used specifically when non-numerical observations and narrative data is needed in the study (Reja et al., 2003). However, clear numerical findings were expected from the survey to enable the integration of findings from aesthetic evaluation and energy assessment phases (see Section 5.2.3).

A quantitative questionnaire, consisting of 20 multiple choice questions was developed for this study. The first questions were mainly personal information questions about the house, income, age, gender, origin, ownership status and household size. Households' income and the number of people living in the household were asked aiming to be used for analysing the financial position of people to identify its relation to other factors such as aesthetics preferences. Also, some questions designed to obtain the participant view on energy efficiency improvement, cost, and timeframe of renovation and most importantly the aesthetic feature of their homes. The aesthetic desire of participants for the internal living spaces and the renovation work have been evaluated. Other questions designed with respect to the difficulties of ISWI from the literature were asked to see if aesthetics can overcome some of those concerns and stimulate householders to implement ISWI. Those difficulties considered in designing the questionnaire were losing internal space, householders' confusion due to current complexity of policies and financial support procedure, poor installation resulting in not achieving the expected saving benefits and cost concerns (see Section 3.1). As was discussed in Section 3.3 in Chapter 3, the existence of organisations to deliver the householders' ambition for renovation plans was suggested to be beneficial not only for improving the homes aesthetically, but also for enhancing the energy efficiency. Such organisations can help the customers through the process and supervise the quality of renovation delivery to achieve the target energy saving considering users' aesthetics preferences. This approach could lead to minimise the barriers for energy efficient measures, especially ISWI, and promote their installations' uptake with high quality standards in a clear path for householders. The last question was designed to seek the views of the participant on the establishment of such organisations responsible for delivering the comprehensive renovation package, including energy improvement and internal decorating based on user’s preferences. Questions are designed mostly as a 5-point scale from ‘strongly agree’ to ‘strongly disagree’ or ‘very important’ to ‘not important’ with the neutral option included. The option of ‘Don’t know’ is also provided to increase the validity of the questionnaire which helps in collecting the neutral responses more precisely and avoiding the number of meaningless responses (Friedman & Amoo, 1999). The designed survey for the purpose of this study is provided in Appendix 2.

Householders’ preferences directly affect the retrofit decisions for their properties. As discussed, the designed questionnaire was looking at enhancing SWI installation as the most effective measure but is the least implemented measure in poorly insulated homes in the UK. Therefore, the target participants for the survey were householders living in the UK, the age of 18 and over and who can contribute to take decisions regarding retrofitting of their property; they may or may not live in solid wall homes, but their views about the importance of aesthetics on renovation and wall insulation of their properties are important. There are vast numbers of solid wall dwellings in the UK, and any UK residents may become the householders of such properties in future.

It is difficult or impractical to conduct surveys to the entire population of specific areas of the study. Specifically for the purpose of this study, it was not going to be possible to survey all the households in the UK, so selecting a sample from the householders living in the UK was the solution. A sample by definition is a portion of a population (Taylor, 2005) and choosing a sample helps in obtaining a manageable part of population which supposedly have the same qualities as the whole (Swetnam & Swetnam, 2007). The sample should be large enough to be significant, represents the entire population and the defects and rationale in sample selection to be acknowledged (Sheth, 2011).

Convenience sampling, which is one of the non-probability sampling techniques, is used in this study. Using convenience sampling is often *a norm* used in different studies (Aarabi et al., 2013; Zandieh et al., 2016; Zolkiffli et al.). The main objective of convenience sampling is to collect information from participants who are easily accessible to the researcher. It is a quick, inexpensive, and uncomplicated method of data collection and it is useful especially for large populations when randomisation is almost impossible (Etikan et al., 2016). However, the convenience sampling method does have its own limitations as highlighted in Section 6.4. To ensure high response rates and easy access, the Salford university staff were selected as the sample to participate in this online survey. The University of Salford has around 2,300 staff members and it could be a good sample for the target population (retrofit decision makers for UK households) for this study as they reflect a variety of gender, age, ethnicity, ownership status and housing typologies. Also, they work in various diverse roles within the university with different income ranges, including admin, human resources, lawyers, finance, IT, estate and maintenance, engineers, technicians, academics, managers, etc. In any survey study, when the sample is selected, many people would be excluded. However, the characteristics of the selected sample is expected to be similar to the target population for the purpose of this study. This is especially true when looking at some of the sample characteristics (such as origin, ownership and old homes) which are similar with whole UK population (see Section 5.2.1).

Sample size determination is another key parameter in any survey study. According to the literature, the relevant survey studies in the field developed their analysis based on about 100-150 responses from participants. This number could be a good indication of the required sample size and validity of the results for this study. For example, Blijlevens et.al (2014) targeted 157 respondents for studying aesthetic pleasure (while their final analysis was performed with total of 108 respondents after removing incomplete questionnaire responses) and Moran et.al (2014) sent 600 questionnaires to householders by envelope with a return rate of 25% achieved for an energy consumption analysis. In another study (Brimblecombe & Grossi, 2005), Brimblecombe chose 100 people to evaluate the public perception of blackening the light-coloured stone in historic buildings for each case in Europe. Any sample will differ from the true population by a certain amount. Confidence intervals and margins of error reflect the fact that there is the room for errors.  The sample size required for this study was calculated from the following formula for large populations (Chaokromthong & Sintao, 2021; Daniel & Cross, 2018; Kothari, 2020) where N= population size; e = margin of error; z = z-score and P = the population proportions:

$$N=P(1-P)z^2/e^2 \qquad \text{(Eq. 2)}$$

For the purpose of this study, 271 respondents are needed, with a 90% confidence interval (z-score=1.645) and a margin of error of +/- 5%, meaning that the calculated results are accurate to within 5% points 90% of the times.

Piloting is important for the overall success of the survey after designing the survey questions but prior to survey distribution. Piloting is a small-scale trial before the main investigation, aiming to assess the questions and research design to be adequate (Sapsford & Jupp, 1996; Sheth, 2011). The peer review and cognitive interview are two well-known piloting methods which were used in this study (Sheth, 2011). In the peer review piloting method, a number of people expert in survey subject or questionnaires are asked to review the questions (Sheth, 2011). In this study, the questionnaire was reviewed and consulted with six research experts and academics to seek their views about the designed questionnaire; this was to ensure the questions were appropriately designed. The questionnaire was amended and improved based on expert feedback and consultation; this process was repeated until no more changes were needed as it is instructed in social science methods and practice (Newing, 2010). The other piloting method, called the cognitive interview, was trailed which involved interviewing the experts to understand how they perceive the questions to ensure they were answered correctly (Sheth, 2011). Hence, the questionnaire was completed by four test respondents and the answers by respondents were explored with them. According to the feedback received, the necessary amendments were implemented to the questions to make sure questions were making sense for participants, prior to its distribution. Both piloting stages performed in this study were with the aim to improve the quality and validity of the questionnaire, without collecting any data.

The comments received during the piloting phases was minor on the English and grammar, length of a few questions, clarity of the questions, and instructions, such as adding photos to some of the questions, adding the ‘don’t know’ option into the available choices, and all were applied to improve the questionnaire. In addition to these efforts, every stage of developing the questionnaire was discussed with researcher’s supervisor. All these processes helped to improve the validity of the questionnaire and outcome of the survey (Sheth, 2011). Ethics documents were also prepared and submitted to university before conducting the survey and data collection, and the comments received from the ethics approval panel were applied. The ethics approval was granted for this research and the ethics approval letter and participants information sheet are presented in Appendix 3 and Appendix 4.

To proceed to the next step after designing and piloting the questionnaire, the online survey design and distribution, as well as importing the data and data analysis procedures, were performed which are explained in following sections.

### 4.3.5 Bristol Online Survey (BOS)

Convenience sampling is one of the non-probability sampling approaches for an online survey where for example, the survey invitation will be circulated to participants by online lists or twitter and respondents self-select to participate in the study (Williamson & Johanson, 2017). The online distribution of surveys is not only effective in terms of time and cost but also has other advantages (Pollfish, 2021a). Online surveys are also beneficial for participants as they provide flexibility over where and when to complete their questionnaire and for the anonymity of their responses (Philip Cleave, 2018) with the latter encouraging more honest and frank answers, than for example interviews, and can help to reduce bias (Marshall, 2005). There are a variety of tools for conducting online surveys with different capabilities. An online survey tool formerly known as the Bristol Online Survey (BOS) is a powerful and flexible online survey which was designed and used for academic research, education and public sector organisations (Newing, 2010; Online surveys (formerly BOS)). The BOS tool was preferred for this study because it is specifically designed for research and education organisations, and it is easy to use and cost effective due to the licence availability at university. Also, it was widely used for different research projects at university and in literature in similar domains and its applicability was confirmed (Charef et al., 2019; Naqvi et al., 2019; Rowe et al., 2018). Hence, the questionnaire was designed for data acquisition, that comprised of closed-ended questions using the Bristol Online Survey and was sent by email to target participants (Salford university staff) directly from the BOS survey tool. Those who accepted the invitation, completed the questionnaire after giving their consent. The survey took place between September 2018 and January 2019, and reminders were sent to participants to engage and answer the questions in order to achieve the target sample. This tool provides a variety of formats for the output data. The response data in .sav format was extracted from BOS to be imported to the SPSS software (version 25) for the analysis.

### 4.3.6 Statistical Package for the Social Science (SPSS)

The key focus behind the data analysis in this study is to explore people views on aesthetic factors in renovation and internal living spaces, and to see whether this factor can be used as a trigger to uptake the application of SWI. The statistical analyses were employed depending on the type and source of the data (Sheth, 2011) and research questions. Analysis is an important task because ineffective data analysis can negate entire data collection, resulting in failure of the project. SPSS software is designed for advanced statistical analysis, it also has a vast library of machine learning algorithms, text analysis, with open-source extensibility integration with big data and seamless deployment into applications (IBM, 2020).

SPSS software (version: 25) was selected for statistical analysis of the questionnaire outcome. This software can perform highly complex data operations and analysis with simple instructions. Its suitability and validity were proved previously in numerous studies, and it was widely used in research survey analysis in the literature (Ali & Au-Yong, 2021; Carpino et al., 2017; Ferdous, 2013). It is also available at the university and is employed for this study. According to the type of questions in the questionnaire, the descriptive statistics method is used for analysis of this study and frequency of the data is reported. A descriptive analysis is an important first step for conducting statistical analysis. It gives an idea of the distribution of data by simplifying the large amount of data in a sensible and comparable way. To investigate the research questions further (see Section 4.3.3), a more in-depth analysis was performed using cross-tabulation analysis through the Chi-square test were performed for relevant questions to describe and determine the possible dependency relationships between categorical (nominal or ordinal) variables for extracting the possible meaningful results. The Chi-square test of independence also known as Chi-square test of association is a non-parametric test and determines whether there is an association between two or more categorical variables or not (i.e., whether the variables are independent or related) (Kent State University, 2022a). The important factors in internal renovation, i.e., aesthetics, cost, energy saving, and time frame, with some personal characteristics' variables (such as age, gender, origin, Per Capita Household Income (PCHI), old houses and ownership) were tested through cross-tabulation of variables with a Pearson's Chi-square test to capture the variables dependency. Furthermore, the view of participants that are living in old houses and/or owner participants were analysed separately to see if they have different views towards renovation factors. People living in old houses, their properties likely to have lower levels of insulation, and owner participants may have different desires compared to other participants in internal renovation of their own properties. Non-parametric correlation (Spearman's rho) also used to check the existence of strong correlation between any two variables of aesthetic, energy saving, cost, and time frame of renovation. These further in-depth analyses provide a deeper understating of the aesthetic effects on users' and its potential contribution to improving retrofit strategies and uptake of ISWI.

To analyse the effect of respondent’s income power on their aesthetic preferences in internal retrofit and compare it with other factors of cost, energy saving and time frame, the Per Capita Household Income (PCHI) factor is introduced. The Equation below is used for PCHI calculation in this study, by dividing the household income (1-7 categories) by the household size (1-5 categories) using Q10 and Q9 data. The PCHI results following calculations are categorized in three categories of low (below 1.99), average (2-3) and high (above 3.1).

$$PCHI = Q10 / Q9 \qquad \text{(Eq. 3)}$$

## 4.4 Combination of Energy Assessment and Aesthetic Evaluation

Lack of clear information about SWI implementation benefits are amongst the main SWI barriers that discourages householders from retrofitting their premises (see Table 3.1) (Weeks et al., 2015; Wilson et al., 2014). Despite all the policies, subsidies, and grants available for SWI such as the Government’s Energy Company Obligations (ECO) scheme, only 9% of houses with solid walls were insulated by the end of 2021, and around 7.7 million houses are still remained uninsulated (Oxley, 2022). Building users decide whether or not do energy renovation in their house in real life. Therefore, estimation of energy saving and $CO_2$ reduction, assuming that all or the majority of the solid wall dwellings will be insulated without considering the householders preferences, does not provide a realistic figure to rely on as a basis for planning for the climate targets. In this study, the aesthetic factor was introduced by employing the homeowners’ interest in IAWI based on the survey results of this research to achieve a more realistic estimation for possible energy saving and emissions reduction.

The amount of energy saved, and $CO_2$ reduction achieved in the energy assessment phase of the methodology will be used along with the questionnaire analysis results from SPSS software in the aesthetic evaluation phase to obtain a more realistic picture for the potential savings by including the user desires. In this approach, the figures extracted from the simulation analysis of ISWI from the valid model, and the user’s responses about aesthetic features, are used to estimate energy saving and $CO_2$ reduction as a result of IAWI. The modified estimation result of annual energy saving and $CO_2$ reduction potentials by using IAWI can be calculated by multiplying the following three results:

1) User desire of IAWI % (SPSS)

2) Number of uninsulated solid wall houses in the UK (assuming they all perform similarly to the

SEH)

3) The estimation of annual energy saving and $CO_2$ reduction of IWI for the case study in the UK (IES-VE)

This calculation is a demonstration only to combine the result of both phases of this research which magnifies a revised figure for energy and $CO_2$ estimations by including the users' preferences compared to the energy saving potential of SWI in different cases studies which multiplies all solid wall houses by the energy/$CO_2$ saving (Gillich et al., 2019). User centred approaches can contribute towards the SWI uptake and grow the market as an innovative and attractive solution for energy retrofit industries. This alteration in energy strategies, to include users' preferences as an innovative solution, would enhance the user interest in IAWI packages leading to increasing the demand and the energy efficiency of existing homes in the UK. Also, Government and policy makers will benefit from the findings of this research in planning for the decarbonisation of the energy sector with more realistic numbers, and for providing the appropriate support to move towards the integration of aesthetic features in SWI in the future. In the end, viable approaches in integrating aesthetics in SWI strategies with a focus on IWI will be discussed, and recommendations will be provided for retrofit industry, policy makers and designers. This is to address the sixth objective of this research and answer to research question of 8 (see Section 1.2).

# Chapter 5: Results and Discussion

The results and discussion of this study are presented in this chapter and outlines the Energy assessment of SWI (Section 5.1), Evaluation of the aesthetic role in promoting SWI (Section 5.2) and Recommendations towards increasing the uptake of SWI (Section 5.3).

## 5.1 Energy Assessment of SWI

The results related to the first phase of this research are discussed in following sections. The developed IES-VE model of the SEH is presented, and the simulation results and experimental data compared to show the validity of the model. Further results obtained from the model simulation analysis related to the energy assessment of SWI are also presented and discussed in detail to answer research questions 1-3 (see Section 1.2).

### 5.1.1 Validation of the IES-VE Model

Figure 5.1 presents the floor plan and 3D view of the developed model of the SEH in IES-VE. The model of SEH was accurately validated against experimental data (temperature and gas consumption) and high accuracy was achieved with the minimum performance gap compared to the experimental data (percentage error is below 1% for daily heating energy consumption (gas) and Root Mean Square Error (RMSE) of 0.7 °C-1.5 °C for temperatures of the different rooms. Table 5.1 shows the actual and simulated results for gas consumption for all the days of the experiment. As can be seen in the table, the performance errors between the developed validated model and the experimental results are 0.28%-11%. for all days of the experiment. Therefore, the percentage error of the valid model is well below the acceptable range (5%-15%) specified in the literature (see validation process in Section 4.3.3 for details).

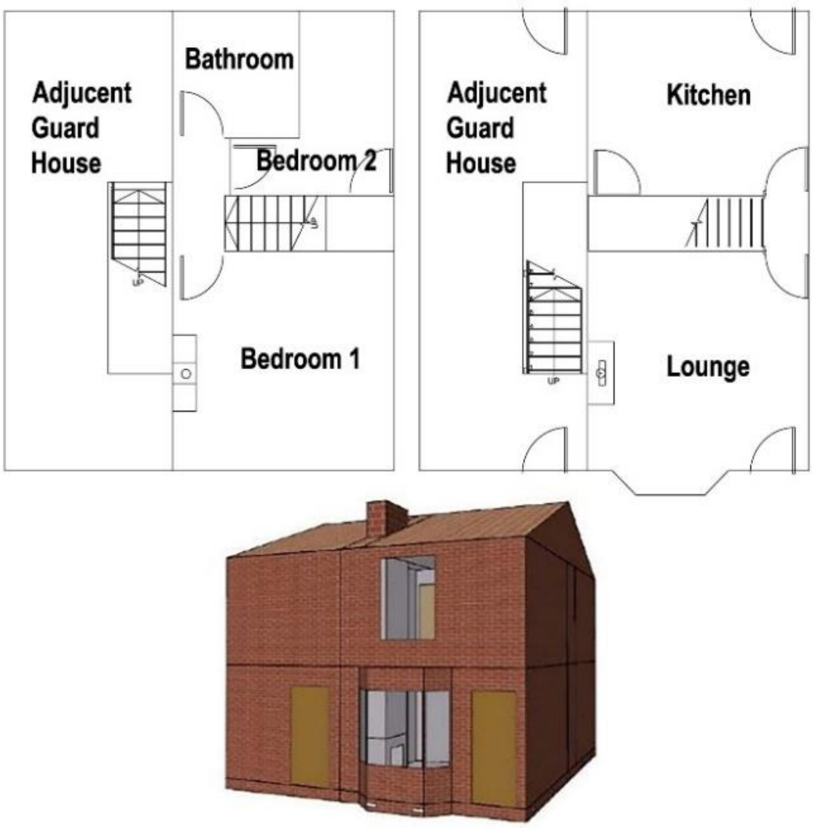


Figure 5.1. The SEH IES-VE model.

Table 5.1. Daily gas consumption results from IES-VE and experiment.

| **Experiment Days** | **Daily GAS Consumption (kWh)** | | **Performance gap** |
|---|---|---|---|
| | **Exp** | **IES-VE** | **Error (%)** |
| Day 1 | 52.95 | 54.1 | -1.98 |
| Day 2 | 55.56 | 53.6 | 3.52 |
| Day 3 | 57.95 | 53.1 | 8.36 |
| Day 4 | 58.74 | 52.2 | 11.13 |
| Day 5 | 49.54 | 49.4 | 0.28 |
| Day 6 | 53.4 | 52.1 | 2.62 |
| Day 7 | 60.56 | 54.2 | 10.50 |

Figure 5.2 presents the sample of validation processes for temperatures in Bedroom 1 and Lounge for day 5 of the experiment. The temperature set-point for the Lounge was higher compared to Bedroom 1 as well as other living spaces. As can be seen in Figure 5.2, the temperature trends are quite similar, confirming a good agreement between the experimental data and the IES-VE simulation results. However, the IES-VE model was observed to lose heat quicker compared to the SEH when the heating profile is set to be off, and this point was also was highlighted in the literature by Ji et al. (2019a).

When the heating turns off, the radiator still releases heat to the designated space in reality, while for the IESVE models, once scheduled heating stops there will be no residual energy into the room to resist the temperature drop (Ji et al., 2019a). The temperature results of the valid model and experiments for day 5 is presented in Table 5.2. The standard deviation of temperature data from experiment and simulation was observed to be 1.25.

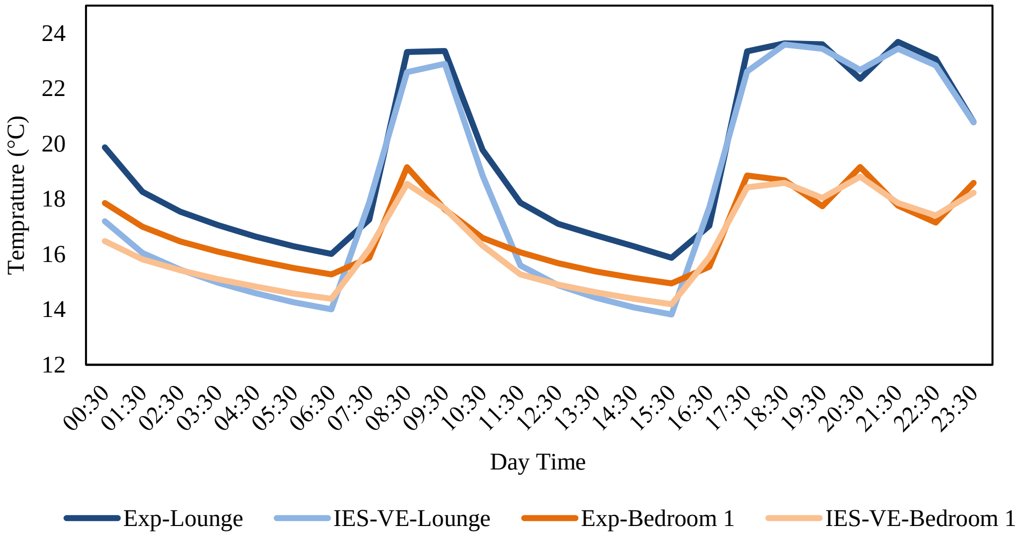


Figure 5.2. Temperature profile from experiment and IES-VE simulation.

