Department of Mechanical and Aerospace Engineering

Energy efficiency retrofits for facilitating the transition to net-zero emissions in UK homes

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: JRob Date: 26/08/2020

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I would like to give my sincere thanks to Dr. Nick Kelly for his advice and guidance over the completion of this project. Secondly, thanks go to each of the lecturers who have made this year both engaging and enjoyable (in person and even on zoom). Love also goes to my family who have supported me throughout my education and put up with me through lockdown. Finally love and admiration to my wonderful friends.

Executive summary

The UK has committed to net-zero greenhouse gas emissions by 2045. For the 28 million homes in the UK, this requires rapid reduction of heat demand and the decarbonisation of the heat supply. Energy efficiency retrofits will play a crucial role in achieving net-zero homes. They are the most accessible way of tapping into the vast energy saving potential within the UK housing stock.

The primary aim of this investigation was to quantify the potential energy savings from several different types of retrofit installation to allow for a cost-optimal route to a net-zero-ready home to be declared.

ESP-r was used to carry out simulations on a typical UK semi-detached house. The types of retrofit measure under investigation were: loft insulation, roof insulation, cavity wall insulation, ground floor insulation, external doors and windows. Multiple iterations of each installation were assessed in isolation for their energy saving potential. The impact of the reduction in air infiltration rate linked to each type of installation was also evaluated for its contribution to the decrease in the building's energy demand. Loft insulation and roof insulation were found to be the most cost-effective methods of improving the performance of the building's thermal envelope. Meanwhile replacing windows and installing ground floor insulation were the least cost-effective when examined in isolation.

The retrofit measures were then applied to the building model in combination to assess how they would perform together. It was found that roof insulation has little benefit when used in combination with loft floor insulation. Meanwhile each of the other installations outperformed the energy savings they achieved when examined in isolation by approximately 10%. The cost-optimal route to a net-zero-ready home was then stated by comparing the peak rate of heat demand for each room with the theoretical rate of heat emission from a low-temperature radiator powered by a heat pump. The total estimated cost of the lowest-cost path to achieving this target of peak rate of heat demand was £3118.16. It involved roof insulation, cavity wall insulation and replacement of external doors and windows.

Table of Contents

List of Figures

List of Tables

Nomenclature

$\dot{Q}_{Rad}$=Rate of radiative heat transfer

$\dot{Q}_{Conv}$=Rate of convective heat transfer

A= total surface area of the radiator (m^2)

C_S= Stefan-Boltzmann constant of black bodies (5.67 W/m^2K^4)

ε = emissivity of radiator surface

ε_n = normal component of emissivity

T_1= Temperature of the radiator surface (K)

T_2= Temperature of the surrounding walls (K)

α=Heat Transfer Coefficient ($\frac{W}{m^2K}$)

θ_1=Temperature of the radiator surface (°C)

θ_0=Temperature of the bulk air mass (°C)

Ra=Raleigh Number

Gr=Grashoff Number

Pr=Prandtl Number

g=Acceleration of mass due to gravity (m/s^2)

h=Height of the radiator (m)

ν = Kinematic viscosity (m^2/s)

Nu= Nusselt number

λ = Thermal conductivity (W/mK)

1. <u>Introduction</u>

The world is facing a climate crisis. Global action has been accelerated by a succession of reports by the IPCC. The latest of which states that we must limit the global average temperature rise to 1.5°C above pre industrial levels in order to mitigate against the worst impacts of climate change (Masson-Delmotte *et al.*, 2018). In light of this, nations around the globe are committing to net-zero emissions targets. The UK has set a target of net-zero emissions by 2045 and currently our biggest sector in terms of emissions is heat with 37% of the total outlay. which is responsible for 37% of the UK's greenhouse gas (ghg) emissions. More specifically, space heating makes up 17% of the UK's ghg total (National Statistics, 2020a). This is shown by figure 1.1 below.