Table 5.2. Hourly temperature data for lounge from IES-VE and experiment for day 5.

| **Day Time** | **Experiment** | **IES-VE** | **Day Time** | **Experiment** | **IES-VE** |
|---|---|---|---|---|---|
| 00:30:50 | 18.5 | 16.82 | 12:30:53 | 17.1 | 15.66 |
| 01:30:53 | 17.5 | 15.97 | 13:30:51 | 16.8 | 15.33 |
| 02:30:49 | 16.9 | 15.48 | 14:30:51 | 16.8 | 15.11 |
| 03:30:51 | 16.5 | 15.07 | 15:30:55 | 16.7 | 15.05 |
| 04:30:54 | 16.1 | 14.74 | 16:30:51 | 22.4 | 23 |
| 05:30:49 | 15.9 | 14.46 | 17:30:50 | 21.6 | 23 |
| 06:30:50 | 15.7 | 14.34 | 18:30:50 | 22.1 | 23 |
| 07:30:55 | 21.7 | 22 | 19:30:49 | 23.1 | 23 |
| 08:30:51 | 22.1 | 22 | 20:30:53 | 23.6 | 23 |
| 09:30:52 | 22 | 22 | 21:30:54 | 21.3 | 23 |
| 10:30:52 | 18.6 | 19.98 | 22:30:53 | 21.4 | 23 |
| 11:30:51 | 17.6 | 16.26 | 23:30:54 | 21.5 | 20.99 |
| **Root Mean Square Error (RMSE)** | | | | **1.25** | |

### 5.1.2 Simulation results discussion

Figure 5.3 shows the annual energy consumption of the SEH valid model pre and post IWI. To simulate the insulated walls, the U-value of the walls were changed from 1.56 W/m²K to 0.2593 W/m²K after the insulation and the results were extracted for AP1=10 $m^3/m^2h$ and AP2=6 $m^3/m^2h$. As shown in Figure 5.3, the heating energy use of 12.31 MWh was reduced to 7.96 MWh and 7.74 MWh after insulation with AP1=10 $m^3/m^2h$ and AP2=6 $m^3/m^2h$, respectively. This means that annual energy savings of between 35% and 37% can be achieved by IWI, depending on AP values.

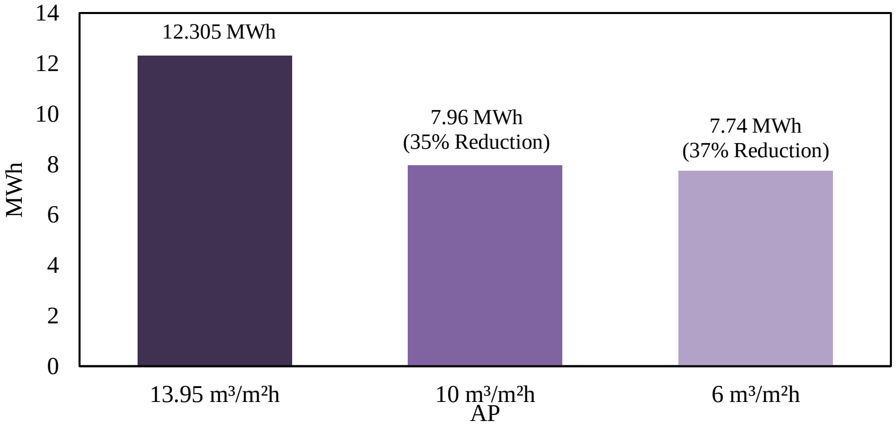


Figure 5.3. Annual heating energy use pre and post IWI in SEH case study (base line wall U-value of 1.56 W/m²K).

Typically, the gross Calorific Value (CV) for each kWh of energy savings is used for reporting the $CO_2$ emissions as used in this study. The value of 0.18385 kg $CO_2e$ per kWh, obtained from UK Government GHG Conversion Factors 2019, was employed for $CO_2$ emission calculations in this study (BEIS and DEFRA, 2019). The annual $CO_2$ reduction of 800 kg $CO_2e$ (with AP1) and 840.2 kg CO2e (with AP2) can be achieved following the wall insulation for the model with a baseline wall U-value of 1.56 W/m²K as presented in Table 5.3. The average gas unit rate of 3.8 pence/kWh (ex VAT) was extracted from a retailer website (UKPower, 2020). VAT was added in cost saving calculations of IWI and the value of 4.56 pence/kWh was used in all cost analyses. The results showed that cost savings of between £198 to £208 per year can be achieved. This saving is considerable compared to the average gas bill price of £676 for households in the UK in 2018 (Rowe, 2019).

Table 5.3. Annual heating energy saving and $CO_2$ reduction potential of IWI in solid wall house with baseline wall U-value of 1.56 W/m²K.

| **SEH validated model** | | |
|---|---|---|
| In situ U-value (W/m²K) | 1.56 | |
| AP ($m^3/m^2h$) | 13.95 | |
| Annual Heating Energy Consumption (MWh) | 12.305 | |
| **Insulated walls** | | |
| U-value insulated wall ($U_{IW}$) (W/m²K) | 0.2593 | |
| AP ($m^3/m^2h$) | $Ap_1$ | $Ap_2$ |
| Annual Heating Energy Consumption (MWh) | 7.96 | 7.74 |
| Annual Energy Saving (MWh) | 4.35 | 4.57 |
| Annual Energy Saving (%) | 35.35 | 37.14 |
| Annual $CO_2$ reduction (kg $CO_2$e) | 800 | 840.2 |
| Annual cost saving (£) | 198.4 | 208.4 |

To extend the analysis of IWI for solid walled houses, similar to the SEH type (end of terrace houses), the model was simulated for a variety of baseline wall U-values and the simulation results are presented in Table 5.4. According to the results, for solid wall houses with different baseline U-values ranging from 0.64 W/m²K to 2.48 W/m²K, the annual heating consumption changed between 9.4 MWh to 14.7 MWh. This means that the annual energy saving was between 19% and 46.2%, depending on the U-values and APs. As expected, the higher energy saving was achieved for solid wall houses with higher baseline wall U-values compared to those with lower baseline wall U-values. Also, the insulated model with AP2 showed about 0.2 MWh/year reduction in heating energy use, compared to the same insulated model with AP1 for different cases. To assess the corresponding environment impacts of wall insulation, the annual $CO_2$ reductions (kg $CO_2$e) were calculated and presented in Table 5.4 as well. The high $CO_2$ reduction with large discrepancy from 328 kg $CO_2$e to 1248 kg $CO_2$e were observed for different solid wall houses, which highlights the importance of the baseline U-values in estimating the potential $CO_2$ reduction of SWI. Policy makers should reflect on this finding when planning for the $CO_2$ emission reduction target of solid wall houses. Furthermore, the potential cost saving of IWI was calculated and presented in Table 5.4. As shown, the cost savings changed from £82.10 to £310.10 annually depending on U-values and APs. Considering the average household gas bill of £557 for 2020 (BEIS, 2021), this corresponds to a 15%-56% savings. It also shows a significant variation in potential cost saving which can mislead the homeowners in decision making towards the implementation of IWI as well as the policy makers in offering the right incentives. The cost saving potential results, reported in the Table 5.4, agree with £200-£300/year that was reported for maximum bill saving following SWI in the literature (see Section 2.7).

Table 5.4. Heating energy saving and $CO_2$ reduction potential of wall insulation in solid brick walls houses with base line wall U-value in range of 0.64 W/$m^2$K to 2.48 W/$m^2$K.

| **Base line walls** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| In situ U-value (W/$m^2$K) | 0.64 | | 1.05 | | 1.4 | | 1.75 | | 2.1 | | 2.48 | |
| AP ($m^3$/$m^2$h) | 13.95 | | | | | | | | | | | |
| Annual Heating Energy Consumption (MWh) | 9.403 | | 10.77 | | 11.83 | | 12.82 | | 13.74 | | 14.71 | |
| **Internally Insulated walls** | | | | | | | | | | | | |
| U-value insulated wall ($U_{IW}$) (W/$m^2$K) | 0.2096 | | 0.24 | | 0.2544 | | 0.2641 | | 0.2709 | | 0.2763 | |
| AP ($m^3$/$m^2$h) | $Ap_1$ | $Ap_2$ | $Ap_1$ | $Ap_2$ | $Ap_1$ | $Ap_2$ | $Ap_1$ | $Ap_2$ | $Ap_1$ | $Ap_2$ | $Ap_1$ | $Ap_2$ |
| Annual Heating Energy Consumption (MWh) | 7.62 | 7.4 | 7.81 | 7.6 | 7.92 | 7.7 | 8.01 | 7.8 | 8.07 | 7.9 | 8.14 | 7.92 |
| Annual Energy Saving (MWh) | 1.8 | 2.01 | 3 | 3.19 | 3.91 | 4.13 | 4.82 | 5.04 | 5.7 | 5.9 | 6.6 | 6.8 |
| Annual Energy Saving (%) | 19 | 21.35 | 27.5 | 29.62 | 33.05 | 34.9 | 37.6 | 39.3 | 41.3 | 43 | 44.7 | 46.2 |
| Annual $CO_2$ reduction (kg $CO_2$e) | 328 | 369 | 544 | 586 | 719 | 759 | 885 | 927 | 1042 | 1083 | 1208 | 1248 |
| Annual cost saving (£) | 82.1 | 91.7 | 136.8 | 145.5 | 178.3 | 188.33 | 219.8 | 229.8 | 259.9 | 269.0 | 301 | 310.1 |

Temperatures inside insulated houses are expected to be higher compared to homes with no insulation. To reveal the precise impact of wall insulation on internal temperatures, the SEH validated model with a baseline U-value of 1.56 was simulated over a year. The total %hours per year that the house spaces were in the temperature range of below 18 °C, between 18°C and 23°C and above 23°C, pre and post insulation were extracted from the model and presented in

Figure 5.4. After wall insulation, the reduction of more than 3% in the total hours when the temperature was below 18 °C and an increase of more than 2% and 1% for the range of 18 °C to 23 °C and above 23 °C respectively.

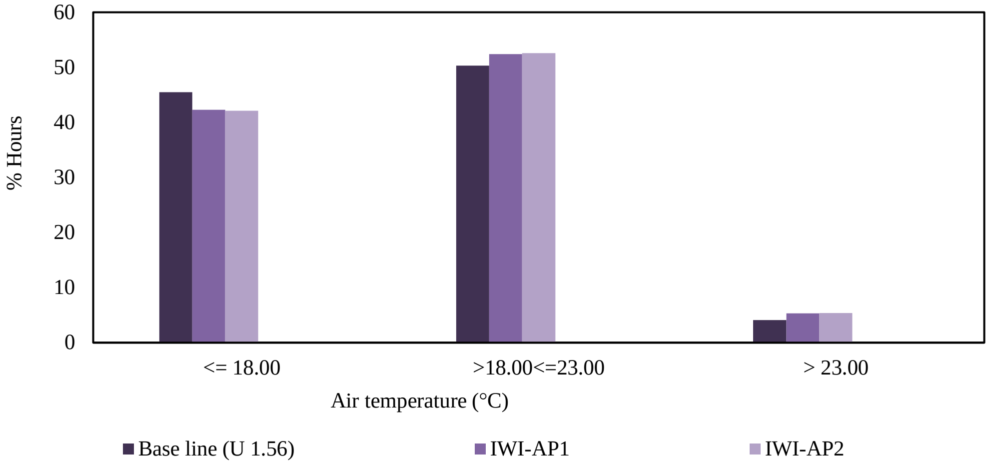


Figure 5.4. Annual effect of insulation on indoor temperature for SEH (base line U-Value=1.56 W/m²K).

The results for other baseline wall U-values are presented in Table 5.5. As shown, the annual %hours in which the temperatures were below 18°C was 43.3% for baseline wall U-values of 0.64 W/m²K. This was reduced to 42% in the insulated case for AP1 and to 41.7% for AP2 representing a 1.3% and 1.6% reduction respectively. Moreover, by increasing the baseline wall U-values from 0.64 W/m²K to 2.48 W/m²K, a continuous reduction in %hours per year that the house temperatures were below 18 °C was observed after insulation for both AP1 and AP2, with the maximum reduction of 4.9% (from 47.1% to 42.2%) for AP2. On the other hand, the annual %hours in which the temperature was between 18 °C and 23 °C were increased by 0.2-3.7 % for AP1 and 0.4-3.8 % for AP2 depending on the baseline U-values. There was also an increase of 0.9-1.2 % for AP1 and 1.1-1.3% for AP2 for temperatures above 23°C. These results suggest that the house is getting generally warmer as more temperatures are in or above the thermal comfort range.

Table 5.5. Annual effect of insulation on indoor temperature.

| **Baseline wall U-values (W/m$^2$K)** | **Base line models** | | | **Internally Insulated models** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AP=13.95 m$^3$/m$^2$h | | | AP$_1$=10 m$^3$/m$^2$h | | | AP$_2$=6 m$^3$/m$^2$h | | |
| | %Hours T<= 18 °C | %Hours 18°C <T<=23°C | %Hours T> 23°C | %Hours T<= 18°C | %Hours 18°C <T<=23°C | %Hours T> 23°C | %Hours T<= 18°C | %Hours 18°C <T<=23°C | %Hours T> 23°C |
| 0.64 | 43.3 | 52.8 | 3.9 | 42 | 53 | 5 | 41.7 | 53.2 | 5.2 |
| 1.05 | 44.4 | 51.5 | 4.1 | 42.2 | 52.6 | 5.2 | 41.9 | 52.8 | 5.3 |
| 1.4 | 45.3 | 50.6 | 4.2 | 42.3 | 52.4 | 5.3 | 42 | 52.6 | 5.4 |
| 1.75 | 46 | 49.7 | 4.2 | 42.4 | 52.3 | 5.3 | 42.1 | 52.5 | 5.4 |
| 2.1 | 46.6 | 49 | 4.4 | 42.5 | 52.2 | 5.4 | 42.2 | 52.3 | 5.5 |
| 2.48 | 47.1 | 48.4 | 4.5 | 42.5 | 52.1 | 5.4 | 42.2 | 52.2 | 5.6 |

The possibility of overheating (temperatures above 23°C) pre and post wall insulation was investigated in more detail for the lowest and highest baseline U-values of solid walls during a year and the results are presented in Figure 5.5. The results of the model with a baseline wall U-value of 0.64 W/m$^2$K showed that for 3.8% of the hours, the temperature was between 23°C to 28°C. Following the wall insulation, this was increased to 4.8% and 4.9% for AP1 and AP2, respectively. In this case, the annual % hours of the temperature above 28°C, was increased only around 0.1% for both AP1 and AP2 while it mainly happened in the loft spaces.

Similarly, the model results for 2.48 W/m$^2$K baseline wall U-value showed that for 4.3% of the hours the temperature was between 23-28°C in a year. After the wall insulation, the annual %hours increased by 0.8% and 1% reaching to 5.1% and 5.3% for AP1 and AP2 respectively. For the temperature range above 28°C, the increase of around 0.1% for both AP1 and AP2 was identified as well, while the majority of this increase occurred in the loft spaces with negligible effects in other spaces.

Bedroom 1 was the only space which experienced temperatures above 28°C for only 2 hours pre wall insulation (about 0.001 %hours annually), however, temperatures over 28°C was observed in Bathroom and Lounge as well as Bedroom 1 during the year after the wall insulation for 3, 5 and 11 hours for AP1 and 4, 5 and 15 hours for AP2 respectively. Also, it should be noted that about 95% of all recorded temperatures above 28°C for pre and post wall insulation occurred in the warmer season, between May-July. Some simple measures such as night ventilation and shading were suggested in the literature to overcome these overheating effects (Gupta & Gregg, 2013; Tink et al., 2018). This issue can be further investigated in future studies by considering the effects of global warming.

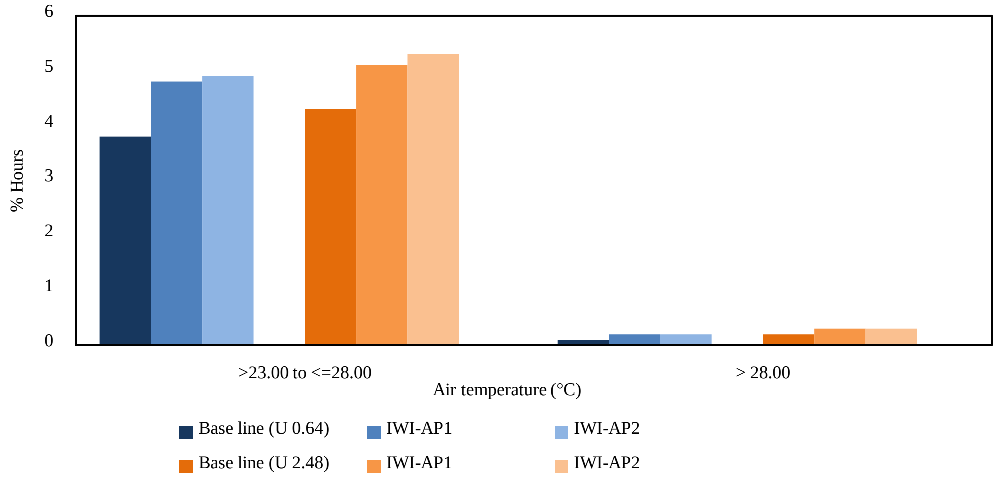


Figure 5.5. Annual effect of insulation on indoor overheating temperature.

The total reduction of 100 mm from the internal surface of external walls is expected after IWI in the SHE uses the insulation laminate board specified in Table 4.3 and considering 25mm battens fixed on the internal wall surface to avoid cold bridging (see Section 4.3.3). The area reduction for the SEH is calculated and only 5% area loss in living spaces were observed after IWI installation. However, the outcome of such calculations cannot be generalised for other solid wall properties as the area loss can differ significantly from one house to another and depends on the type and quality of the wall interior and selected insulation material and the technique used for implementing the SWI.

## 5.2 Evaluation of Aesthetic role in Promoting SWI

The results obtained in the second phase of this research are presented and discussed in this section. The preliminary and more in-depth statistical analysis of the response data performed and the importance of aesthetics in renovation for householders and its role in uptake of ISWI were evaluated. The results in this section are developed based on survey analysis to answer the research questions 4-7 (see Section 1.2).

### 5.2.1 Survey Results and Preliminary Statistical Analysis

The questionnaire contained 20 categorical questions. Considering the question types and large sample size, a series of descriptive statistical analyses were performed to provide more insights from the results which directly or indirectly answer research questions of 3 and 4 (see Section 1.2). Out of 2,296 invitations, 306 responses were received in which 273 participants selected ‘Yes’ for the consent question (Q1) to participate in this study (33 participants selected ‘No’ and were not able to answer the rest of the survey questions). Therefore, the target of 271 sample size required for this study (see Section 4.3.4) was met. As part of the preliminary statistical analysis, the frequency of participant’s responses to the survey questions are presented in following parts.

### ***Basic Information of Respondents***

Figure 5.6 shows the age groups of participants, confirming a good distribution of age among the participants (Q2). The participants gender (Q3) was about equal with 50.2% and 49.8% of the participants being female and male respectively. Therefore, the gender characteristics of the sample is similar to the population of the UK by gender (~50.6% female and 49.4% male in 2020) (Clark, 2022). Most of the participants, 225 responses, (~84%) were of UK origin (Q4), while 43 participants (~16%) were of non-UK countries and the remaining 5 participants preferred not to reveal their origin. This is also a good representative of the UK population, with 9.5 million (~14%) non-UK-born (Stickney, 2021). Participants who were living in solid brick wall houses were 63% of the total participants (Q5). The build dates of the respondent’s homes are presented in Figure 5.7 showing that most of the respondents were living in homes post 1950, while 97 participants (around 35% of participants) were living in homes built before 1930 (similar build time to SEH) and possibly have solid walls (Q6). This proportion of old houses of participants is similar to the number of old houses suitable for SWI with no/poor wall insulation (7.7 million solid wall and 1.75 million cavity wall) in the UK which count for around 33% of the total UK housing stock (BRE (Building Research Establishment), 2014; CCC (Committee on Climate Change), 2019; Hansford, 2015)

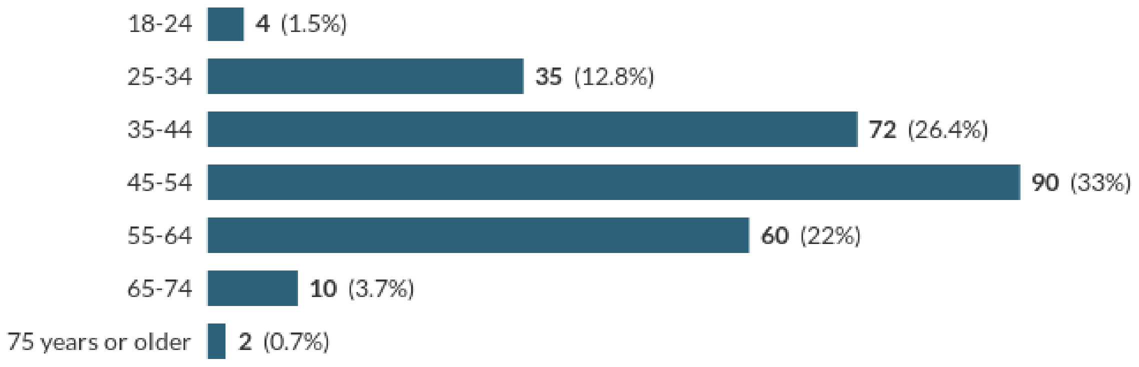


Figure 5.6. Age distribution of participants.