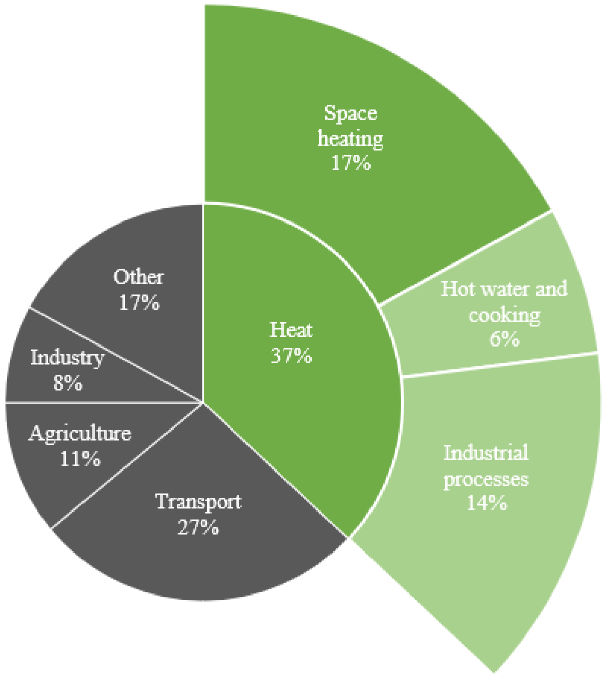


Figure 1.1: Breakdown of UK ghg emissions by sector in 2018

The majority of this space heating portion can be attributed to domestic heating. This investigation will focus on how to deliver net-zero for the domestic space heating. Each sector has its unique decarbonisation challenges and space heating is no different. Currently, 85% of homes in the UK utilise natural gas boilers as their primary space-heating system (Sonnichsen, 2020). Over the coming years, these 23.8 million homes will need to switch to a low-carbon alternative. For the majority of homes, this is likely to be a heat pump. However this transition cannot and will not take place quickly. The heat pump industry is still scaling up and working to drive down the cost of the technology, meanwhile swathes of technicians must be trained in order to carry out the vast number of installations required before 2045.

Simply waiting for homes to all switch to heat pumps is far from optimal if the goal is to minimise the ghg emissions that are produced prior to 2045. Since an estimated 75% of homes occupied in 2050 exist today (Wright, 2008), it is crucial that energy-efficiency retrofits play a large role in the UK's decarbonisation strategy. Improving the efficiency of a building's thermal envelope through retrofit measures such as insulation works to reduce emissions from gas boilers in the short term. Indeed, Rosenow *et al*. found that over a quarter of domestic energy can be cost-effectively mitigated by 2035 (Rosenow *et al.*, 2018). However, by reducing the inherent energy demand of homes, this will also allow for smaller heat pump units to be used. This has several clear benefits, not least saving homeowners money, but also reducing the peak load on the electricity network. This factor will become increasingly important as different sectors such as transport and industry all look to electrify. Thus, any work taken to limit the future increase in peak load will limit the network upgrades that are required and save taxpayer's money.

Clearly, the benefits of widespread domestic retrofit are significant and numerous. This investigation seeks to plot a course through the various retrofit options to propose a cost-optimal way for homeowners to prepare their homes for the net-zero future. The report proceeds with a short introduction to the history of energy retrofit policy in the UK. A literature review will then provide academic context for the investigations undertaken. The methodology sets out the technical inputs and boundary conditions for the simulations that are carried out. It also provides the rationale behind the decisions made in creating a representative building model and relevant test scheme. The results of the investigations are then presented and discussed in chapter 4. Chapters 5 and 6 then round off the report by offering recommendations for future work and discussing the limitations of the study before providing salient conclusions.

2. Literature Review

This literature review proceeds with a short introduction to the key retrofit schemes in the UK. This introduction provides context for the evaluation of journal papers that follows (section 2.2-2.7) as well as the topics discussed in the rest of the report

2.1 Policy Summary

The following is a brief summary of the recent UK government schemes designed to promote and incentivise the installation of energy saving retrofit measures in UK homes.

2.1.1 Carbon Emissions Reduction Target (CERT): 2008-2012

CERT was a legally binding obligation for energy suppliers to work towards carbon reduction targets. The scheme was guided in its methodology for meeting targets by the Gas and Electricity Order of 2008. The broad target was for suppliers to reduce lifetime CO_2 emissions by 293 million tonnes by the end of 2012. The suppliers surpassed this target, with savings of 296.9 Mt CO_2 (Ofgem, 2013a).

2.1.2 Community Energy Saving Programme (CESP): 2009-2012

CESP was characterised by its focus on delivering energy efficiency upgrades to low-income areas of the UK. Partnerships between local authorities, energy companies, housing associations and community groups were utilised to break down common barriers to retrofit. These barriers include lack of capital, lack of energy awareness and tenant-landlord split incentives (Elsharkawy and Rutherford, 2015). Up to its closure in 2012, the scheme provided 16.31 Mt CO_2 of emissions reductions, 84.7% of its 19.26 Mt CO_2 target (Ofgem, 2013b).