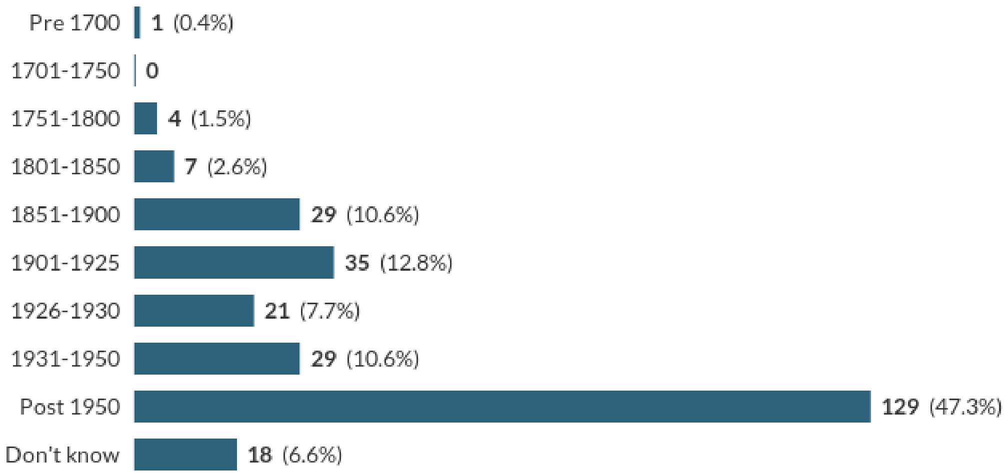


Figure 5.7. Build dates of participants' homes.

Around 81% of participants owned their house (43% owner and 38% mortgage owner) and the rest of participants were renting from private landlords, housing associations, and local authorities by 15%, 3.7% and 0.7% respectively (Q7). Participants were living mainly in semi-detached houses (36.6%) and the rest of participants responded to the other house types in order of detached (24.9%), terraced/mews/town houses (24.9%), flat (9.9%), bungalow (2.2%) and others (1.5%). The number of people living in a household were 1 for 12.8%, 2 for 37.7%, 3 for 23.1%, 4 for 20.5% and more than 4 for 5.9%. The pie chart below reports the household income range of participants. As can be seen the majority of participants (~70%) have household incomes ranges between £20,000-£80,000.

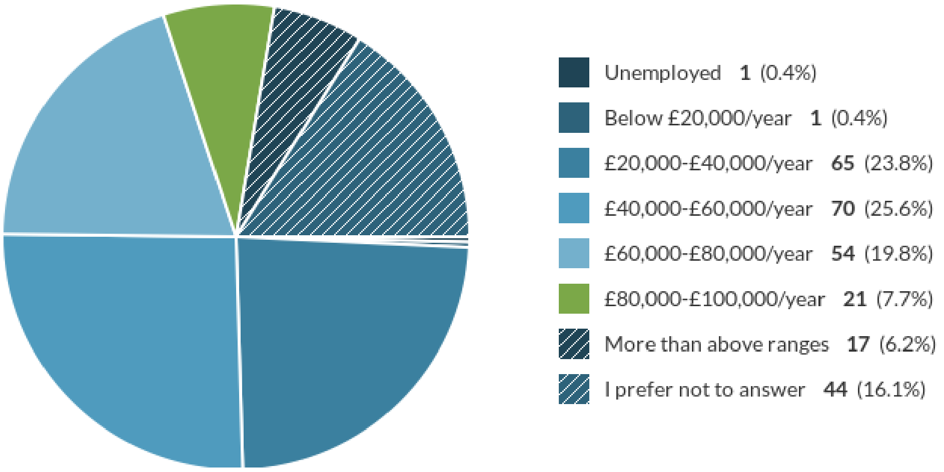


Figure 5.8. Participants households' income.

*Views on Energy improvement*

The participants' views on energy efficiency have been evaluated in Q15, Q16 and Q17-2. The participants showed a significant interest in energy improvement of their homes (99.2% in Q15). However, when it comes to their priority, only 42.6% of participants give priority to energy efficiency in renovation (Q16). This drop could be related to the current difficulties existing in energy efficiency strategies and markets discussed in the literature (see Section 3.1). Similarly, in Q17-2 more than 90% of the participants agreed with the importance of energy efficiency measures in internal renovations. These results confirm the prior findings from the literature and show that although energy efficiency is clearly important to the users, it is not currently on their renovation priority list (Gram-Hanssen, 2014).

*Interest in aesthetics*

Q11, Q12, Q13, Q14, Q17 and Q18 and Q19 are about the aesthetic evaluation among the respondents for their living spaces and renovations. Figure 5.9 shows the participants agreement in percentage for aesthetic related questions. As can be seen, the interest in aesthetic in internal living spaces (Q11) and importance of aesthetic in retrofit (Q12) are very high with participants' valid percentage agreement of more than 90%, however, there is a slight drop of 4.6% for aesthetic consideration in retrofit. This slight lower preference for aesthetic compared to strong aesthetic preference in Q11, may be related to other factors associated with renovation such as perception of cost increase or time delays of renovation (see Figure 5.9). The aesthetic features in retrofit products were questioned without and with increases in product cost in Q13 and Q14. The high agreement of 99.3% and 88.6% are obtained among the respondents respectively. The importance of some factors in renovation such as aesthetic, energy efficiency, cost and time were questioned in Q17. The analysis of participants' responses shows that aesthetic feature is an important factor in renovation by 90.1% support. In Q18 the wall insulation panels with aesthetic features were examined to obtain the view of participants about the aesthetic feature inclusion in IWI. More than 50% of the responses are in favour of such ideas and a further 27.6% neutrally responded, which might be related to not being familiar with the aesthetic panel as people have not still experienced it in a real application. According to the literature, IWI would reduce the internal space slightly depending on the type of insulation and this might be a negative point that might cause some people to be reluctant to implement the internal insulation. Q19 was designed to check whether including aesthetic features to wall insulation would encourage the users to internally insulate the wall of their homes to benefit from both aesthetic and energy efficiency despite the slight decrease in internal spaces. It was found that above 65% of the participants agreed and found aesthetic to be an encouraging factor. This question has also received high neutral responses (24.1%) compared to other questions, in other words, only around 10% of participants disagree with this question. One way to look at these neutral responses is that aesthetic features can encourage people to rethink the implementation of IWI, even if they lose the internal spaces slightly. The neutral view of respondents shows the potentials which might lean toward agreement in future once people learn more about the benefits of the new approach if successful.

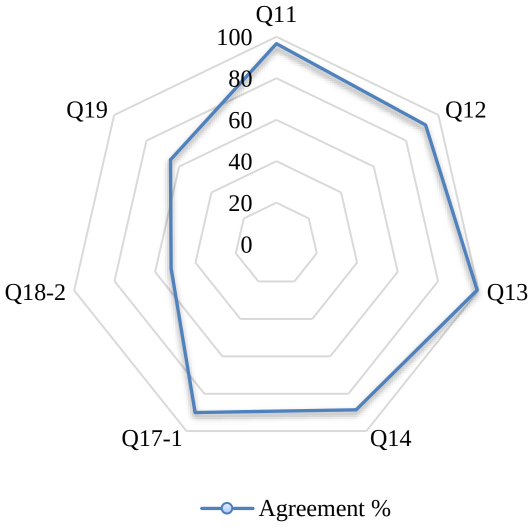


Figure 5.9. Participants' agreement in valid percentages about Aesthetics related questions.

*Cost and time of renovation*

As stated previously, from Q13, about 10.7% of participants responded less positively about aesthetic products which have higher costs compared to Q14. This slight drop reflects the importance of cost for the users in renovation, and it is an important factor for participants as expected because it was also discussed in the literature. Also, the importance of cost and time in renovation was analysed from participants answer to Q17. The responses shows that the participants believe both factors were important, however, cost factor was the most important factor in renovation with 91.6% according to the participants responses. Moreover, time frame criterion was indicated to have the importance of 65% from participants view in renovation projects.

### *Renovation criteria overview*

The renovation criteria i.e., aesthetic, energy efficiency, cost and time were evaluated in the questionnaire and the impression of participants about the importance of all the criteria were assessed in Q17. Figure 5.10 shows the importance of renovation criteria of aesthetic, energy efficiency, cost, and time of renovation according to the participants' responses in valid percentages to the Likert scale question of Q17. As can be seen, aesthetic, cost and energy saving criteria achieved quite similar responses in all the scales, but time frame is different showing the least importance level compared to the other three criteria.

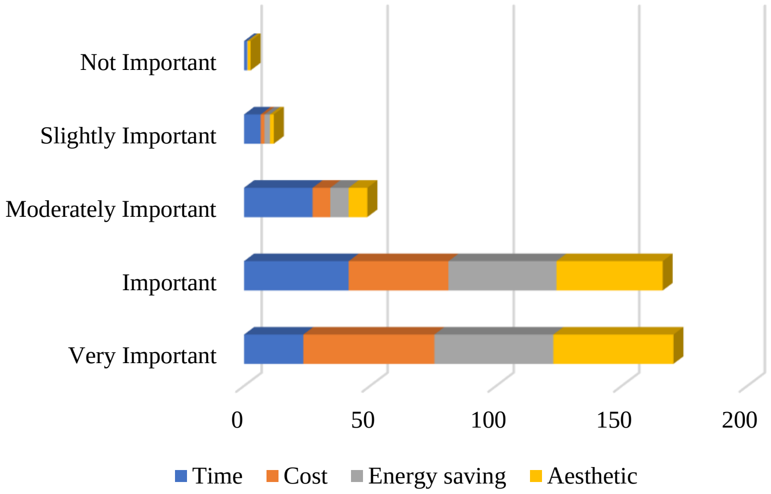


Figure 5.10. Participants' responses to renovation criteria of the study in valid percentages.

Figure 5.10 compares the importance of renovation criteria by considering only the response percentages for 'very important' and 'important'. As can be seen, all criteria are highly important in renovation, however, cost, energy efficiency and aesthetic seem to be more important having their percentage almost the same and higher than time frame. This will prove the significance of aesthetic in renovation which can be as important as cost and energy efficiency factor and shows the necessity of aesthetic consideration in renovation. Furthermore, aesthetic being the high importance criteria in renovation, its consideration in energy efficiency technologies can increase the users' interest to energy efficiency measures as long as reasonable costs can still be offered to them.

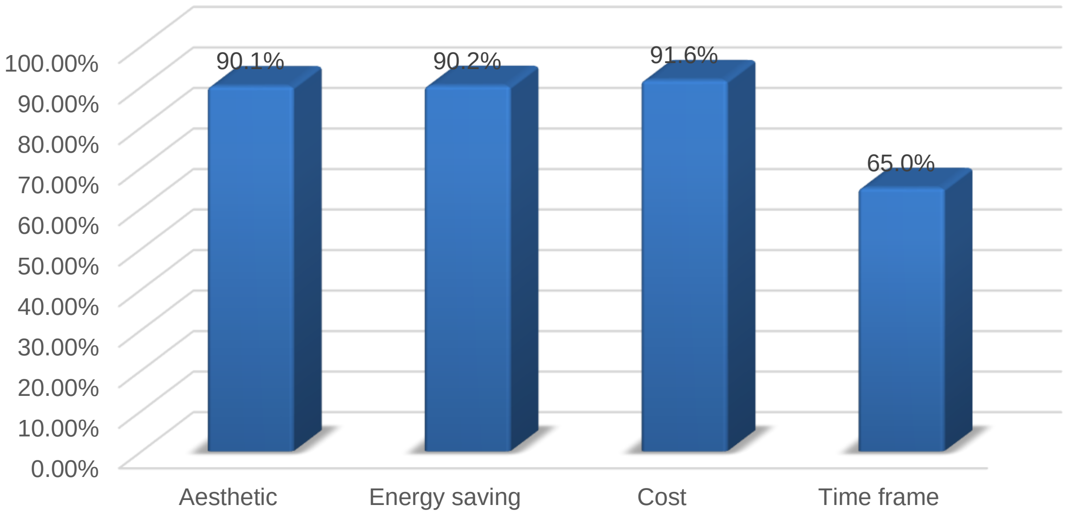


Figure 5.11. The valid percentage of criteria importance (important and very important) in internal renovation according to participants responses.

Figure 5.11 shows the frequency distributions of responses to Q20 about agreement of participants with existence of organisations offering the comprehensive renovation package consisting of energy and aesthetic improvement based on users' preferences (see Section 3.3). The responses were relatively positive with around 67 participants selecting 'Strongly agree', 127 participants selected 'Agree' and 56 participants selected 'Neutral'. Moreover, 9, 2 and 12 participants selected 'Disagree', 'Strongly disagree' and 'Don't know' respectively. It should be noted that the number of responses of 'Neutral' and 'Don't know' were relatively high which can be related to the fact that participants do not have prior experience or knowledge about such organisations and services or may have thought that doing renovation through these companies may be much more expensive compared to, for example DIY or local contractors. There is a high chance that the view of participants who responded neutrally lean towards the agreement once efficient experience of such organisations in terms of time and cost of renovation and achieving the expected aesthetic and SWI saving benefits after renovation could be perceived by the society. Such organisations would be supported by the government, and they can do installations at scale with trained and specialised builders and installers which can reduce the cost and assure the quality of delivery (Chris, 2019; Elderkin, 2011). The aim of these organisations is to provide more legitimate, comprehensive, and professional IWI packages to the users compared to the existing contractors or builders.

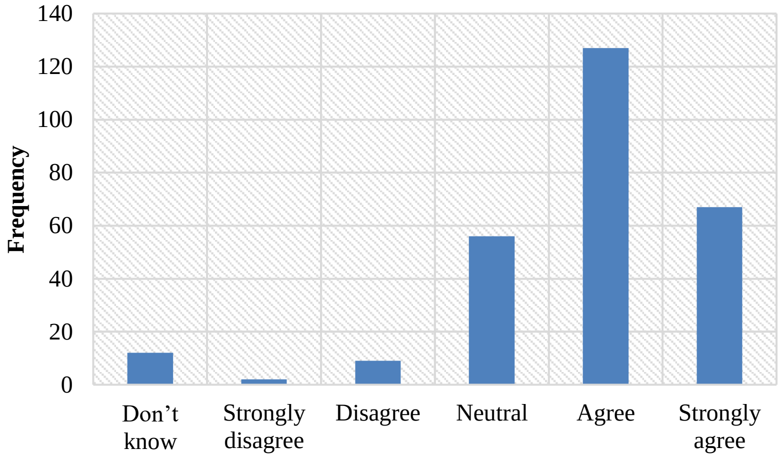


Figure 5.12. Participants responses about existence of organisation to deliver the comprehensive renovation package (aesthetic and energy efficiency).

### 5.2.2 Further in-depth analysis of the survey

The focus of this analysis is to extract useful information from the response data to compare aesthetic factor with other renovation factors and to identify if there is any meaningful relationship between renovation factors, such as aesthetic and other variables, which can contribute to improving SWI retrofit strategies. This section uses some cross-tabulation analysis through the Chi-square test of independence as the descriptive statistical method for data analysis. A lower Chi-square value indicates a smaller variation between observed and expected responses. SPSS, like many statistical programs, uses a significance level of .05, indicating that there is a 5% risk of concluding association while there is no actual correlation.

Some respondents may be unwilling to accurately read the questions or may just tick the answers to proceed to the next question. Designing the 5-point Likert scale for Q17 was to encourage the respondents to engage in responding to questions effectively and to get their views on the importance level of each factor. However, to analyse the responses, all the 5-point scale responses were put in only two categories of ‘important’ and ‘not important’. The first four scales have a level of importance. statistically in order to differentiate between the level of ‘important’ and ‘not important’, aggregation would enable separation of the two opinions. The first four scales were considered as one category of ‘important’ as there is some degree of importance within each scale and the fifth scale alone was considered as a separate category. Table 5.6 shows the overview summary of the responses for each factor. For Aesthetic and Time frame factors, one response was ‘I don’t know’ so it is a missing value and is not included in the table. As the overall view suggests, all the four factors have very similar important values in internal house retrofit. From Table 5.6, cost factor is the most important factor as no one selected not important option; however, the other factors are important similarly which is strongly proven by the responses.

Table 5.6. Overall significance frequency of four under study internal house retrofit factors.

| | | | **Aesthetic** | **Energy saving** | **Cost** | **Time frame** |
|---|---|---|---|---|---|---|
| **Significance** | Important | Frequency | 269 | 272 | 273 | 269 |
| | | % | 98.9% | 99.6% | 100.0% | 98.9% |
| | Not important | Frequency | 3 | 1 | 0 | 3 |
| | | % | 1.1% | 0.4% | 0% | 1.1% |
| Total | | Frequency | 273 | 273 | 273 | 273 |
| | | % | 100.0% | 100% | 100.0% | 100% |

To look at the responses more accurately, the distribution of the responses in the Likert scale of 1 to 5 from ‘very important’ to ‘not important’, for the four factors are shown in Table 5.7. Looking at the responses, the majority of the answers are in first two columns of the Likert scale i.e., ‘important’ and ‘very important’ for all four factors. However, the frequency of the responses in other scales rather than these is higher for time frame compared to other factors. This suggests that time frame is of less priority in internal house retrofit among all four factors. Figure 5.13 and Figure 5.14 presents two radar graphs which visualise the outcome of the presented results from Table 5.7. As Figure 5.13 clearly shows, the response trends for three factors of aesthetic, energy saving, and cost are fairly the same whereas time frame trend is different from the other factors and is of the least priority for the participants. Also, in Figure 5.14 along with each individual scale, the combination of the first two scale of ‘very important’ and ‘important’ responses are plotted to visualise the importance level of aesthetic (90.1%), energy saving (90.2%), cost (91.6%) and time frame (65%) in internal house retrofit which are aligned with what was previously presented in Figure 5.11.

Table 5.7. Aesthetic, energy saving, cost and time frame factors priorities in internal house retrofit for participants.

| | Aesthetic | | Energy saving | | Cost | | Time frame | |
|---|---|---|---|---|---|---|---|---|
| | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % |
| Very Important | 130 | 47.8 | 129 | 47.3 | 142 | 52.0 | 64 | 23.5 |
| Important | 115 | 42.3 | 117 | 42.9 | 108 | 39.6 | 113 | 41.5 |
| Moderately Important | 20 | 7.4 | 20 | 7.3 | 19 | 7.0 | 74 | 27.2 |
| Slightly Important | 4 | 1.5 | 6 | 2.2 | 4 | 1.5 | 18 | 6.6 |
| Not Important | 3 | 1.1 | 1 | .4 | 0 | 0.0 | 3 | 1.1 |
| Total | 272 | 100.0 | 273 | 100.0 | 273 | 100.0 | 272 | 100.0 |

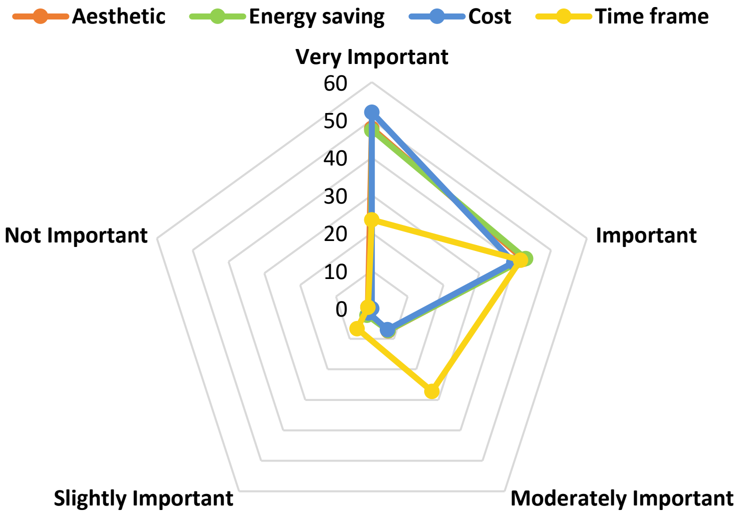


Figure 5.13. Radar graph for percentages of all participants' responses about four understudy internal retrofit factors.

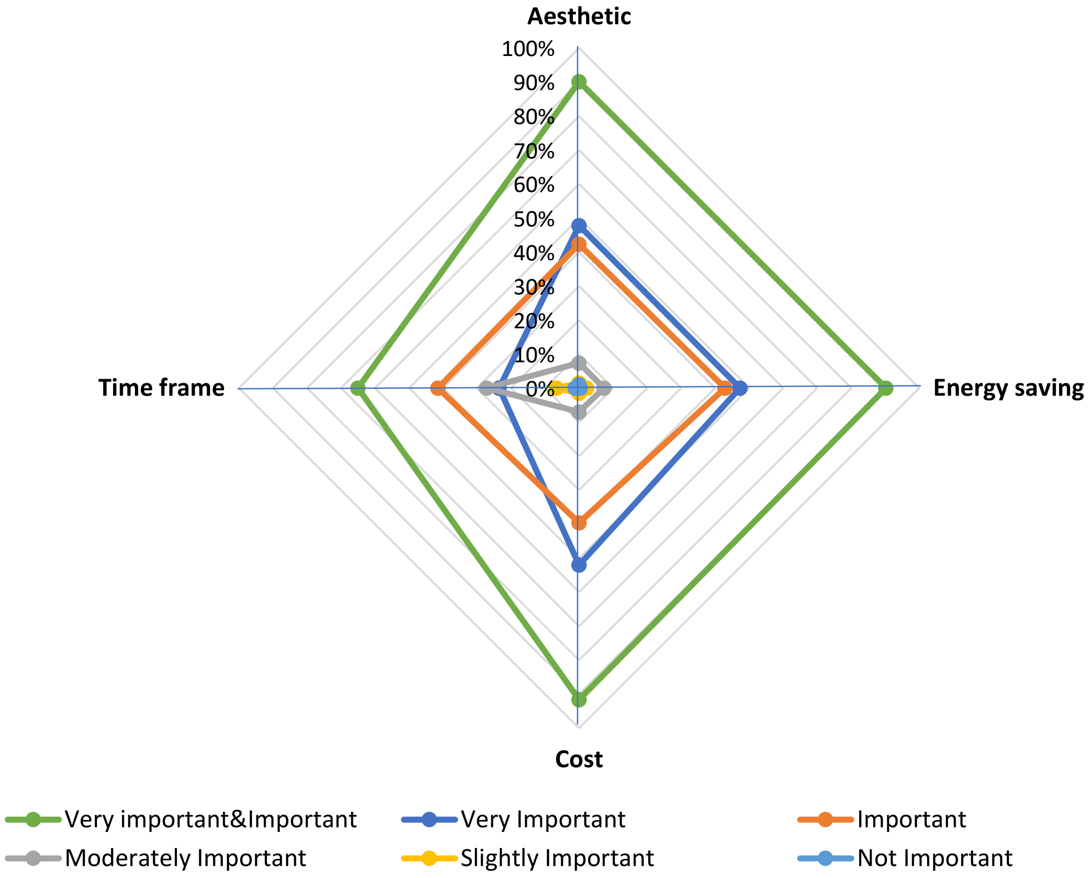


Figure 5.14. The spider graph for aesthetic, energy saving, cost and time frame factors priority level in internal house retrofit for participants.

To see the relationship between the variables questioned in Q17 and PCHI (See Section 4.3.6), the cross-tabulation analysis is performed on each variable, and the results are presented in following tables. Table 5.8 shows the contingency table from cross tabulation analysis between variation of PCHI and aesthetic factor in internal house retrofit for 229 participants who specified their income range (Out of 273, 44 participants did not reveal their income range). The Chi-square test results are also presented in this table. As can be seen, aesthetic factor is important for respondents in low, average, and high categories of PCHI. However, the higher the PCHI is the more important aesthetic is going to be for respondents in internal house retrofit. Considering the analysis for both ‘very important’ and ‘important’ columns, all the households with PCHI in the high category believed aesthetic is an important or highly important factor in internal house retrofit. The Chi-square test table shows the Pearson Chi-square and Fisher exact test. Since the condition for Pearson Chi-square test is not met (i.e. 7 cells (46.7%) have expected count less than 5. The minimum expected count is 17), the Fisher exact test results are referred. From the results, it cannot be concluded that there is a dependency between PCHI and Aesthetic statistically in internal house retrofit since the significance value is above the cut-off point of 0.05. There is not enough evidence to reject the Null Hypothesis of ‘no relationship’, therefore, independence must be assumed.

To compare the view of all participants with owner participants, the same analysis is performed only for owner participants and very similar results are obtained. The aesthetic importance for house owners with low PCHI is reduced slightly by less than 1% (0.9%). However, this is not the case for homeowners in the other two categories; the same figures obtained for high PCHI category and almost negligible increase (0.1%) for householders with average PCHI.

Table 5.8. a) Cross tabulation and b) Chi-square test for distribution of per capita household income and aesthetic factor in internal house retrofit among all participants who specified their income.

**a) Crosstab**

| | | | Aesthetic | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Very Important | Important | Moderately Important | Slightly Important | Not Important | Total |
| **Per Capita Household Income (PCHI)** | Low | Count | 57 | 52 | 11 | 1 | 2 | 123 |
| | | Expected Count | 56.9 | 53.7 | 8.6 | 2.1 | 1.6 | 123.0 |
| | | % within PCHI category | 46.3% | 42.3% | 8.9% | 0.8% | 1.6% | 100.0% |
| | Average | Count | 41 | 43 | 5 | 3 | 1 | 93 |
| | | Expected Count | 43.0 | 40.6 | 6.5 | 1.6 | 1.2 | 93.0 |
| | | % within PCHI category | 44.1% | 46.2% | 5.4% | 3.2% | 1.1% | 100.0% |
| | High | Count | 8 | 5 | 0 | 0 | 0 | 13 |
| | | Expected Count | 6.0 | 5.7 | .9 | .2 | .2 | 13.0 |
| | | % within PCHI category | 61.5% | 38.5% | 0.0% | 0.0% | 0.0% | 100.0% |
| **Total** | | Count | 106 | 100 | 16 | 4 | 3 | 229 |
| | | Expected Count | 106.0 | 100.0 | 16.0 | 4.0 | 3.0 | 229.0 |
| | | % within PCHI category | 46.3% | 43.7% | 7.0% | 1.7% | 1.3% | 100.0% |

**b) Chi-Square Tests**

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 5.263[a] | 8 | .729 | .720 | | |
| Fisher's Exact Test | 4.674 | | | .791 | | |
| N of Valid Cases | 229 | | | | | |

a. 7 cells (46.7%) have expected count less than 5. The minimum expected count is .17.

b. The standardized statistic is -.705.

The similar analysis was performed for PCHI and energy saving factor in internal house retrofit variables. The analysis results for both cross tabulation and Chi-square tests are presented in Table 5.9 below. As the results suggest, energy saving is also an important factor (very important + important) for all households with different PCHI when retrofitting their house internally. However, there is a contradiction between aesthetic and energy savings variables in these two sets of analyses. The lower the PCHI is, the more energy saving but the less aesthetic factor is important for respondents in internal house retrofit. This could be because people with lower financial income care more about their energy bills compared to people in better financial positions. The similar results were obtained from Chi-square test analysis; the Fisher exact test shows the P value of higher than 0.05 which advises the results are not statistically significant, meaning that the two variables of energy saving and PCHI are likely to be independent as no effect was detected from the test.

Also, the same analysis by considering the responses from the homeowner participants only is performed and the obtained results are very similar, but a slight increase (3%) is observed for householders in high PCHI category. This means that although energy retrofit is of interests of all the participants, it is the more important factor for the homeowners.

Table 5.9. a) Cross tabulation and b) Chi-square test for distribution of per capita household income and energy saving in internal house retrofit among all participants who specified their income.

a) **Crosstab**

| | | | **Energy saving** | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | Very Important | Important | Moderately Important | Slightly Important | Not Important | |
| **Per Capita Household Income (PCHI)** | Low | Count | 54 | 60 | 7 | 2 | 0 | 123 |
| | | Expected Count | 55.9 | 56.4 | 7.5 | 2.7 | .5 | 123.0 |
| | | % within PCHI category | 43.9% | 48.8% | 5.7% | 1.6% | 0.0% | 100.0% |
| | Average | Count | 45 | 40 | 4 | 3 | 1 | 93 |
| | | Expected Count | 42.2 | 42.6 | 5.7 | 2.0 | .4 | 93.0 |
| | | % within PCHI category | 48.4% | 43.0% | 4.3% | 3.2% | 1.1% | 100.0% |
| | High | Count | 5 | 5 | 3 | 0 | 0 | 13 |
| | | Expected Count | 5.9 | 6.0 | .8 | .3 | .1 | 13.0 |
| | | % within PCHI category | 38.5% | 38.5% | 23.1% | 0.0% | 0.0% | 100.0% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Total** | Count | 104 | 105 | 14 | 5 | 1 | 229 |
| | Expected Count | 104.0 | 105.0 | 14.0 | 5.0 | 1.0 | 229.0 |
| | % within PCHI category | 45.4% | 45.9% | 6.1% | 2.2% | 0.4% | 100.0% |

| **b) Chi-Square Tests** | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 9.969[a] | 8 | .267 | .221 | | |
| Fisher's Exact Test | 9.160 | | | .311 | | |
| N of Valid Cases | 229 | | | | | |

a. 7 cells (46.7%) have expected count less than 5. The minimum expected count is .06.

b. The standardized statistic is .604.

The next table shows the related cross tabulation and Chi-square tests results for PCHI and cost factor in internal house retrofit variables. As the results suggest, cost is another important factor in internal house retrofit according to the response data for all households with different PCHI, none of the participants considered this factor to be not important. However, this level of certainty did not exist for other three variables of aesthetic, energy saving, and time frame presented in Table 5.8, Table 5.9 and Table 5.11. Cost importance from the responses (which include both ‘very important’ and ‘important’ options) suggests that participants with both low and high PCHI care slightly more about the cost with 93.5% and 92.3% values compare to participants in the average PCHI category (89.3%). This result suggests that people with low or high financial income care about cost more compared to people in average incomes. Looking at the Fisher exact test (the condition for Pearson Chi-square test is not met), the P value is higher than 0.05 (the statistical significance value) and the results are not statistically significant. Therefore, no effect was observed, and it cannot be concluded that a significant dependency exists between aesthetic and PCHI variables. Analysing the data for the owner participants only shows the similar trend but lower percentages for results compared to the result analysis of all response data. The asymptotic significance values are not below the statistically significant value which again suggests variables independence.

Table 5.10. a) Cross tabulation and b) Chi-square test for distribution of per capita household income and cost in internal house retrofit among all participants who specified their income.

**a) Crosstab**

| | | | Cost | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Very Important | Important | Moderately Important | Slightly Important | Not Important | Total |
| **Per Capita Household Income (PCHI)** | Low | Count | 70 | 45 | 7 | 1 | 0 | 123 |
| | | Expected Count | 62.3 | 50.5 | 8.1 | 2.1 | 0.0 | 123.0 |
| | | % within PCHI category | 56.9% | 36.6% | 5.7% | 0.8% | 0% | 100.0% |
| | Average | Count | 42 | 41 | 8 | 2 | 0 | 93 |
| | | Expected Count | 47.1 | 38.2 | 6.1 | 1.6 | 0.0 | 93.0 |
| | | % within PCHI category | 45.2% | 44.1% | 8.6% | 2.2% | 0% | 100.0% |
| | High | Count | 4 | 8 | 0 | 1 | 0 | 13 |
| | | Expected Count | 6.6 | 5.3 | .9 | .2 | 0.0 | 13.0 |
| | | % within PCHI category | 30.8% | 61.5% | 0.0% | 7.7% | 0% | 100.0% |
| **Total** | | Count | 116 | 94 | 15 | 4 | 0 | 229 |
| | | Expected Count | 116.0 | 94.0 | 15.0 | 4.0 | 0.0 | 229.0 |
| | | % within PCHI category | 50.7% | 41.0% | 6.6% | 1.7% | 0% | 100.0% |

**b) Chi-Square Tests**

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 9.574[a] | 6 | .144 | .132 | | |
| Fisher's Exact Test | 9.007 | | | .138 | | |
| N of Valid Cases | 229 | | | | | |

a. 4 cells (33.3%) have expected count less than 5. The minimum expected count is .23.

b. The standardized statistic is 2.270.

Further analysis for two variables of PCHI and time frame factor in internal house retrofit is performed and the results are presented in Table 5.11. As the results suggest alike previously analysed factors, time frame of internal house retrofit is also important factor (very important + important) for all households with different PCHI. The time frame factor corresponds to 65% of responses in low, 63.4% of responses in average and 76.9% responses in high categories of PCHI. More than 10% increase is observed for importance of time frame factor for participants with high PCHI. Therefore, emphasising on minimum planning time frame for internal house retrofit should be considered specially for people with the high PCHI. The obtained results from Chi-square test analysis shows that the P value is higher than 0.05 for Fisher exact test and the results are not statistically significant, and the dependency between these two variables cannot be concluded (Fisher exact Chi-squared (8) = 6.399; p=0.591>0.05).

Considering the owner participants only, the obtained results agree with the analysis results for all participants, but the importance level of time frame factor is about 7-8% higher for householders in high PCHI compared to other two other PCHI categories.

Table 5.11. a) Cross tabulation and b) Chi-square test for distribution of per capita household income and time in internal house retrofit among all participants who specified their income.

**a) Crosstab**

| | | | **Time frame** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Very Important | Important | Moderately Important | Slightly Important | Not Important | Total |
| **Per Capita Household Income (PCHI)** | Low | Count | 26 | 54 | 34 | 7 | 2 | 123 |
| | | Expected Count | 25.2 | 54.8 | 31.7 | 9.7 | 1.6 | 123.0 |
| | | % within PCHI category | 21.1% | 43.9% | 27.6% | 5.7% | 1.6% | 100.0% |
| | Average | Count | 20 | 39 | 22 | 11 | 1 | 93 |
| | | Expected Count | 19.1 | 41.4 | 24.0 | 7.3 | 1.2 | 93.0 |
| | | % within PCHI category | 21.5% | 41.9% | 23.7% | 11.8% | 1.1% | 100.0% |
| | High | Count | 1 | 9 | 3 | 0 | 0 | 13 |
| | | Expected Count | 2.7 | 5.8 | 3.3 | 1.0 | .2 | 13.0 |
| | | % within PCHI category | 7.7% | 69.2% | 23.1% | 0.0% | 0.0% | 100.0% |
| **Total** | | Count | 47 | 102 | 59 | 18 | 3 | 229 |
| | | Expected Count | 47.0 | 102.0 | 59.0 | 18.0 | 3.0 | 229.0 |
| | | % within PCHI category | 20.5% | 44.5% | 25.8% | 7.9% | 1.3% | 100.0% |

**b) Chi-Square Tests**

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 7.331[a] | 8 | .501 | .505 | | |
| Fisher's Exact Test | 6.399 | | | .591 | | |
| N of Valid Cases | 229 | | | | | |

a. 6 cells (40.0%) have expected count less than 5. The minimum expected count is .17.

b. The standardized statistic is .165.

The result analysis presented so far, shows that all the aesthetic, energy saving, cost and time frame are important factors in internal house retrofit for all the participants within different PCHI categories. The bar graph below (Figure 5.15) represents the summary of the results provided in the tables above for better comparison of aesthetic, energy saving cost and time frame factors in relation to PCHI according to 229 participants' responses.

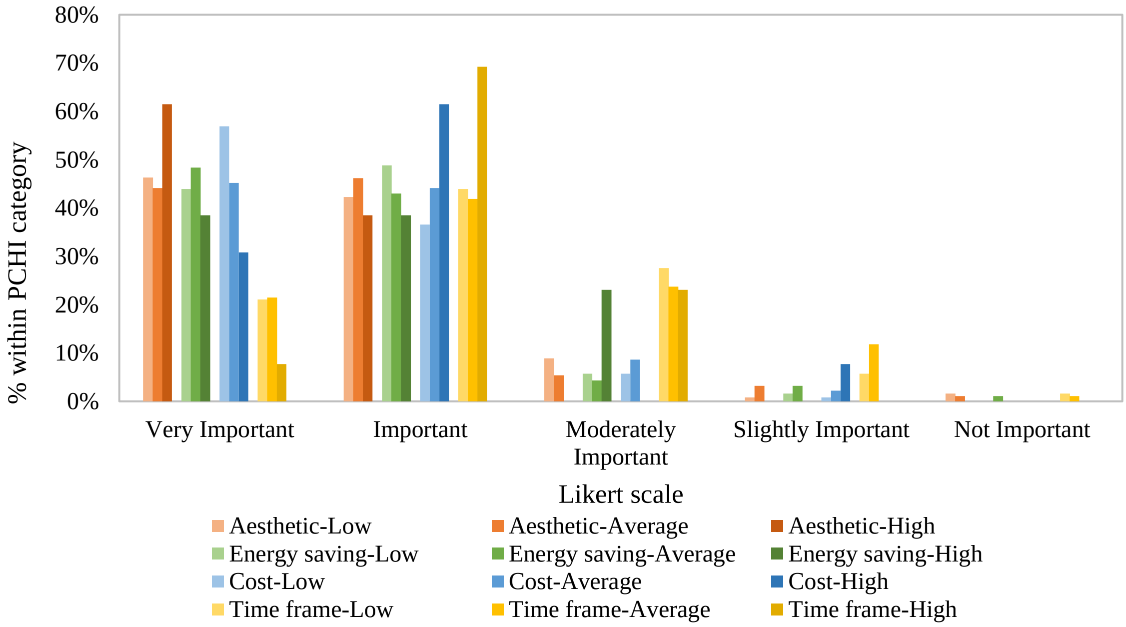


Figure 5.15. Bar graph for aesthetic, energy saving cost and time frame factors according to participants' PCHI.

The importance level is calculated in count, expected count and percentages within PCHI category, by adding the number of responses for both 'very important' and 'important' options. The summary results for the four variables and PCHI variables are presented in Table 5.12. As can be seen, time frame is observed to be of less importance in internal house retrofit compared to other three factors for participants, but still is a considerable factor in internal home retrofit. However, all three factors of cost, energy saving, and aesthetic have very high but close importance with total values of 91.7%, 91.3% and 90% respectively which proves these three factors should be equally considered in house retrofit internally.

Table 5.12. Importance of aesthetic, energy saving, cost and time frame factors in internal house retrofit for participants.

| | | | Aesthetic | Energy saving | Cost | Time frame |
|---|---|---|---|---|---|---|
| **Per Capita Household Income (PCHI)** | Low | Count | 109/123 | 114/123 | 115/123 | 80/123 |
| | | Expected Count | 109.0 | 114 | 115.0 | 80.0 |
| | | % within PCHI category | 88.6% | 92.7% | 93.5% | 65% |
| | Average | Count | 84/93 | 85/93 | 83/93 | 59/93 |
| | | Expected Count | 84.0 | 85.0 | 83.0 | 59.0 |
| | | % within PCHI category | 90.3% | 91.4% | 89.3% | 63.4% |
| | High | Count | 13/13 | 10/13 | 12/13 | 10/13 |
| | | Expected Count | 13.0 | 10.0 | 12.0 | 10.0 |
| | | % within PCHI category | 100% | 77% | 92.3% | 76.9% |
| **Total** | | Count | 206/229 | 209/229 | 210/229 | 149/229 |
| | | Expected Count | 206.0 | 209.0 | 210.0 | 149.0 |
| | | % within PCHI category | 90% | 91.3% | 91.7% | 65% |

There is not much difference in the importance level of the studied internal home retrofit factors for participants in all PCHI categories. The results show that aesthetic factor is as important as cost and energy saving for the participants, in which the latter two factors are very well-known factors in internal home retrofit in the literature, but the former is missing. Currently almost all of incentives or proposed plans for retrofitting the house mainly consider the cost and energy saving factors only and they lack including the aesthetic factor in retrofit supports. The results suggest that including the aesthetic preferences of residences as one of the most significant factors in the retrofit plans can greatly encourage householders to retrofit their homes, where energy saving, or cost incentives alone could not be effective in homeowner decisions to implement the retrofit measures. It was highlighted in the literature that the proposed plans for retrofitting the existing UK homes should be more encouraging for homeowners (Hansford, 2015). The result of this research has quantitively proved the aesthetic importance for driving the retrofit which is missing in the current retrofitting plans, policies, and procedures to make the existing, poorly or no insulated homes energy efficient. Aesthetic is a key factor which needs to be included to create more encouraging and practical energy retrofit plans. According to the results, it is recommended that the energy retrofit industry and internal home improvement industry work together more closely. It will be beneficial as they can offer IWI with not only the benefit of energy saving, but also with the redecorating options for the householders to add aesthetic features to the customer satisfaction level. Policy makers can also start to think about the inclusion of redecorating incentives in energy retrofit plans for IWI as a solution for the low interest in SWI in the UK.

Table 5.13 presents the values obtained for importance of all the studied factors in internal home retrofit from the view of participants living in pre1930 or solid wall homes only. The data for Q5 and Q6 were filtered to show only the responses for the participants who live in old houses. (Filter: Q6 <= 7 / Q5 = 1). 201 participants are identified to be living in solid wall homes or homes that were built pre-1930. The view of people living in older properties (high chance of having no/poor insulation level) is analysed separately because they may have different views towards renovation factors due to the drawbacks of their uninsulated homes. As can be seen in the table, the view of participants who are living in the old houses are very similar to the responses of all the participants. Most of them believed that all the factors especially the aesthetic, energy saving, and cost are important in internal home retrofit. More people stated that time frame is a moderately important factor compared to the other three factors. Only one participant thought that aesthetic, energy saving, and time frame factors are not important in retrofitting the home internally, however, the importance of these factors were recognised by all other participants. Considering the sum of very important and important responses of participants, aesthetic, and cost both have the same highest importance level of 91.5%.

Table 5.13. Aesthetic, energy saving, cost and time frame factors priorities in internal house retrofit for participants living in pre1930 or solid wall homes.

| | **Aesthetic** | | **Energy saving** | | **Cost** | | **Time frame** | |
|---|---|---|---|---|---|---|---|---|
| | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % |
| Very Important | 98 | 49.0 | 91 | 45.3 | 102 | 50.7 | 41 | 20.4 |
| Important | 85 | 42.5 | 89 | 44.3 | 82 | 40.8 | 92 | 45.8 |
| Moderately Important | 13 | 6.5 | 17 | 8.5 | 14 | 7.0 | 51 | 25.4 |
| Slightly Important | 3 | 1.5 | 3 | 1.5 | 3 | 1.5 | 16 | 8.0 |
| Not Important | 1 | .5 | 1 | .5 | 0 | 0 | 1 | .5 |
| Total | 200 | 100.0 | 201 | 100.0 | 201 | 100.0 | 201 | 100.0 |

Furthermore, the same analysis is performed only for owners living in pre1930 or solid wall homes using the filter for Q7, Q5 and Q6. (Q7 <= 2 & Q5 = 1 / Q6 <= 7). Out of

220 owner participants (about 81% of all participants), 171 participants are living in old homes and their views about the importance level of internal retrofit factors are presented in Table 5.14. The results suggest the similar trends to the previous table, but considering very important and important responses, aesthetic is the most important factor amongst other factors. In both Table 5.13 and Table 5.14, the aesthetic and cost factors have slightly higher response percentages to 'very important' compared to energy saving factor. This shows that aesthetic factor which was overlooked in the past should now be the focus of internal retrofits planning for the UK homes.

Table 5.14. Importance of aesthetic, energy saving, cost and time frame factors in internal house retrofit for owner participants living in pre1930 homes or solid walls.

| | **Aesthetic** | | **Energy saving** | | **Cost** | | **Time frame** | |
|---|---|---|---|---|---|---|---|---|
| | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % | Frequency | Valid % |
| Very Important | 87 | 51.2 | 77 | 45.0 | 83 | 48.5 | 34 | 19.9 |
| Important | 68 | 40.0 | 76 | 44.4 | 72 | 42.1 | 75 | 43.9 |
| Moderately Important | 12 | 7.1 | 14 | 8.2 | 13 | 7.6 | 46 | 26.9 |
| Slightly Important | 2 | 1.2 | 3 | 1.8 | 3 | 1.8 | 15 | 8.8 |
| Not Important | 1 | .6 | 1 | .6 | 0 | 0.0 | 1 | .6 |
| Total | 170 | 100.0 | 171 | 100.0 | 171 | 100.0 | 171 | 100.0 |

Similar to the Table 5.12, Table 5.15 was developed only for participants living in old houses (i.e. pre 1930s or solid wall dwellings) to demonstrate their views about the four factors according to their PCHI level. Out of 201 participants who lived in old homes, 31 participants did not prefer to reveal their income, therefore, the analysis is performed with 170 valid responses. The trends of the results are fairly similar to the responses from all participants; however, it seems the aesthetic factor is a slightly more important factor for participants from old homes. This suggests that improving the aesthetical features internally is even more of a priority in retrofitting the solid wall and old housing stock, hence, considering this factor can make a real difference in promoting retrofitting measures in wall insulation.

Table 5.15. Importance of aesthetic, energy saving, cost and time frame factors in internal house retrofit for participants who are living in old homes (solid wall or pre 1930s dwellings).

| | | | Aesthetic | Energy saving | Cost | Time frame |
|---|---|---|---|---|---|---|
| **Per Capita Household Income (PCHI)** | Low | Count | 86/93 | 87/93 | 88/93 | 64/93 |
| | | Expected Count | 86.0 | 87.0 | 88.0 | 64.0 |
| | | % within PCHI category | 92.5% | 93.6% | 94.7% | 68.8% |
| | Average | Count | 60/68 | 62/68 | 60/68 | 41/68 |
| | | Expected Count | 60.0 | 62.0 | 60.0 | 41.0 |
| | | % within PCHI category | 88.2% | 91.1% | 88.2% | 60.3% |
| | High | Count | 9/9 | 7/9 | 8/9 | 7/9 |
| | | Expected Count | 9.0 | 7.0 | 8.0 | 7.0 |
| | | % within PCHI category | 100% | 77.8% | 88.9% | 77.8% |
| **Total** | | Count | 155/170 | 156/170 | 156/170 | 112/170 |
| | | Expected Count | 155.0 | 156.0 | 156.0 | 112.0 |
| | | % within PCHI category | 91.2% | 91.7% | 91.8% | 65.9% |

According to the result analysis of the participants responses presented in Table 5.12 and Table 5.15, some recommendations for home retrofitting are extracted. In general, considering all participants, energy saving, aesthetic and cost seems to be of similar importance level for participants in low- and average-income categories. For participants in high income category, the aesthetic factor was the most important factor and other three factors of cost, energy saving, and time frame were similarly important. Understanding the individuals' needs in internal house retrofit to adapt the retrofit strategies would enhance the interest and application of retrofit measures such as ISWI. According to the result analysis provided, aesthetic factor is as important as cost and energy saving factor and in cases was more important. Cost and energy are two well-known important factors which are included in the industry and Government retrofit strategies but aesthetic which is proved to be almost equally as important as the other two factors, has not been included in any of the retrofit strategies so far. Aesthetic factor needs to be added to the retrofit strategies of old housing stock to encourage the implementation of wall insulation. Among the retrofit measures, IWI is one of the important and effective measures which needs attention in energy saving of old homes or solid wall homes; including aesthetic factor in the case of SWI should be the priority in developing the new retrofit strategies. Aesthetic factor beside the cost and energy saving in IWI in energy retrofit strategies can considerably enhance the uptake and further encourage people to implement the IWI. It is also important that the IAWI can be installed in an appropriate time frame to minimise the disruption for the occupant. The requirements and priorities of people in any financial circumstances should be considered in retrofitting homes and specially in the case of wall insulation to promote the uptake of insulation for the solid wall homes. For groups of people for whom one factor has more priority, the other factors can act as encouragement measures to facilitate the retrofit plan and make it more attractive for customers.

In another analysis the view of participants about the four prementioned factors are investigated according to their age groups. According to Table 5.16, the majority of participants were in the 35-64 age range. Looking at all the responses in different age groups, within 35-64, participants believe that aesthetic factor is almost as important as the cost and energy saving factors, and time frame is the lowest priority factor for them in internal house retrofit. Participants in the 18–34-year-old category believe aesthetic and cost are the most important factors with 97.4% and energy saving, and time frame are in their later priorities with 84.6% and 71.8% agreement within this age category. For the case of 65-year-old and older participants, energy saving, and cost have the highest priority and aesthetic and time frame were in order the third and fourth priority for participants. As only the combination of the important and very important scales considered in the table, the Chi-square test results is not computed since all the variables are a constant and there is no variation in responses. Therefore, the Chi-square test is performed for individual factors separately considering the full Likert scale and age variable but no dependency between them is identified.

Table 5.16. Importance of aesthetic, energy saving, cost and time frame factors in internal house retrofit according to age categories of all participants.

| | | | Aesthetic | Energy saving | Cost | Time frame |
|---|---|---|---|---|---|---|
| Age | 18-34 | Count | 38/39 | 33/39 | 38/39 | 28/39 |
| | | Expected Count | 38.0 | 33.0 | 38.0 | 28.0 |
| | | % within age category | 97.4% | 84.6% | 97.4% | 71.8% |
| | 35-44 | Count | 62/72 | 67/72 | 68/72 | 45/72 |
| | | Expected Count | 62.0 | 67.0 | 68.0 | 45.0 |
| | | % within age category | 86.1% | 93.1% | 94.5% | 62.5% |
| | 45-54 | Count | 80/89 | 83/90 | 82/90 | 64/90 |
| | | Expected Count | 80.0 | 83.0 | 82.0 | 64.0 |
| | | % within age category | 89.9% | 92.2% | 91.2% | 71.1% |
| | 55-64 | Count | 56/60 | 52/60 | 52/60 | 32/60 |
| | | Expected Count | 56.0 | 52.0 | 52.0 | 32.0 |
| | | % within age category | 93.3% | 86.7% | 86.7% | 53.3% |
| | 65 years or older | Count | 9/12 | 11/12 | 10/12 | 8/11 |
| | | Expected Count | 9.0 | 11.0 | 10.0 | 8.0 |
| | | % within age category | 75% | 91.7% | 83.3% | 72.7% |
| **Total** | | Count | 245/272 | 246/273 | 250/273 | 177/272 |
| | | Expected Count | 245.0 | 246.0 | 250.0 | 177.0 |
| | | % within age category | 90.1% | 90.2% | 91.6 | 65% |

Table 5.17 is cross tabulation for gender and the four factors being studied. Comparing male and female participants, with their distributions almost equal, it seems time frame and aesthetic are more important for female respondents compared to male participants while energy saving, and cost factors are almost equally important for participants in both gender categories. Like previous analyses, the aesthetic, energy

saving, and cost factors are a higher priority for the participants compared to time frame.

Table 5.17. Importance of aesthetic, energy saving, cost and time frame factors in internal house retrofit according to gender categories for all participants.

| | | | **Aesthetic** | **Energy saving** | **Cost** | **Time frame** |
|---|---|---|---|---|---|---|
| **Gender** | Male | Count | 117/135 | 123/136 | 124/136 | 83/135 |
| | | Expected Count | 117.0 | 123.0 | 124.0 | 83.0 |
| | | % within gender category | 86.7% | 90.5% | 91.2% | 61.4% |
| | Female | Count | 128/137 | 123/137 | 126/137 | 94/137 |
| | | Expected Count | 128.0 | 123.0 | 126.0 | 94.0 |
| | | % within gender category | 93.5% | 89.8% | 92% | 68.6% |
| **Total** | | Count | 245/272 | 246/273 | 250/273 | 177/272 |
| | | Expected Count | 245 | 246.0 | 250.0 | 177.0 |
| | | % within gender category | 90.1% | 90.2% | 91.6% | 65% |

The participants' origin variable is also studied to see whether participants responded differently to the four factors due to their origins and potential cultural differences. The results are presented in Table 5.18. The number of participants in the UK origin category is 225 and the participants with non-UK origin are 43. Comparing the results in percentages for UK and Non-UK origins shows that aesthetic, cost, and energy saving factors have the highest priority for participants of both categories. Aesthetics and cost were similarly the most important factors among UK participants, however, for non-UK participants cost factor has a higher priority compared to aesthetic and energy saving factors. Non-UK participants have additional concerns about the cost factor in renovation compared to UK-participants. It may be related to additional living cost exposed on non-UK participants such as the cost of visa applications and/or traveling abroad to visit family. The time frame factor is still a less important factor for both categories of participants, but it seems this factor is in higher priority for non-UK participants compared to participants with UK Origin.

Table 5.18. Importance of aesthetic, Energy saving, cost and time frame factors in internal house retrofit according to participants' Origin.

| | | | Aesthetic | Energy saving | Cost | Time frame |
|---|---|---|---|---|---|---|
| **Origin** | UK | Count | 203/224 | 202/225 | 203/225 | 140/224 |
| | | Expected Count | 203.0 | 202.0 | 203.0 | 140.0 |
| | | % within Origin category | 90.7% | 89.8% | 90.2% | 62.5% |
| | Non-UK | Count | 37/43 | 39/43 | 42/43 | 34/43 |
| | | Expected Count | 37.0 | 39.0 | 42.0 | 34.0 |
| | | % within Origin category | 86% | 90.7% | 97.7% | 79.1% |
| **Total** | | Count | 240/267 | 241/268 | 245/268 | 174/267 |
| | | Expected Count | 240.0 | 241.0 | 245.0 | 174.0 |
| | | % within Origin category | 89.9% | 89.9% | 91.4% | 65.1% |

As discussed so far, no matter how we categorise the data to analyse (i.e., income, origin, gender, or age, for all participants, only owner participants or participants living in old houses) aesthetic, energy saving, cost and time frame factors are very similarly important in all cases. The response data for all the factors have very similar trends, and the trends for aesthetic, energy saving, and cost are almost a match.

Further analysis was conducted to find out whether any two variables are strongly correlated and the increase in importance of one variable can cause similar or reverse effect on the other variable. Thus, Spearman correlation analysis was conducted to find the strength and direction of association between the aesthetic, energy saving, cost and time frame variables and the results are presented in Table 5.19. As the variables are ordinal (from Likert scale type questions), non-parametric Spearman correlation analysis was used in SPSS. When data are measured in ordinal level, they are said to be non-parametric and the Spearman correlation test needed to be used (Solutions, 2016). From the table, the correlation between the variables is likely to exist because P values (Sig. (2-tailed)) are less than 0.05. Therefore, the null hypothesis of no correlation between variable will be rejected and the alternate hypothesis which is the existence of the correlation will be accepted (Weiss & Weiss, 2017). However, from the correlation coefficients, while a positive association exists, the correlation is weak as the correlation coefficients are very small in the table (varying between 0.168-

0.292). Therefore, it cannot be strongly concluded that by increasing the importance of one variable, that the importance for the paired variable also increases.

Table 5.19. The nonparametric correlations analysis for understudy variables.

| | | | Aesthetic | Energy saving | Cost | Time frame |
|---|---|---|---|---|---|---|
| **Spearman's rho** | Aesthetic | Correlation Coefficient | 1.000 | .218** | .168** | .127* |
| | | Sig. (2-tailed) | . | .000 | .005 | .037 |
| | | N | 272 | 272 | 272 | 271 |
| | Energy saving | Correlation Coefficient | .218** | 1.000 | .280** | .198** |
| | | Sig. (2-tailed) | .000 | . | .000 | .001 |
| | | N | 272 | 273 | 273 | 272 |
| | Cost | Correlation Coefficient | .168** | .280** | 1.000 | .292** |
| | | Sig. (2-tailed) | .005 | .000 | . | .000 |
| | | N | 272 | 273 | 273 | 272 |
| | Time frame | Correlation Coefficient | .127* | .198** | .292** | 1.000 |
| | | Sig. (2-tailed) | .037 | .001 | .000 | . |
| | | N | 271 | 272 | 272 | 272 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Earlier, in Section 4.4.2, the response frequencies for Q15 and Q16 were reported. A more profound result analysis for these two questions is discussed here. From 264 participants (count as almost 97% of all the participants) who liked to do energy retrofit to improve the energy efficiency of their homes, only 34.5% of them (91 out of 264 participants) stated that energy efficiency is their priority during the retrofit due to the difficulties or uncertainties existing currently in the retrofit process. Around 21% neutrally responded, meaning that they are not sure if they still prioritise the energy efficiency in home retrofit. This drop in the results can be related to the existence of difficulties in current approaches which slow down the application of SWI as discussed in Chapter 3 Section 3.1 (Brannigan & Booth, 2013; BRE (Building Research Establishment), 2014). Although, people may be interested and aware of the benefits of SWI, the majority of them do not feel confident to implement this measure in their homes due to the current unclear path for retrofitting the solid walls (See Section 2.8 in Chapter 2). One sensible solution for the existing issues could be centralising the retrofitting of the old homes through professional organisations who ensure the standard delivery of retrofit measures specially for SWI. The participants' strong answers in Q20, in agreement with the existence of such organisations (71%) is a proof for validity of the proposed solution. Further 21% neutral responses could lean towards the agreement once the strategy is initiated and publicised in the market and its benefits can be perceived by potential customers.

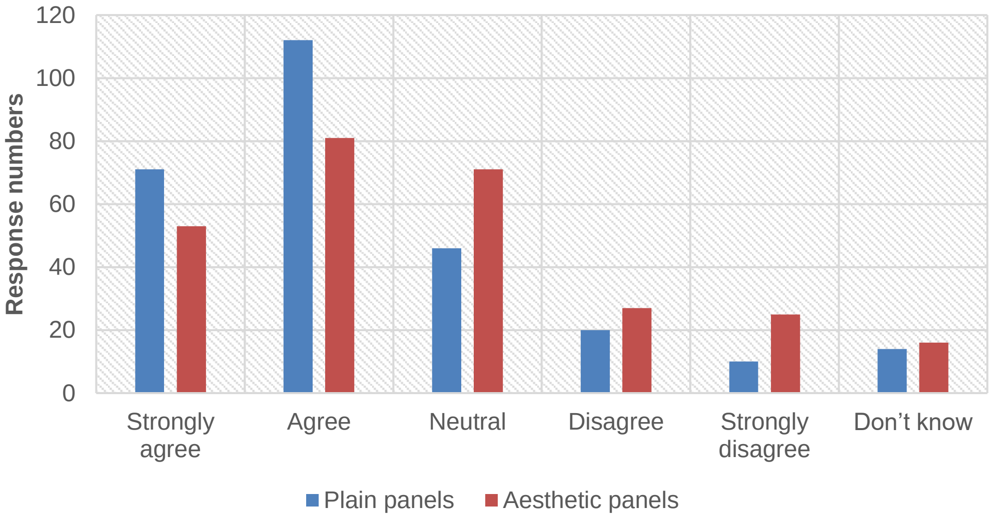


Figure 5.16. Plain vs aesthetic panel.

In Q18, the insulation panels with and without aesthetic features were questioned, the participant's responses are compared in bar graph presented in Figure 5.16. As can be seen the trend of responses for both panel types are similar while the participants seem to agree with plain panels with more confidence compared to the aesthetic panel. Also, these data are analysed using Paired sample T-test to identify the statistical difference between two panels (Kent State University, 2022b). The paired sample T-test is used to compare the means of two response data because the participants had to state their level of agreement with both panels. In the scale of 1 to 5 from strongly agree to strongly disagree, it is found that the responses to the plain panel are 2.19 and to aesthetic panel are 2.59 on average. Therefore, the responses to aesthetic panels are in the neutral position whilst participants are in positive agreement for plain panels. Paired sample T-test reported a mean difference of 0.394 between the two options. The summary of Pair sample T-test is T (253) =-3.230; P=0.001; $CI_{95\%}$ [-0.634, -0.154]. The neutral position of respondents about aesthetic panels could probably be because people are unsure as it is a new product which has not yet been implemented in the market. Also, it could be related to participants preference to have their own decisions on the final look rather than an already set decoration on the panel.

### 5.2.3 Integration of Aesthetic in internal wall insulation

To integrate the results from survey and energy analysis (research question 8, Section 1.2) aesthetic in energy Manchester city is selected as an exemplar to demonstrate the calculation considering the results from both phases. The selection of this city for demonstrating the calculation is because the energy saving benefits of SWI was assessed using a Manchester weather file in the first phase of the study. Further studies (see Appendix 5) showed that Manchester, according to its climatic profile, would provide a middle point between all possible savings in different parts of the United Kingdom as presented in Table 5.20. It is, therefore, possible to assume that SWI energy saving results for Manchester, could provide a good estimate for the possible saving across United Kingdom.

Table 5.20. Annual heating energy savings of solid brick wall case study located in selected cities post wall insulation, (Seifhashemi & Elkadi, 2022).

| City | Camborne | Manchester | Aberdeen | Heathrow |
|---|---|---|---|---|
| Energy Saving (MWh/year) | 3.81 | 4.35 | 4.9 | 3.72 |
| Energy Saving (kWh/m$^2$/year) | 42.27 | 48.20 | 54.36 | 41.27 |
| Energy Saving (%/year) | 35.71 | 35.31 | 35.38 | 35.16 |

As of 31 March 2020, there are approximately 234,290 residential properties in Manchester (Manchester City Council, 2020). Considering the total number of UK homes (~29million) and assuming the same ratio of solid wall homes in the UK for Manchester, it can be estimated that around 65,000 solid wall properties would exist in Manchester and still 59,000 can be estimated to be uninsulated (CCC (Committee on Climate Change), 2019; Hansford, 2015). The survey results analysis confirmed the high importance of the aesthetic factor in internal home retrofit for residences, with 90.1% of participants stating that aesthetic is ‘important’ or ‘very important’ in their response. Furthermore, comparing the responses for all factors in internal renovation indicated that aesthetic factor is as important as the cost and energy saving factors. This result revealed the importance of aesthetic and a big gap in energy retrofit strategies especially for the promotion of SWI programme within the UK. Therefore, having the aesthetic factor included in home retrofitting plan of existing properties along with energy saving and cost factors will be an important driving force to grow the energy retrofit market for ISWI.

In addition, according to the survey results, among two products with the same costs for wall internal surface retrofit, almost all participants (99.3%) prefer the aesthetically appealing product. This percentage is still very high (88.6%) even if the cost of the aesthetically appealing product is higher. This also suggests that including the aesthetic in energy retrofit strategies can help in lowering the cost concerns in retrofit plans and ultimately contribute to the promotion of SWI by attracting more households towards retrofit. With implementation of such strategies, people will become more interested to do energy retrofit plans while they can benefit from new aesthetical finishes of the internal space. Furthermore, many households are retrofitting their properties voluntarily for having a more aesthetically appealing space and this is a profitable business in the UK. By combining the aesthetics and energy saving, it is very likely that those people with the interest in aesthetic improvement of properties consider energy saving factor, also people whose intention is to do energy retrofit would like to benefit from aesthetic aspects in internal retrofit. Ultimately, having both groups of customers benefit from the internal aesthetic insulation will result in an increase in demand and application of IWI. From the results, it is inferred that the aesthetic factor has a very important role in internal house retrofit and it has a great potential in promoting the uptake of ISWI, leading to effective energy saving in existing housing stock in the UK.

Calculating the energy saving following the energy retrofit measure by a presumption that all the UK homes would apply the energy retrofit measure, does not provide a genuine picture of what will happen in reality by users, and relying on such predictions may mislead the government in their emission goals. In fact, the combination of energy saving potential and survey analysis results of peoples' preferences for the specific retrofit measures should be taken into account to predict the benefits and help to design the flexible adaptive approaches for retrofitting the householder's properties. According to Section 5.1.2, the annual energy saving of 4.57 MWh and 840 kg $CO_2e$ emission reduction (or nearly 37%) were achieved following ISWI for the SEH case study building. Assuming all the solid wall properties in Manchester performing like our case study building (SEH), about 59,000×4.57 MWh= 269,630 MWh Energy consumption reduction and 59,000×840 kg $CO_2e$=49.56 $ktCO_2e$ emission reduction annually can be expected if IWI is implemented in all these properties. However, as discussed, this figure is not a realistic estimation since it lacks users' impact on SWI implementation. For example, the current strategies of SWI which lack user preferences, could not achieve the expected progress, and only around 9% of solid wall properties had energy improvement by SWI (Oxley, 2022). The results proved that adding aesthetic beside the currently available incentives for cost and energy saving factors, can effectively increase the implementation of SWI. The tendency towards home improvement to achieve aesthetical features is higher compared to energy retrofits or renovations according to the literature (Gram-Hanssen, 2014). This research also highlighted that combining these two renovation approaches (aesthetic renovation and energy retrofit) can help in overcoming some of the issues of IWI. For example, the results suggested that with inclusion of aesthetic features, the participants' desire to insulate the walls despite the reduction in the internal house will have the valid percentage of 65.3% according to Q19. In this question, 24.1% neutral valid responses were reported. Therefore, aesthetically appealing wall insulation can lead to expansion of the retrofit market and achieving energy saving targets of existing stocks. This calculation roughly estimates possible energy savings as a result of IAWI based on the outcome of Q19. The question specifically aims to examine the level of positivity among respondents towards IAWI, despite the negative concerns for losing internal space. According to the results of this question, the modified approximation for energy saving of the IAWI for Manchester can be calculated with the following data as shown below. In the user centred approach from this study, it can be estimated that approximately 176.07 GWh energy saving and 32.36 ktCO$_2$e emission reduction can be achieved in Manchester alone using the data of Q19 (see calculation below).

User desire of IAWI % (SPSS): 65.3%

Number of uninsulated solid wall houses in Manchester ~ 59000,

The estimation of annual energy saving and CO$_2$ reduction of IWI for the case study in Manchester (IES-VE): 4.57 MWh and 840 kg CO$_2$e

Annual energy saving: 65.3% x 59000 x 4.57=176,068.4 MWh ~ 176.07 GWh

Annual CO$_2$ reduction: 65.3% x 59000 x 840= 32,362,680 kgCO$_2$e ~ 32.36 ktCO$_2$e

Considering the Manchester saving results as the middle point for all UK (see Table 5.20), the calculation below shows the estimation of annual energy saving and CO$_2$ reduction of IAWI for the total of UK old houses (remaining 7.7 million solid wall and furthur1.75 million hard to treat cavity wall) suitable for SWI (BRE (Building Research Establishment), 2014; CCC (Committee on Climate Change), 2019; Oxley, 2022).

Annual energy saving: 65.3% x $9.45x10^6$ x 4.57= 28,200,784.5 MWh ~ 28,200.8 GWh

Annual $CO_2$ reduction: 65.3% x $9.45x10^6$ x 840= 5,183,514,000 $kgCO_2e$ ~ 5,183.5 $ktCO_2e$

# Chapter 6: Summary, Conclusions, and Recommendations

## 6.1 Summary

This research set out to develop a solution for the promotion of ISWI in the UK through integrating aesthetic features in the strategies and awareness about its energy-saving benefits. To achieve this aim, this thesis was structured around 6 research objectives. First, a critical literature review about the subject from both the energy and aesthetic perspectives was conducted and presented in Chapter 2 and Chapter 3 of this study. The analytical literature review helped to provide an overall conceptual framework, bridging the gap between energy studies and design/aesthetic features of SWI retrofit and develop the methodology of the research. The conceptual framework was presented and discussed in Chapter 1 Section 1.4. The research methodology used in this research was discussed in detail in Chapter 3. The research methodology consists of two main phases: energy assessment of SWI and aesthetic evaluations. The energy assessment phase was developed to address the first two objectives of this research with the focus on quantifying the energy saving benefits of ISWI, the outcomes were discussed in Chapter 5 Section 5.1 in detail. The aesthetic evaluation phase was developed in relation to the objectives three, four and five of this research, to investigate the role of aesthetics importance in internal renovation for householders and the possible success of aesthetic integration to increase the uptake of IWI. The results obtained were presented and discussed in Chapter 5 Section 5.2 of this report. To address the last objective of this research, following the results obtained from the two phases of the study, the integration of energy and aesthetic measures together were discussed, and recommendations were made for increasing the uptake of IWI in uninsulated UK dwellings. The related discussions are presented in Sections 5.2.3 and 6.3 of this thesis. This work therefore has addressed two main gaps in this area which inhibit the implementation of SWI. These two gaps arose from the literature and were related to a lack of clarity on the energy-saving benefits of SWI and the lack of innovative approaches and absence of aesthetic considerations in SWI strategies leaving householders unsure and resistant to SWI implementation. Therefore, the findings of this research will contribute towards developing a solution to unlock the demand for IWI by providing accurate data for energy-savings and recommending the internal aesthetic wall insulation (see Section 1.3). The research methodology consists of experimental, numerical, and survey approaches for SWI and effectively answered the research questions. The findings clearly confirmed the plausibility of the hypothesis of this research for the studied population sample. A conclusion summary of the results from this study are presented in the following sections of this chapter.

## 6.2 Conclusions arising from this study

This thesis was built upon the immediate need for making old dwelling stock in the UK more energy efficient in order to meet the $CO_2$ emission reduction targets and mitigate the effects of climate change. In Chapter 2 the findings highlighted the importance of wall insulation as the most effective energy-saving measure when retrofitting old solid wall houses. Despite all the policies, subsidies, and grants available for SWI, the progress of SWI has been very slow compared to other energy retrofit measures in old uninsulated dwellings (Hansford, 2015). The critical literature review conducted for this study revealed the main difficulties and barriers which directly or indirectly slowed down the implementation of SWI. Innovative and encouraging retrofit plans are urgently required to unlock the demand for implementation of SWI in old houses to improve their energy performance (Hansford, 2015). This research was designed to contribute towards understanding the more realistic potential energy-savings and $CO_2$ reduction from SWI as well as the role of aesthetics and attractiveness in promoting the uptake of SWI in the UK.

Some major barriers were identified for SWI in Chapter 2, Section 2.8. The analysis showed that the lack of clear and accurate data for householders about the benefits of SWI has caused reluctance and uncertainty in implementation of SWI. To contribute to tackling this issue, this thesis has assessed the extent of energy-saving and emission reduction benefits of SWI (Chapter 4, Section 4.1). Also, looking at the issue of SWI slow progress from another perspective, this thesis has interrogated the lack of attention to the importance of aesthetics in SWI strategies. Aesthetic is a well-known factor which has been widely used in the building industry to inspire marketing and increase demand. However, this aspect has not previously been considered in energy retrofit strategies. Simultaneously, the literature shows that concerns related to losing the aesthetic features of property was reported among the existing difficulties which inhibits the implementation of SWI. The discussion in Chapter 3 Section 3.3 shows that aesthetic renovation is more important for internal spaces and is happening routinely as an approach by residents. Hence, the theory of integrating the aesthetic factor in ISWI and its potential in improving the energy efficiency of solid wall houses was also explored in this study. Therefore, this study was performed over two phases of energy assessment, through energy simulation of the SEH, and a survey assessment for aesthetic evaluation to explore the aesthetic importance and aesthetic preferences in renovation. The main conclusions of each phase are presented in the following sections.

### 6.2.1 Energy assessment phase

During the energy assessment phase, the benefits of IWI for a variety of solid wall U-values were investigated with an accurate validated digital simulation model. SEH was the case study in this research, which is a solid wall, end terrace house built identical to pre-1919 Victorian type houses and is located within an environmentally controlled chamber at the University of Salford. Since the building is in a laboratory environment, experimental data have been accurately collected to validate the model and analyse the actual performance of the solid walls and the energy retrofit measures. While the results and analyses were developed based on the simulation, in-situ measurement of software input data such as U-values and APs as well as the precise validation process was performed to develop a reliable model with a minimum performance gap with the actual experiments. Characteristic data required by the model such as AP, U-values and other building specifications were obtained from previous research studies for the SEH. Also, a precise floorplan from accurate building measurements were used in developing the IES-VE simulation model. Some experiments were conducted in the steady-state condition, where the chamber temperature was kept at a constant temperature of 5°C during the data collection, which represents a cold day in winter. The experimental data including heating energy consumption (gas), room temperatures and chamber conditions, such as temperature and humidity were collected for modelling and validation of the IES-VE model of the case study.

Uncertainties in U-values of solid walls may result in a significant over- or under-estimation of potential savings from SWI. In this study, the benefits of ISWIs were assessed for a variety of baseline U-values in the range of 0.64 to 2.48 W/m²K as suggested by literature for solid brick wall houses. First, the energy performance of the SEH case study pre- and post- IWI was analysed. The baseline U-value of 1.56 W/m²K (pre insulation) from the measurement was used in the model for the simulation of the pre-IWI performance. The U-value of the walls were changed from 1.56 W/m²K to

0.2593 W/m²K after applying the IWI in the model and the results were extracted for AP1=10 $m^3/m^2h$ and AP2=6 $m^3/m^2h$ for post IWI. To extend the analysis of IWI for solid wall houses similar to the SEH, different baseline U-values between 0.64 W/m²K to 2.48 W/m²K were used from the literature to study the performance of the uninsulated solid brick walls in different scenarios.

During the validation process a good agreement between the SEH model and experimental data was achieved. The result for percentage error was below 1% for daily heating energy consumption (gas), and the Root Mean Square Error (RMSE) for temperatures of different rooms was just between 0.7 °C-1.5 °C. The heating energy use of 12.31 MWh for the baseline U-value of 1.56 W/m²K is reduced to 7.96 MWh and 7.74 MWh after insulation with AP1=10 $m^3/m^2h$ and AP2=6 $m^3/m^2h$ respectively. Furthermore, the results suggest that solid wall houses with higher baseline U-values consume more energy compared to the solid wall houses with lower U-values, hence IWI could lead to more savings in such dwellings. As the baseline wall U-value decreases from 2.48 to 0.64 W/m²K, the energy saving potential reduces from 46.2% to 19%, which is still a significant figure for energy saving and the corresponding cost saving varies between £310.10 to £82.10 respectively. The analysis of the energy saving revealed that IWI is an effective measure for retrofitting solid wall houses and should be prioritised in retrofitting these types of properties. A large discrepancy was observed in energy savings and $CO_2$ emissions reduction in solid wall houses depending on the baseline U-values. These results highlight the importance of wall U-values in energy saving potentials. This finding is very important for setting the emissions target reduction for solid wall homes by regulatory bodies, policymakers, and relevant stakeholders.

The environmental benefits of the IWI were also evaluated by calculating the annual $CO_2$ reduction (kg $CO_2e$) resulting from IWI. The results revealed a large variation for $CO_2$ reduction ranging on the baseline U-value selected in the model. This highlights the importance of the baseline U-value in estimating the potential $CO_2$ reduction of IWI. This discrepancy in $CO_2$ reduction is suggested to be considered by the policy makers when analysing the targets for the $CO_2$ reduction of solid wall houses. The potential cost saving of IWI was also analysed in this study and the annual cost savings of between £82.10 (-15%) to £310.10 (-56%) were obtained depending on U-values and APs. Again, a significant variation in potential cost saving exists with a clear impact on homeowner decision making towards the implementation of IWI. Having the expertise of the baseline U-value measurements is recommended within the professional companies responsible for IWI to help the homeowners make an informed decision as well as policy makers so they can offer the right support.

One main concern for IWI would be the possibility of overheating, especially during the summer. Internal temperature variations within and out of the thermal comfort range were evaluated in this study. Thermal comfort in internal spaces was improved in all cases with IWI, however, the percentage of hours with the temperature above 23°C were increased by wall insulation. This overheating effect inside the house was observed in the warmer seasons even before insulating the walls and the increase of temperatures over 28°C on living spaces was negligible post wall insulation. The annual percentage of hours with a temperature above 28°C was increased by around 0.1%, although this mainly happened in the loft spaces. Some simple measures such as night ventilation and shading were suggested in the literature to overcome this minor overheating effect.

In summary, the result of this phase presented more realistic figures for energy saving, $CO_2$ reduction, and cost saving potential of IWI in solid brick wall houses. It is important for the industries involved in retrofit to provide a realistic estimation of savings for IWI by paying more attention to the key parameters affecting the energy performance of SWI, such as U-values. Providing realistic numbers will help householders understand the benefits of IWI and make better informed choices when considering retrofit measures for their solid wall properties.

### 6.2.2 Aesthetic evaluation phase

The potential of an aesthetic factor increasing the demand for SWI were explored in the aesthetic evaluation phase. The importance of aesthetic features in internal spaces were evaluated using the outcomes from an online survey tool. The survey questions were designed with respect to the negative aspects of the reputation of wall insulation, which were captured from the literature. The survey study received a total of 273 valid responses in almost equal distribution of male and female participants with varying age groups, incomes, ethnicities, and house types. The survey was first piloted to improve the questionnaire based on the feedback received from the pilot participants. The Bristol Online Survey tool was used to distribute and conduct the survey and the results were analysed by SPSS software. Descriptive statistical analyses were performed, beside basic frequency analysis, and the data were investigated in-depth for further analysis.

The results from the survey analyses support the energy assessment phase by the promotion of SWI implementation through a better understanding of the aesthetic impacts. The initial questions in the survey gathered basic information about the respondents. The results show that there was a good representation of all age groups among the participants. The participant's gender was almost equal with 50.2% female and 49.8% male respondents. About 82.4% of the participants were of UK origin and 15.8% were of non-UK countries, and a further almost 1.8% who preferred not to reveal their origin. There was a significant number of the participants living in solid brick wall homes that were built before 1930 (like the SEH). The household incomes for most participants were between £20,000-£80,000.

The next questions were directly related to the purpose of the research. Questions were designed mostly as a 5-point scale from 'strongly disagree' to 'strongly agree' or 'very important' to 'not important'. The option of 'Don't know' was also provided to achieve more precise data. The participant views on energy efficiency improvement, cost and timeframe of renovation, and more importantly about the aesthetic features were evaluated. It was observed that 99.2% of the participants are keen to improve the energy efficiency of their homes, however, only 42.6% were looking at it as their priority for house retrofit. This drop in percentages reveals that uncertainties exist among households which slowed down the energy retrofit implementation as confirmed in the literature. Moreover, there was a high agreement with internal wall decoration, with over 96% in favour of aesthetic appearance of living space. There was a slight drop in participant opinion about aesthetic consideration in retrofit, but it was still high with about 90% of the participants in agreement. This drop was revealed to be due to the cost concerns in other questions because 99.3% of participants selected aesthetically appealing among the products with the same functionality, quality, and cost. However, when the cost increment for aesthetically appealing products was added, 88.6% of participants were willing to pay extra within their budget for aesthetic features for their living space. On the other hand, this also confirms that a high percentage of participants are ready to pay extra to achieve aesthetic improvement, which again highlights the importance of the aesthetic in convincing people towards a retrofit plan.

The importance of other factors, such as energy saving, cost, and time frame along with the aesthetics of internal retrofit was also evaluated in this research. Categorising the responses into the two categories of important and not important showed that aesthetics, energy saving, cost, and time frame are highly important in internal retrofit for participants with 98.9%, 99.6%, 100% and 98.9% in agreement respectively. However, in reviewing the responses most of them were in the first two scales of very important and important, so the importance priority of the four-understudy factors (aesthetics, energy saving, cost, and time frame) was analysed more closely in the following step. From this analysis, it was identified that aesthetics, energy saving, and cost are almost equally important for participants with more than 90% whereas timeframe with 65% is of less priority for participants in internal renovation. A cross-tabulation analysis was performed for these four understudy factors versus various categories such as PCHI, age, gender, and country of origin. These analyses were performed for all participants, including those living in old homes and homeowners, to compare different cases. No matter how the data was categorised for analysis i.e., income, origin, gender or age, the response rate for all were almost always well matched. This confirmed that the aesthetic factor importance is almost the same level of importance to cost and energy saving in internal renovation, while it was not considered in current retrofit strategies.

According to the responses, we can conclude that the aesthetically appealing products received a high percentage of acceptance (99.3%). However, only 10.7% of the participants ignore the aesthetic aspect of the product due to higher costs. It was observed that adding aesthetic features to ISWI will alter the negative concerns about losing internal space for most participants, with only about 10% in disagreement. More than half of the participants were in support for insulating the walls with IAWI to benefit from the aesthetic and energy improvement in a single package, while about 20% disagreed. Over 70% of the participants agreed with the establishment of organisations to deliver both aesthetic and energy improvements in one package to design the retrofit plan based on user’s preferences and implement and supervise the process to achieve the target energy saving. The neutral responses were high in some extent to this question, which could be due to the newness of the subject for participants that may not have experience of such organisations. The agreement figures may have the potential to increase even more when the benefits of this approach are perceived by the public. The severity of aesthetic importance for SWI may vary for people with different gender, income, age and country of origin, however, the very significant impact of aesthetic factors in internal renovation was proved to be conclusive from the analyses. The results have also confirmed the importance of aesthetic in encouraging residents to engage with SWI projects, and the necessity of aesthetic integration in current retrofit strategies. The findings from the energy assessment and aesthetic evaluation phases were integrated, and it was roughly estimated that the annual energy saving of 176.07 GWh and a $CO_2$ reduction of 32.36 kt$CO_2$e can be achieved after IAWI in Manchester’s old houses using a user-centred approach. The estimation was extrapolated for the entire UK stock of old houses suitable for SWI and gives the potential annual energy saving and $CO_2$ reduction of 28,200.8 GWh and 5,183.5 kt$CO_2$e calculated, respectively.

Based on the findings of this study, it can be concluded that including aesthetic in planning the related energy retrofit strategies to IWI can directly or indirectly impact on enhancing the implementation of SWI, leading to unlocking the demand by introducing the IAWI package. This increase in demand will happen by increasing the number of potential customers that will benefit from IAWI as it targets both groups of people with aesthetic and/or energy improvement goals in their renovation. This will give more flexibility to people who want to redecorate their solid wall house based on their personal interest to use the IAWI and improve the energy efficiency of their homes. It also creates an opportunity for homeowners who want to do the energy retrofit to benefit from aesthetic improvement of their home walls at the same time.

Finally, some recommendations are presented in the following section to provide viable approaches to the integration of the energy and aesthetic results of this study (research question 8, Section 1.2).

## 6.3 Recommendation towards uptake of the solid wall insulation

Aesthetic inclusion was proven to be an encouraging factor in internal renovation, and it was even found to be the priority for most participants (see Section 5.2). The results clearly illustrate that aesthetics can help in lowering the cost concerns of households in retrofit plans, which could further lead to the uptake of IWI. From the results, it can be concluded that aesthetic is a promising option to be included in energy efficiency measures to make the transition of homes to become more energy efficient easier and faster. In fact, aesthetic, which had been generally neglected in the past, can facilitate the fast delivery of energy efficiency measures, especially SWI, and should be considered in SWI strategies in future. Therefore, the proposed solution in integrating the aesthetic factor in energy retrofit strategies, especially for the case of SWI, is highly recommended.

One issue of SWI strategies is that the existing aesthetic texture finish on the internal side of uninsulated wall surfaces may be lost after insulation; most of the IWI products that are currently in the market are unattractive, therefore, the insulation products would not be an aesthetically satisfactory replacement for the residences. After installation of the internal insulation panels, the wall surfaces are required to be redecorated with paint or other decorative material available in the market. It is currently the responsibility of the users to finish off the work through DIY or contractors. This forces extra cost and disruption time on top of the cost and time required for the IWI implementation.

Establishment of professional organisations to centralise the delivery of combined retrofit (energy improvement and internal decorating) is another recommendation arisen fror the results of the survey analysis (Q20) and supported by the barriers in energy retrofit of solid wall houses (see Sections 3.1 and 3.3). These organisations will be responsible and will monitor the whole process to avoid some of the existing issues in SWI, such as contractor credibility, unknown quality of work, and unknown performance outcomes (Weeks et al., 2015) as well as the misunderstanding and confusion for homeowners about the financial support due to the complexity and inconsistencies in the policies (Hansford, 2015; Putnam & Brown, 2021).The integration of aesthetic into IWI could be done via product design, which means that aesthetically appealing internal insulation products can be developed and marketed. These products could be developed, for example, in modular design with aesthetical patterns embedded on them. Also, in another approach, aesthetic improvement can be included into the IWI implementation, meaning that performing the internal decoration and improving the aesthetical aspect of internally insulated wall, aligned with customer preferences, to be performed within the same retrofit package with professionally trained installers. Having the aesthetic and IWI integrated in the same retrofit package would make a significant contribution in the quality delivery of renovation and increasing demand which can lead to increasing the uptake of the SWI.

Another suggestion is the extension of financial support or incentives to cover the redecorating cost of the wall surfaces after insulation. The financial support and subsidies available now are mainly for the cost of the insulation panels and installation of the IWI and does not include the redecoration aspect. This suggestion will benefit from the integration or close collaboration of home improvement and energy retrofit companies because there would be a cost saving involved if the insulation and decoration of the walls happens in the same renovation package at the same time, and it is possible to bring down cost effectively even more by doing the projects at mass scale as highlighted in the literature (Chris, 2019; Elderkin, 2011). At the same level, this option will be encouraging for the customers intending to insulate their homes as they will benefit from the incentives available for redecorating of their homes after insulation. More people with aesthetic and/or energy saving retrofit intentions will be targeted in this approach and benefit from IAWI.

This will help users to benefit from the holistic support available before, during, and after the retrofit process from the design stage to delivery of the retrofit project and will enable monitoring the progress of SWI. The relevant information about the available retrofit supports and incentives offered should be publicised and communicated by such organisations effectively to the public, especially to the residents of uninsulated old properties. It is important in gaining interest and it is more effective when conveying a simple, targeted message in a streamlined way (CCC (Committee on Climate Change), 2016a). Communications with the public in a clear and easy way to understand can greatly help to increase potential customers. This approach will ensure the high-quality delivery of ISWI with satisfactory outcomes for the homeowners and will also contribute to achieving energy saving targets set by the government.

Following on from reviewing the literature and the outcome of both phases of this study a number of recommendations for industry, policy makers, and designers are developed and discussed in the next sections.

### 6.3.1 Recommendations for retrofit industry

Although energy retrofit industries are aiming to improve the energy efficiency of poorly insulated homes, their strategies and performance for the implementation of SWI must be improved, to increase the uptake and delivery of SWI as around 91% of solid wall homes in the UK remain to be insulated. It is good practice for the retrofit industries to provide customer service training for their employees to provide the best support for their customers effectively, since residents of old homes play the main role in decision making on the implementation of retrofit. Energy retrofit and home improvement should not be separate. In fact, renovation companies should work in an integrated approach, where homes are being renovated and improved in terms of both energy and aesthetic aspects in retrofitting old houses. Furthermore, centralising the retrofit measures for old housing stock is recommended from the findings of this research and supported by the literature (Pardalis, 2021). This could be achieved by integration or close collaboration of home improvement and energy retrofit companies, as a single actor, to offer both energy saving and aesthetic incentives to householders in one single package. In this way, SWI retrofit, and home improvement can be implemented collectively, which is not only easier for customers but also helps to supervise the delivery of IAWI and prevent any unexpected damage to the wall insulation during the process. Such one-stop-shop business models were also suggested in the literature to accelerate energy efficiency renovations (Pardalis, 2021; Pardalis et al., 2019).

The establishment of such integrated and centralised organisations to exclusively perform energy and aesthetic renovation of solid wall dwellings especially in case of ISWI, can be beneficial in many ways to facilitate the engagement of householders in renovation (see Section 3.3). Following on from the results of this study, it is important to clarify all factors of aesthetic, energy saving, cost, and time in the retrofit project to maximise the attractiveness of the package for the customers, and to minimise the disruption time of the retrofit process for homeowners and deliver projects according to schedules suitable for customers. This will minimise the cost of the whole project due to the integration of the retrofit and decoration by the same organisation as well as doing the renovation on a mass scale and can reduce the costs by half (Chris, 2019; Elderkin, 2011), and provide customer service for all the steps of the project such as design, material selection, supervision of the project and after care service to gain customer trust (Brown et al., 2018). Such an integrated approach can help in reducing the barriers for householders and provide a clear path with less annoyance for homeowners compared to when they must search for financial support, deal with different contractors, or self-decorating to finish off the work. Organisations should target the trigger point when householders are ready to do renovation to offer their attractive package to increase the delivery of retrofit in old houses (CCC (Committee on Climate Change), 2016a).

It would be important to provide users of a clear rough estimate of the energy savings and hence the economic benefits of retrofitting of their houses. The retrofit industry would do so with reference to Table 5.4, which is developed in this thesis. Educating householders about patterns of energy use after the energy retrofit is important to achieve the expected savings (Hardy et al., 2018). They should also ensure the professional quality of the delivery of projects and avoid unexpected damage to installation panels by employing trained installers to follow the standards and have supervision for proper installation of the IAWI package to maximise the energy saving promises. This will facilitate the informed decision of householders to perform IWI. Also, it is crucial that the industries well train their installers on installation techniques to perform high-quality insulation, achieving the optimum energy savings. Distribution of wall insulation products is better to be exclusive to such centralised organisations to avoid the installation of insulation panels by unskilled individuals. This can help increase the professional quality delivery of renovation work which would result in improving the current bad reputation of SWI due to poor insulation installation or damage to the insulation product during re decoration of wall surfaces after insulation by unprofessional craftsman or DIY, as highlighted in the literature (BRE (Building Research Establishment), 2014).

Informing customers about available funds and subsidies and providing support in the application process should be another part of the offered services by the retrofit industries interested (Hansford, 2015; Putnam & Brown, 2021). It is recommended that retrofit industries invest in creating the aesthetically appealing insulation products and consider the option of aesthetic customization in their products to facilitate the variety of customers' tastes. Also, they should consider producing such internal insulation products and techniques to minimise the living space reduction after wall insulation. All of these improvements would help in making a very clear path for householders to engage and benefit from IAWI. These are often a relatively cheap intervention, but they complement each other within one work package and would work towards removing the barriers for householders.

### 6.3.2 Recommendations for policy makers

Despite all the policies, subsidies and grants available for SWI, such as the Government's Energy Company Obligations (ECO) scheme, the progress in SWI has been very slow (Oxley, 2022). More attention to the social dimension of renovation in new policies is essential, and policy measures should recognise the role of householders and their preferences in the renovation process (Abreu et al., 2017). Except financial support for the cost of energy efficiency measures, occupants as users of the buildings in the domestic sector and their needs were rarely considered in energy demand reduction strategies and policies (Haines, 2014). Among different projects and policies in different countries, Kalmar in Sweden is a successful example of collaboration between different actors and local inhabitants (Ruggiero et al., 2021) where the corporate strategies and citizens' desires are considered (Berthod et al., 2022). As the results of this study indicated (see Section 5.2), aesthetics can play a critical role in promoting the IWI but currently no policy exists to support such an approach. More attentions to the social dimension of renovation in new policies is essential, and policy measures should recognise the role of householders and their preferences in the renovation process (Abreu et al., 2017). Policy makers should develop policies in support of the integration of aesthetical householders' demands in implementing SWI. In such policies, the financial support, or incentives available for energy retrofit should be extended to cover the redecorating cost of the wall surfaces after wall insulation aligned with the customer's satisfaction. This support should also be offered not only to customers with intentions to do energy retrofit, but also to customers with aesthetic improvement goals in a way that, for example, if they use aesthetically appealing wall insulation panels with energy saving benefits the cost of aesthetic improvement will be supported. This will ensure that SWI strategies are more encouraging and attractive for customers. The available supports and policies about SWI should be much clearer and simpler to understand for householders and industries. Furthermore, these new supportive policies about SWI should be communicated widely and clearly to the public to minimise the hassle and complexity for householders (CCC (Committee on Climate Change), 2016a). Advertisement and publicising the new attractive approaches for SWI is crucial for a better understanding of the service by the public, and for informing householders about the existence of the available offers for them. All these are necessary because successful energy policy for buildings requires educational and training initiatives, and elimination of the bureaucratic processes (Gazis, 2017). Policymakers should support the collaboration between home improvement, energy retrofit industries, and the householders, for the renovation of the UK old dwellings in an integrated approach where Government can ensure the most positive outcome. In developing the policies, policy makers should consider the needs of householders with old housing stock, who are the main potential users of IWI. The policy makers should ensure that continuity exists in policy and management programmes to support IAWI, and the new strategies should be implemented, monitored, and revised according to the needs of old dwellings' householders until the predicted outcome can be achieved (Gazis, 2017).

Policy makers should also support centralising the retrofit measures where home improvement and energy retrofit industries are merged or work closely for home renovations of UK old dwellings (see previous section). This centralisation can lead to more effective support from government and enhance customer trust and satisfaction with less hassle and complexity for householders which are key to successful policy (CCC (Committee on Climate Change), 2016a).

### 6.3.3 Recommendations for designers

Developing an attractive approach for the uptake of SWI is perceived to be more for the retrofit industries and policymakers, however, this does not take away the responsibility from designers. Improving the aesthetic features of the property is a motive to retrofitting (Pelenur, 2014; Weeks et al., 2015), therefore, the role of designers is critical in facilitating the engagement of householders to SWI implementation for their old dwellings. The effective communication between designers and customers is vital in developing the aesthetical designs based on the customer's demands. Designers can use the possible visualising techniques such as sketches, 3D or 2D modelling tools for direct communication with consumers for better understanding of the customers' requirements and finalising the aesthetic designs. Designers and developers should continuously seek their customers' views about aesthetical demands and feed that into product design to contribute to improving this interconnected approach. They can ensure their designs are based on customers' aesthetical preferences while its implementation is not negatively affecting the insulation product.

Interior designers who work for the home improvement industry should consider the environmental impacts of their design (Stieg, 2006). Designers should integrate the energy efficiency and aesthetic improvement in their design and discuss the benefits with customers. Designers, as the first point of communication with customers, have a very important part in persuading the householders in using the IAWI. Proper energy advice can positively impact the household's decision to adopt an energy retrofit measure (Owen & Mitchell, 2015). Interior designers should be creative in their designs and employ the IAWI in their aesthetical design as much as possible. They, as intermediate, should direct customers to designs and packages for a positive sustainable outcome (Zaunbrecher et al., 2021). They should agree the aesthetic preferences with customers at the design stage before implementation of insulation, and customers should be given the choice to choose their favourable decorative material from variety of available or customisable products. This will add to the attractiveness of the encouragement plans for the uptake of IAWI. They should encourage IWI for old dwellings where possible, as beside saving more energy and cost compared to ESWI (Brannigan & Booth, 2013; Loucari et al., 2016), the aesthetic improvement of internal spaces is more of a priority for householders (da Luz Reis & Dias Lay, 2010), and both can be achieved in an integrated approach. In this centralising scenario, designers should work within established organisations to design and facilitate the retrofit process for householders.

Product designers should also improve the design of insulation products, not only to be energy efficient but also to be aesthetically appealing. Creating such products for internal spaces should be the priority as the research results showed that the aesthetic aspect of the internal spaces has a high priority for the residents. The aesthetic improvement of the walls internally should be provided from a variety of attractive insulation materials that are also practical i.e., easy to maintain and install to the walls. Designers should include a variety of patterns in IAWI product design to match the different tastes of customers and should also consider customisable options for aesthetic pattern of the product to adapt to different tastes and customers preferences.

## 6.4 Research limitations

This study had some limitations which can be addressed in the future. The result of the energy assessment phase of this study was reported for a validated computer model simulation result. However, the validation has been done using the in-situ measurements and experimental data collected from case study (SHE) without wall insulation. There were funding and time constraints to insulate the solid walls of SEH and collect the data after wall insulation for the purpose of this study. While the model was validated accurately against experimental data, and it was reliable with below 1% performance gap, the model would benefit from the post insulation data in the future. The results of the energy assessment were also limited to one typology, which was an end terrace solid wall house. Furthermore, the simulation results are limited to the accuracy of the software and errors of the experimental equipment used for data collection, however, the model was validated against experimental data and measurement tools were calibrated before conducting the experiments to minimise the errors.

In the design of the questions, while the neutral option in Likert scale questions was beneficial to capture the view of unbiased participants, rephrasing this option to become clearer, such as ‘neither agree or disagree’, could be beneficial to avoid confusion between ‘don’t know’ and the middle position response for respondents. This could increase the reliability of survey results and reduce the neutral attitude of the respondents in the future. Furthermore, the questionnaire was limited to the closed-end questions as non-numerical observations and narrative data was not needed for the purpose of this study. However, having open ended questions beside close ended questions could reduce the chance of a bias which may occur in the case of close-ended questions (Reja et al., 2003).

While the researcher was satisfied with the selected population sample participating in the survey with the convenience sampling method, due to the time constraints, it was not possible to explore the view of more samples across the UK about aesthetics to conclude a more comprehensive conclusion. The findings and recommendations of second phase of this study are based upon a sample of 273 in a quantitative survey. Future researchers have the opportunity to expand the boundary of knowledge of this current research by taking a larger and more diverse sample. Furthermore, this study has used a convenience sampling method from the University of Salford staff members. The selected sample had similar characteristics with the target population in many aspects, such as proportion of old houses, origin, and gender. However, convenience sampling has its own limitations (Etikan et al., 2016) and probability sampling methods can be explored in the future. Notwithstanding these limitations, this study offers an insight into the importance of aesthetics in renovation for householders and its potential in the uptake of ISWI in the UK.

The outcome of integration analysis is mainly based on a single house typology and energy assessment results for Manchester weather data. While Manchester is considered to provide an average climatic data for the UK, more diversity in housing types with local weather information would provide more accurate results for better estimations. Finally, this survey is designed to suit UK solid wall housing and population. The results of this survey study can be country specific due to political, economic, social, and cultural context, and therefore, country-specific questionnaires may be needed in future studies for different countries.

## 6.5 Recommendations for future research

The methodology adopted and the results from this study provide an insight for possible areas of future research for improving the design, construction, and evaluation of SWI in the UK. There is also an opportunity to contextualise the results of this research in different parts of the world and under different climate conditions where solid walls are prevalent or are still being used as a construction method. A number of potential areas are recommended for the investigation in any future research.

This research was the first study that investigated the aesthetic preferences of occupants in relation to SWI and specifically in ISWI. More research is still required to understand the aesthetic preferences of the householders in the UK context. The findings should be implemented in the product market and could contribute to an increase in product development of relevant industries to create an aesthetically attractive wall insulation for potential customers. Also, the survey results of this study are based on the data collected from Manchester residents. It would be beneficial to explore the views of a wider target population, with different sampling methods across the UK on the subject using this or other relevant surveys. Furthermore, the aesthetic preferences of the people from the result of this or any future studies about SWI should be clearly communicated with the industry to improve their products as well as to the government bodies to be considered in future incentives and policies. It can effectively contribute towards increasing the popularity of SWI, which has so far not been very successful.

Furthermore, to the best of our knowledge, there is no specific data available to identify the number of aesthetic home improvements in the old stock in the UK. Exploring this area and providing accurate data could help not only in targeting the potential participants to take part in the survey studies in this area, but also can be helpful for expanding the results of this study.

This research clearly illustrated the direct benefits of IAWI, and it raised the question of what can be the indirect benefits of IAWI, for example on the healthcare system and job market? It would be interesting but challenging to explore its impact on the health and wellbeing of occupants following IAWI and the potential benefit to the job market to reap the indirect benefits of the proposed solution.

The case study used for energy analysis was an end terrace house with brick solid walls, however, exploring the saving potentials of IWI in other dwelling typologies and solid wall types (stone, metal, timber and etc.) in the UK in addition to energy assessment of this study (see Table 5.4) is recommended. This can be used for energy benefit estimations, which can be used for future references of retrofit industries and householders, are recommended for providing energy benefit estimations for customers.

Lastly, the effect of global warming on the energy saving benefits of SWI, and possible heating penalties in warmer seasons, should be considered in more detail for evaluating future saving potentials of IWI in solid wall properties considering the climate change and rising energy costs.

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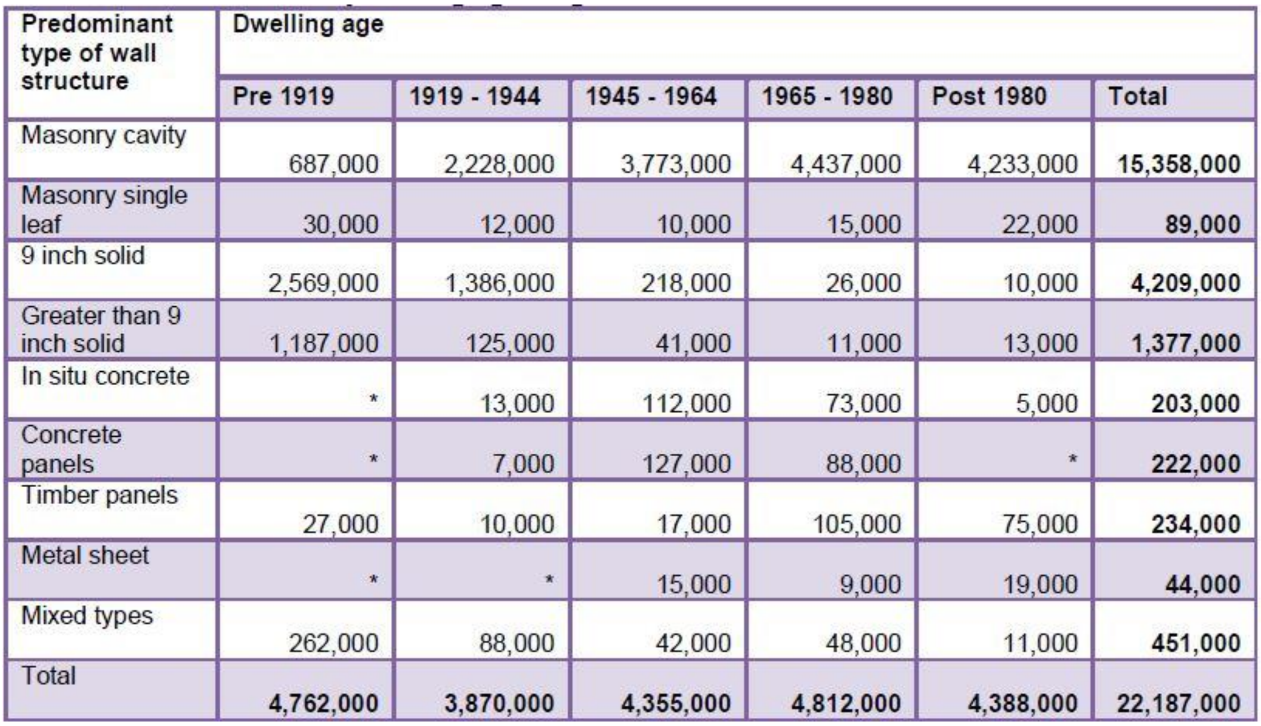
# Appendices

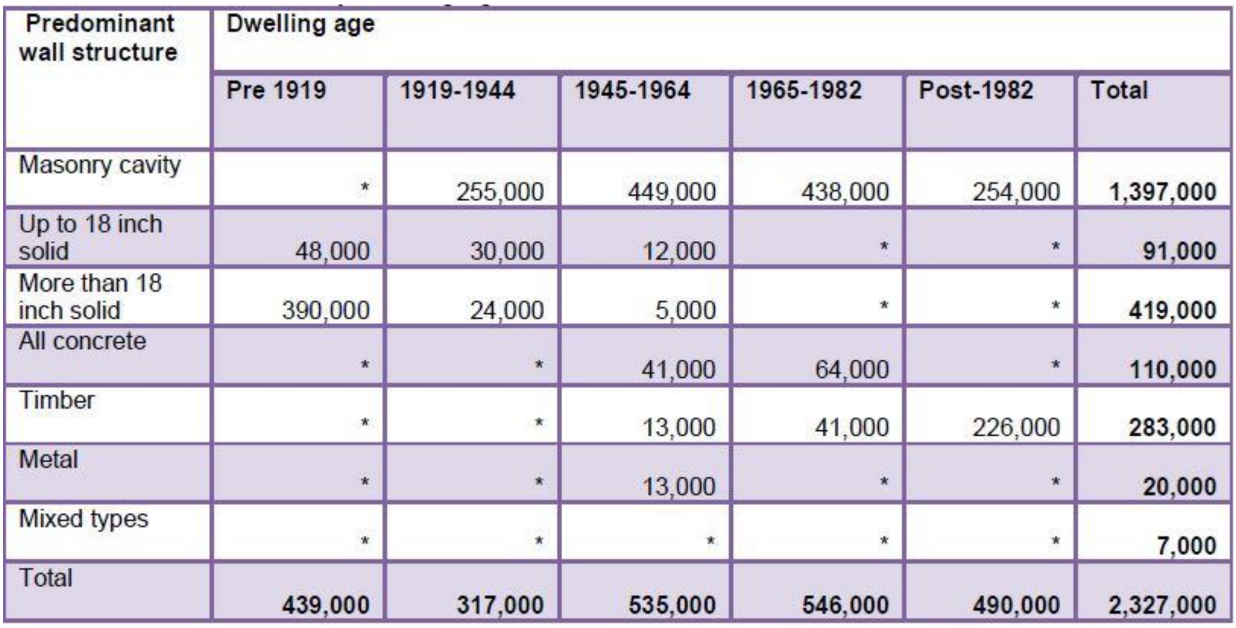
## Appendix 1. Wall structure by dwelling age, UK

Table A- 1. Wall structure by dwelling age; England (BRE (Building Research Establishment), 2014).



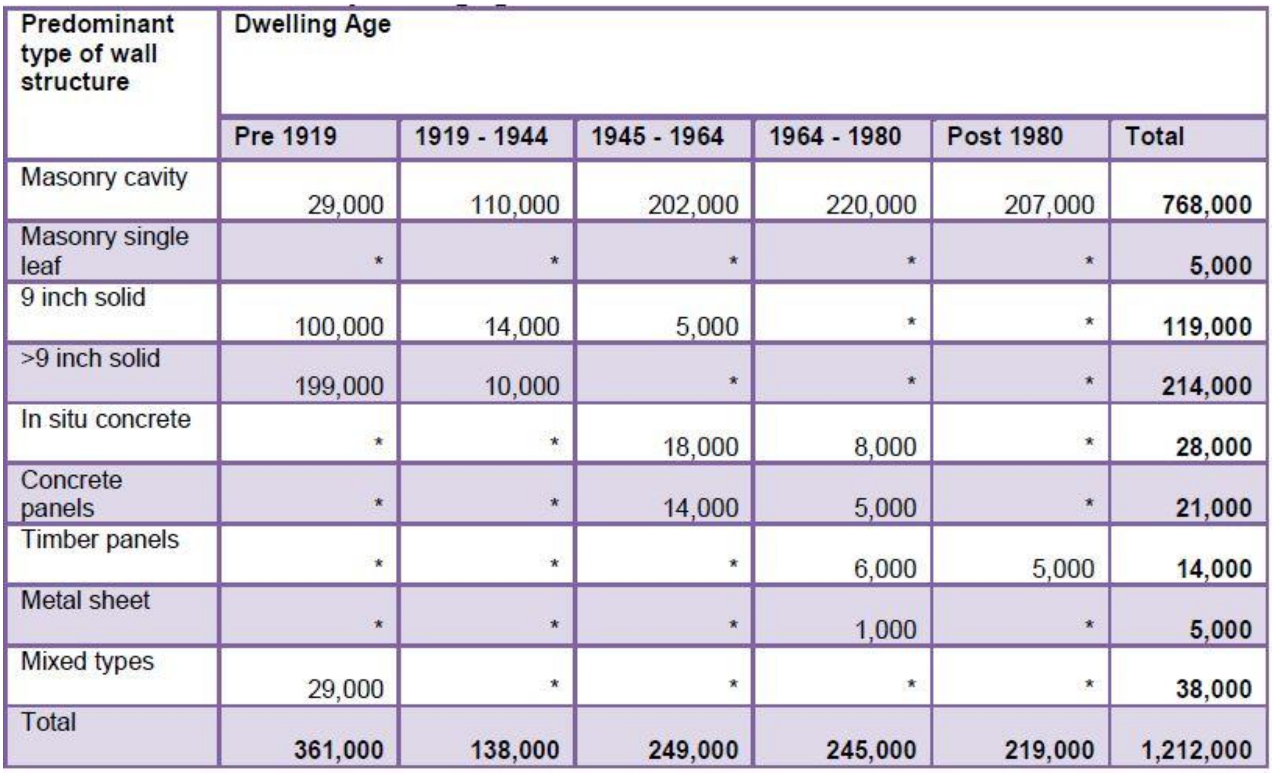
| Predominant type of wall structure | Dwelling age | | | | | |
|---|---|---|---|---|---|---|
| | Pre 1919 | 1919 - 1944 | 1945 - 1964 | 1965 - 1980 | Post 1980 | Total |
| Masonry cavity | 687,000 | 2,228,000 | 3,773,000 | 4,437,000 | 4,233,000 | **15,358,000** |
| Masonry single leaf | 30,000 | 12,000 | 10,000 | 15,000 | 22,000 | **89,000** |
| 9 inch solid | 2,569,000 | 1,386,000 | 218,000 | 26,000 | 10,000 | **4,209,000** |
| Greater than 9 inch solid | 1,187,000 | 125,000 | 41,000 | 11,000 | 13,000 | **1,377,000** |
| In situ concrete | * | 13,000 | 112,000 | 73,000 | 5,000 | **203,000** |
| Concrete panels | * | 7,000 | 127,000 | 88,000 | * | **222,000** |
| Timber panels | 27,000 | 10,000 | 17,000 | 105,000 | 75,000 | **234,000** |
| Metal sheet | * | * | 15,000 | 9,000 | 19,000 | **44,000** |
| Mixed types | 262,000 | 88,000 | 42,000 | 48,000 | 11,000 | **451,000** |
| Total | **4,762,000** | **3,870,000** | **4,355,000** | **4,812,000** | **4,388,000** | **22,187,000** |

Table A- 2. Wall structure by dwelling age; Scotland (BRE (Building Research Establishment), 2014).



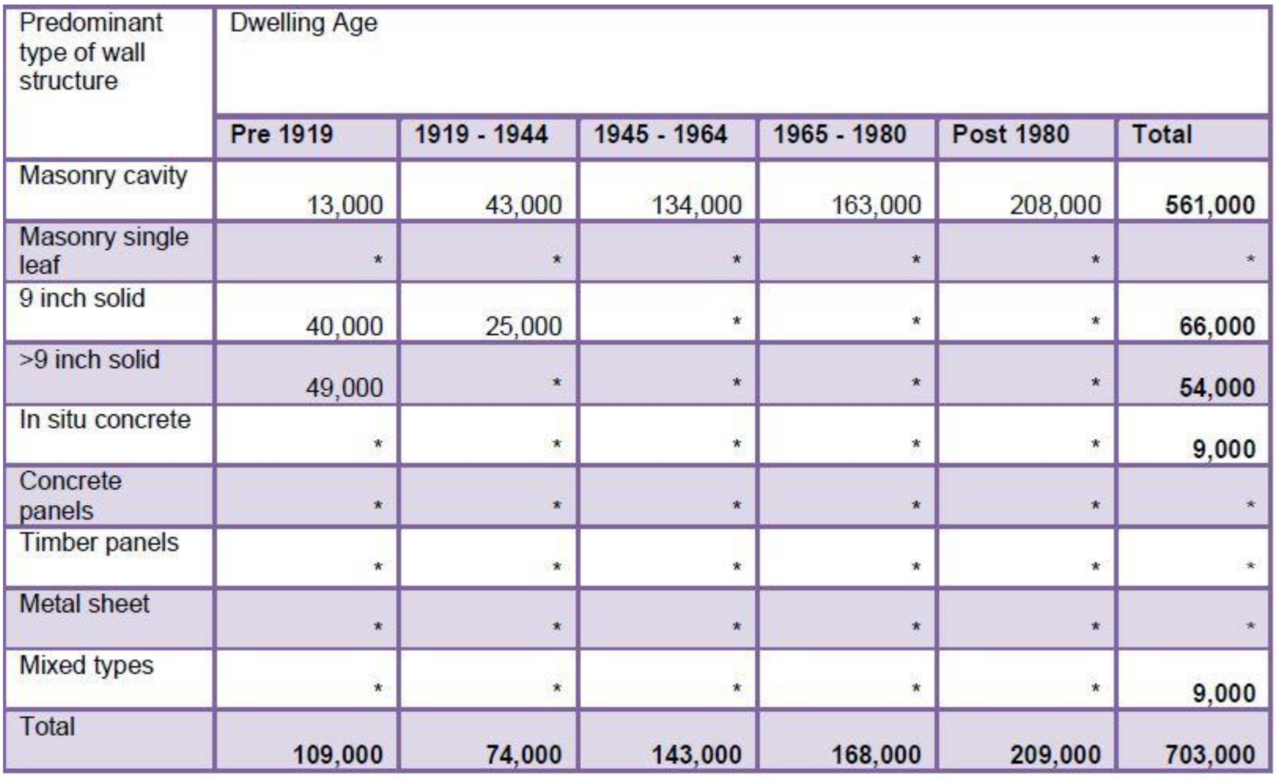
| Predominant wall structure | Dwelling age | | | | | |
|---|---|---|---|---|---|---|
| | Pre 1919 | 1919-1944 | 1945-1964 | 1965-1982 | Post-1982 | Total |
| Masonry cavity | * | 255,000 | 449,000 | 438,000 | 254,000 | **1,397,000** |
| Up to 18 inch solid | 48,000 | 30,000 | 12,000 | * | * | **91,000** |
| More than 18 inch solid | 390,000 | 24,000 | 5,000 | * | * | **419,000** |
| All concrete | * | * | 41,000 | 64,000 | * | **110,000** |
| Timber | * | * | 13,000 | 41,000 | 226,000 | **283,000** |
| Metal | * | * | 13,000 | * | * | **20,000** |
| Mixed types | * | * | * | * | * | **7,000** |
| Total | **439,000** | **317,000** | **535,000** | **546,000** | **490,000** | **2,327,000** |

Table A- 3. Wall structure by dwelling age; Wales (BRE (Building Research Establishment), 2014).



| **Predominant type of wall structure** | **Dwelling Age** | | | | | |
|---|---|---|---|---|---|---|
| | **Pre 1919** | **1919 - 1944** | **1945 - 1964** | **1964 - 1980** | **Post 1980** | **Total** |
| Masonry cavity | 29,000 | 110,000 | 202,000 | 220,000 | 207,000 | **768,000** |
| Masonry single leaf | * | * | * | * | * | **5,000** |
| 9 inch solid | 100,000 | 14,000 | 5,000 | * | * | **119,000** |
| >9 inch solid | 199,000 | 10,000 | * | * | * | **214,000** |
| In situ concrete | * | * | 18,000 | 8,000 | * | **28,000** |
| Concrete panels | * | * | 14,000 | 5,000 | * | **21,000** |
| Timber panels | * | * | * | 6,000 | 5,000 | **14,000** |
| Metal sheet | * | * | * | 1,000 | * | **5,000** |
| Mixed types | 29,000 | * | * | * | * | **38,000** |
| Total | **361,000** | **138,000** | **249,000** | **245,000** | **219,000** | **1,212,000** |

Table A- 4. Wall structure by dwelling age; Northern Ireland (BRE (Building Research Establishment), 2014).



| Predominant type of wall structure | Dwelling Age | | | | | |
|---|---|---|---|---|---|---|
| | **Pre 1919** | **1919 - 1944** | **1945 - 1964** | **1965 - 1980** | **Post 1980** | **Total** |
| Masonry cavity | 13,000 | 43,000 | 134,000 | 163,000 | 208,000 | **561,000** |
| Masonry single leaf | * | * | * | * | * | * |
| 9 inch solid | 40,000 | 25,000 | * | * | * | **66,000** |
| >9 inch solid | 49,000 | * | * | * | * | **54,000** |
| In situ concrete | * | * | * | * | * | **9,000** |
| Concrete panels | * | * | * | * | * | * |
| Timber panels | * | * | * | * | * | * |
| Metal sheet | * | * | * | * | * | * |
| Mixed types | * | * | * | * | * | **9,000** |
| Total | **109,000** | **74,000** | **143,000** | **168,000** | **209,000** | **703,000** |

# Appendix 2. Questionnaire: Internal aesthetic and energy efficient retrofit

**1.**Participant Consent: Do you agree to participate in this study? (I have read and understood the participant information sheet for the above study and what my contribution will be, I understand the purpose and nature of this study and I am participating voluntarily. I have been given the opportunity to ask questions via phone and email. I understand that any information provided will be used anonymously and safely. I understand that I can withdraw from the study at any time, without any penalty or consequences). Required
More info

● Yes
○ No

**Questionnaire**

**2.**How old are you? *Required*

○ 18-24
○ 25-34
○ 35-44
○ 45-54
○ 55-64
○ 65-74
○ 75 years or older

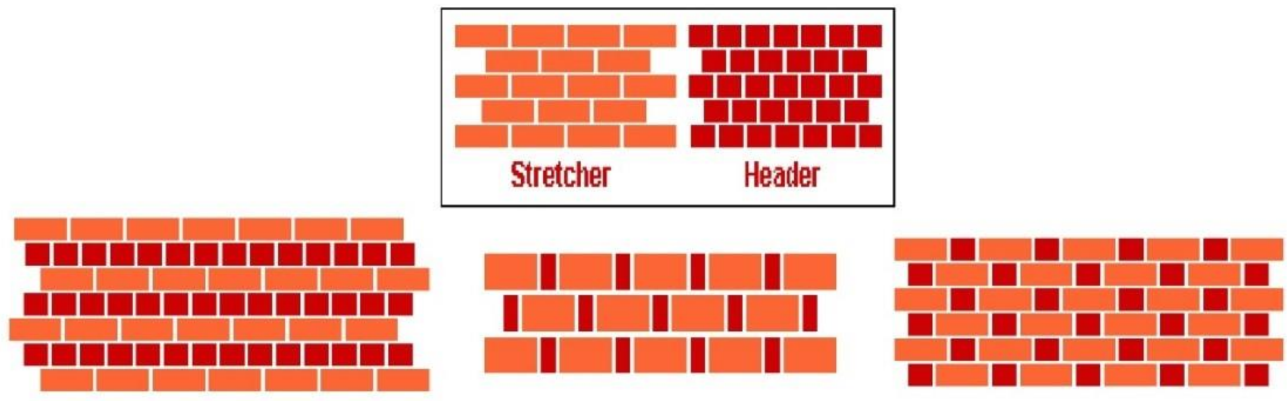
**3.**What is your gender? *Required*

○ Male
○ Female

**4.**What is your origin? *Required*

○ UK
○ Non-UK
○ Prefer not to answer

**5.**Are you living in a brick home with solid walls? ie. The wall consists of the combination of header and stretcher in the layout of bricks (like any of the pictures below)



*Required*

○ Yes
○ No. My home is made of bricks, but the brick pattern is different
○ No. My home is not made of bricks
○ Don’t know

**6.** When was your home built? *Required*

○ Pre 1700
○ 1701-1750
○ 1751-1800
○ 1801-1850
○ 1851-1900
○ 1901-1925
○ 1926-1930
○ 1931-1950
○ Post 1950
○ Don’t know

**7.** What is the ownership status of your home? *Required*

○ Owner
○ Mortgage owner
○ Rent- Private landlord
○ Rent- housing association
○ Rent- local authority

**8.** What type of property are you living in? *Required*

○ Detached house
○ Semi-detached house
○ Traced/mew/town house
○ Bungalow
○ Flat
○ Other

**9.** Including yourself, how many people live in your household? *Required*

○ 1

○ 2
○ 3
○ 4
○ More than above

**10.** What is your household income? *Required*

○ Unemployed
○ Below £20,000/year
○ £20,000-£40,000/year
○ £40,000-£60,000/year
○ £60,000-£80,000/year
○ £80,000-£100,000/year
○ More than above ranges
○ I prefer not to answer

**11.** The design of wall surface internally (such as painting, wallpaper, and decorative patterns) is important for the aesthetic appearance of living space and wellbeing of occupants. *Required*

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree
○ Don’t know

**12.** Improving the living space features aesthetically is important in my house retrofit. *Required*

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree
○ Don’t know

**13.** There are two products for wall internal surface retrofit. They both have the same functionality and quality standard. But one of them is aesthetically appealing for you. Which one do you choose to buy If the cost is the same? *Required*

○ I will choose the one which is aesthetically appealing
○ I will not choose the one which is aesthetically appealing

**14.** There are two products for wall internal surface retrofit. They both have the same functionality and quality standard. But one of them is aesthetically appealing for you. Which one do you choose to buy If the cost is different? *Required*

○ I will select the attractive one even if I have to pay more money but within my budget as I care about aesthetic feature of my living space

○ Aesthetic feature of internal space is not that important to me, so I will select the cheaper one

**15.** Would you like to improve energy efficiency of your home? *Required*

○ Yes
○ No
○ Don't know

**16.** Energy improvement may not be my priority during retrofit, because of different reasons such as uncertainties in time and cost of installation, unclear added value to the property, potential saving in energy bills, difficulties in finding the professional and trustful contractors. *Required*

○ Agree
○ Disagree
○ Don't know

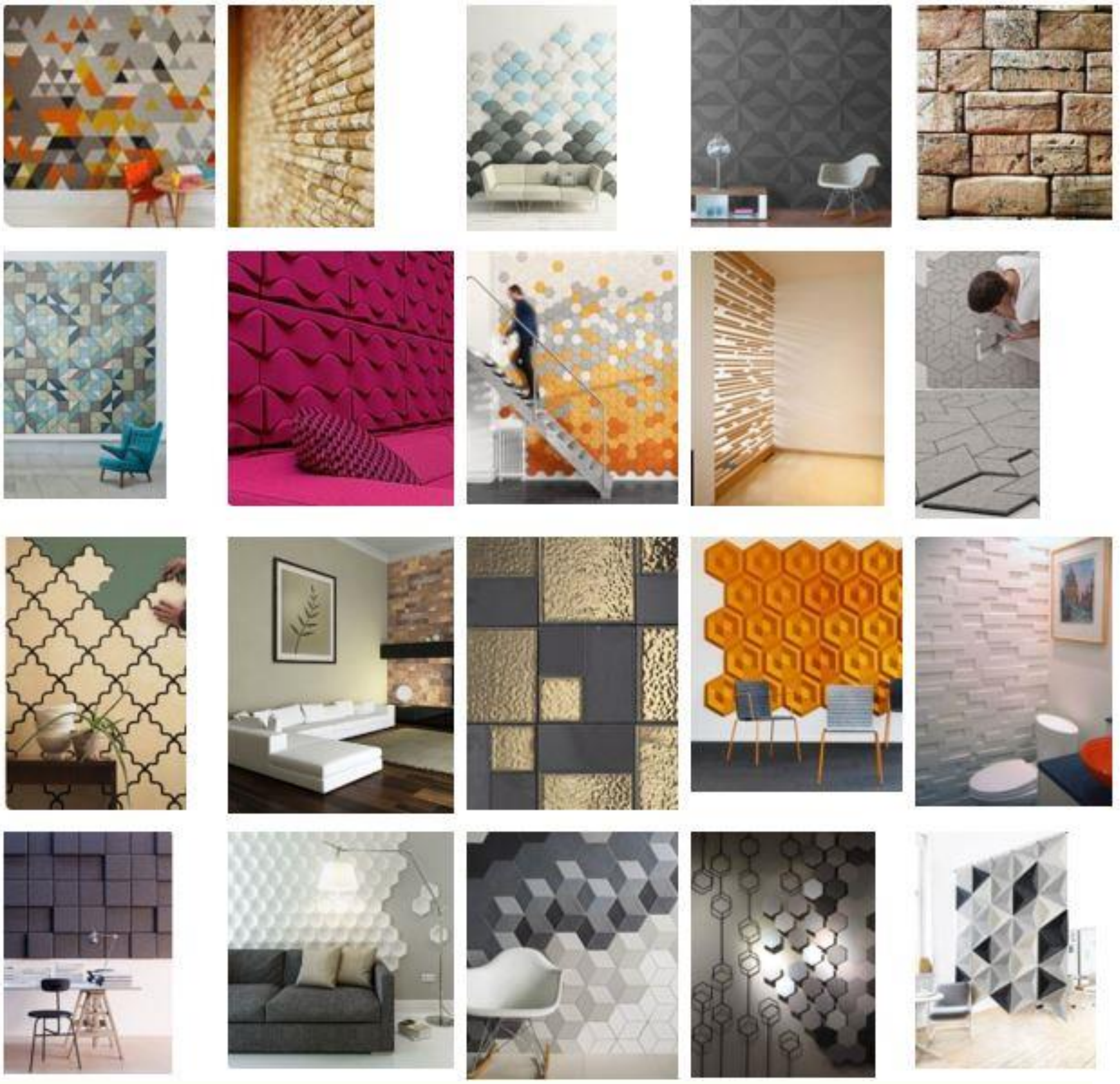
**17.** In the house retrofit internally, how important are the following factors for you? *Required*

| | Very Important | Important | Moderately Important | Slightly Important | Not Important | Don't know |
|---|---|---|---|---|---|---|
| Aesthetic | ○ | ○ | ○ | ○ | ○ | ○ |
| Energy saving | ○ | ○ | ○ | ○ | ○ | ○ |
| Cost | ○ | ○ | ○ | ○ | ○ | ○ |
| Time frame | ○ | ○ | ○ | ○ | ○ | ○ |

**18.** If you decide to do energy retrofit by internal wall insulation in your house, how do you feel about two following options (A and B)?

**(A)** The plain panels which also need extra work in terms of painting or applying wallpaper after installation. Picture below is an example only.

**(B)** The aesthetic panels which include decorative features and patterns of your choice; The pictures below show some possible patterns of aesthetic panels for demonstrations only.



| | *Required* | | | | | |
|---|---|---|---|---|---|---|
| | Strongly agree | Agree | Neutral | Disagree | Strongly disagree | Don’t know |
| (A) The plain panels- Extra work needed for decorating the panel after installation | ○ | ○ | ○ | ○ | ○ | ○ |
| (B) The aesthetic panels with decorative features and patterns on them | ○ | ○ | ○ | ○ | ○ | ○ |

**19.**Some people may be reluctant to apply Internal wall insulation because it might reduce the internal house space slightly depending on the type of insulation. However, including aesthetic features to wall insulation may be encouraging to use as they can benefit from two features (aesthetic and energy efficiency) in one product at the same time in internal retrofit. To what extent do you agree or disagree? *Required*

○ Strongly agree

○ Agree

○ Neutral

○ Disagree

○ Strongly disagree

○ Don’t know

**20.** Professional organisations should initiate to deliver the combined retrofit (energy improvement and internal decorating) as a single package to promote the internal wall insulation application. Such companies/organisations design the retrofit plan based on user’s preferences and implement and supervise the process to achieve the target energy saving. To what extent do you agree or disagree? *Required*

○ Strongly agree

○ Agree

○ Neutral

○ Disagree

○ Strongly disagree

○ Don’t know

# Appendix 3. Ethics approval

**Research, Innovation and Academic Engagement Ethical Approval Panel**

Doctoral & Research Support
Research and Knowledge Exchange,
Room 827, Maxwell Building
University of Salford
Manchester
M5 4WT

T +44(0)161 295 5278

www.salford.ac.uk

5 September 2019

**Mahsa Seifhashemi**

Dear Mahsa

**<u>RE: ETHICS APPLICATION STR1819-21 – The role of aesthetics in energy efficient strategies: the case of solid wall houses in the UK</u>**

Based on the information you provided, I am pleased to inform you that your application STR1819-21 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting S&T-ResearchEthics@salford.ac.uk

Yours sincerely,

Dr Devi Prasad Tumula
Deputy Chair of the Science & Technology Research Ethics Panel

# Appendix 4. Participant information sheet

### Project Title

The role of aesthetics in energy retrofit strategies: the case of solid wall houses in the UK.

### Project focus

In UK domestic sector, 36% of Carbon emission belongs to solid wall dwellings. However, the solid wall insulation application has not been very successful so far. The potential of energy saving and $CO_2$ reduction from wall insulation is high considering the vast number of solid wall dwellings in the UK. Adding aesthetic concept in internal wall insulation as the motivation and possibly time and cost-effective method in renovation to contribute in uptake of solid wall insulation, is the main hypothesis, which will be examined during this research.

### What do you want me to do?

You are required to respond to a questionnaire containing 20 questions and It will last approximately 10 minutes. Please complete the questionnaire at your earliest convenience, but **no later than 30th of October 2019**.

### Do I have to take part?

Your participation is entirely voluntary. You are free to withdraw from the study if you change your mind at any stage without giving any reasons.

### How will you protect my confidentiality and anonymity?

All participants will be anonymised by a code number assigned to each person and their identity will not be revealed at any point. The information you give will be treated strictly confidential in line with the GDPR. All participants have the right to enquire about their involvement and withdraw from this research at any stage. You will not be able to be identified or identifiable in any reports or publications. All data will be kept in a password protected university computer. All hard copies will be kept in a locked cabinet that will be accessible by the candidate only.

### What will happen to the results?

The results of the project will be used to write my dissertation and publish journal papers and reports. If you wish to be given a copy of any papers resulting from the research, please feel free to contact me.

### Contacts for further information

If you have any queries or questions about this research and your participation, please do not hesitate to contact me:
Mrs Mahsa Seifhashemi
Email S.M.Seifhashemi@Salford.ac.uk
Phone No: 0161 295 4420.

# Appendix 5. Environmental and Energy Assessment of Solid Wall Insulation Technology for Different Climate Zones in the UK

12th Annual International Conference on Architecture
Athens Institute for Education and Research (ATINER)
4-7 July 2022, Athens, Greece

Mahsa Seifhashemi1 , Hisham Elkadi[1]

## Abstract

Thermal retrofit of the existing homes is crucial for tackling the UK's fuel poverty and achieving the net-zero carbon target. Among all the retrofit options, solid wall insulation (SWI) has great potential for energy saving and $CO_2$ reduction. However, the progress of SWI has been very slow with a significant number of solid wall homes remaining to be insulated. Different barriers were identified to halt SWI application. One of those is the lack of accurate information and awareness about SWI energy benefits. Therefore, this study intends to evaluate the energy benefits and indoor temperature changes following SWI in 4 different climate zones (North-West, North-East, South-West and South-East) across the UK. To achieve this aim, the Salford energy house, a typical end of trace solid wall property, was modelled in IES-VE software and the benefits of SWI in terms of energy consumption, $CO_2$ emission and cost were investigated for the selected 4 cities of Camborne, Manchester, Aberdeen, and Heathrow representing each UK climate zone. The results showed a significant annual energy saving of about 35% by implementing the SWI where the U-value and AP are changing from U=1.56 $W/m^2K$, AP=13.95 $m^3/m^2h$ to U=0.2593 $W/m^2K$, AP1=10 $m^3/m^2h$. The maximum energy saving was achieved for Aberdeen at 54.36 $kWh/m^2/year$. This was estimated to be about 900 kg $CO_2$ reduction per year. The cost-saving was found to be £260 to £343 yearly for the selected cities in 4 climate zones of the UK.

# Appendix 6. Publications

Seifhashemi, M., & Elkadi, H. (2022). Aesthetic appealing wall insulation: a novel user-centred solution for uptake of solid wall insulation in the UK. Building and Environment, 224 (2022)109550.

Seifhashemi, M., & Elkadi, H. (2022). Environmental and energy assessment of solid wall insulation technology for different climate zones in the UK. 12th Annual International Conference on Architecture, Athens Institute for Education and Research (ATINER), Athens, Greece, 4-7 July 2022.

Seifhashemi, M; Elkadi, H; & R. Fitton, (2020). The impact of baseline wall U-value on energy performance of solid wall insulation, Proceedings of the 5th IBPSA England, Conference on Building Simulation and Optimization (Virtual), Loughborough, UK: 21-22 September 2020.