2.1.3 Green Deal: 2012-2015

The Green Deal was created to allow homeowners access to energy efficiency retrofits at no upfront cost. The idea was to utilise the cost-savings from installing the measure to meet the monthly repayments. These finances were subject to the so-called ‘Golden Rule’ whereby the monthly repayments should not be greater than the potential cost savings for the first year of the loan. In theory, the homeowner would see no increase in their bills, and once the work had been paid off, they would see the cost benefits of the reduced energy demand.

Criticism was levelled at the scheme as the loans had a fixed interest rate of 7% for up to 25 years. This rate was higher than commonly available home-loans at the time. A number of energy providers suggested this rate was too high and would make the golden rule difficult to adhere to. Moreover, low-users of energy were often not able to achieve the energy savings required to make the finances work. Furthermore, many accused the scheme of stifling competition and growth within the retrofit supply chain. This is because only a limited number of suppliers were given certified as Green Deal suppliers at a time when it was viewed as crucial to support new growth in the market to drive consumer-end costs down.

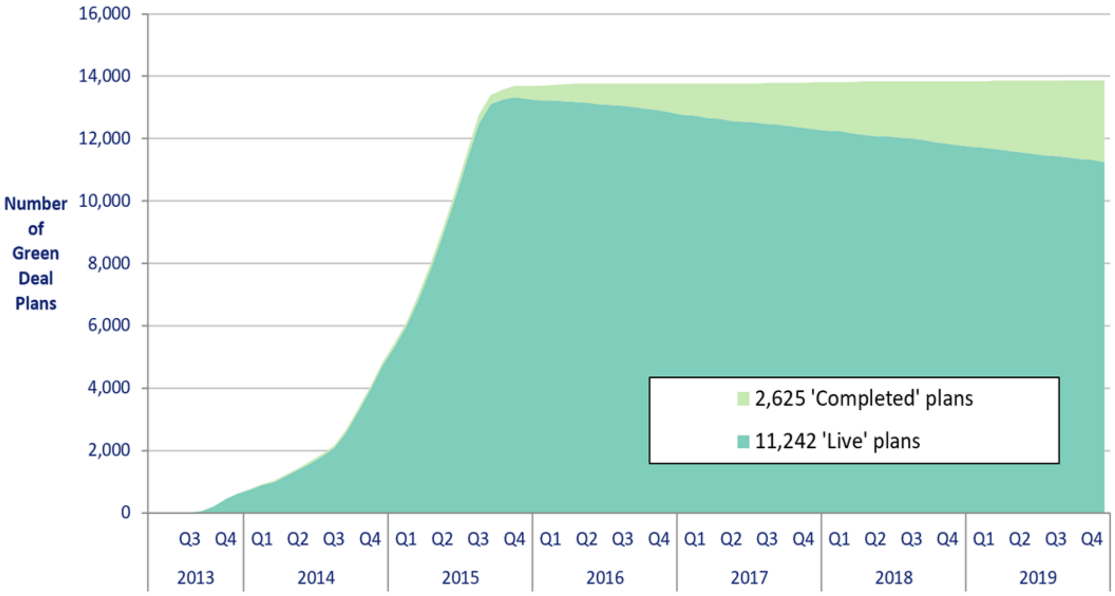


Figure 2.1: Cumulative total of Green Deal plans 2013-2019

Figure 2.1 shows the cumulative number of Green Deal plans that were initiated. The total plateaus during 2015 as the government announced in July of that year that there would be no mor public funding for Green Deal plans. Protection of taxpayer money after a modest initial take-up was cited as the primary reason for the scrapping of finance for the scheme (Department of Energy & Climate Change, 2015). The few plans that were taken out post-2015 were privately financed as the programme framework remains in place for private investors. Few plans are yet completed as the financing plans run for up to 25 years.

2.1.4 Energy Company Obligation (ECO): 2013-Present

ECO began in January of 2013 as a replacement for the CESP and CERT schemes and to work alongside the Green Deal. It is currently on its third phase ‘ECO3’ at the time of writing. The premise of the scheme is to make large energy suppliers responsible for delivering energy performance improvements to homes in the UK. These obligations were quantified by the Home Heating Cost Reduction Obligation (HHCRO) which concentrated on low-income and vulnerable households. Secondly the Carbon Emissions Reduction Obligation (CERO) which focussed on hard-to-tackle properties, and finally the Carbon Saving Community Obligation (CSCO) which prioritised low-income areas for the receipt of energy saving measures. (Ofgem, 2018). Each of these sub-obligations carried specific targets for emissions or cost reductions as appropriate. Loft insulation, wall insulation and boiler replacements made up 79% of the installations carried out through ECO (Oxley, 2020).

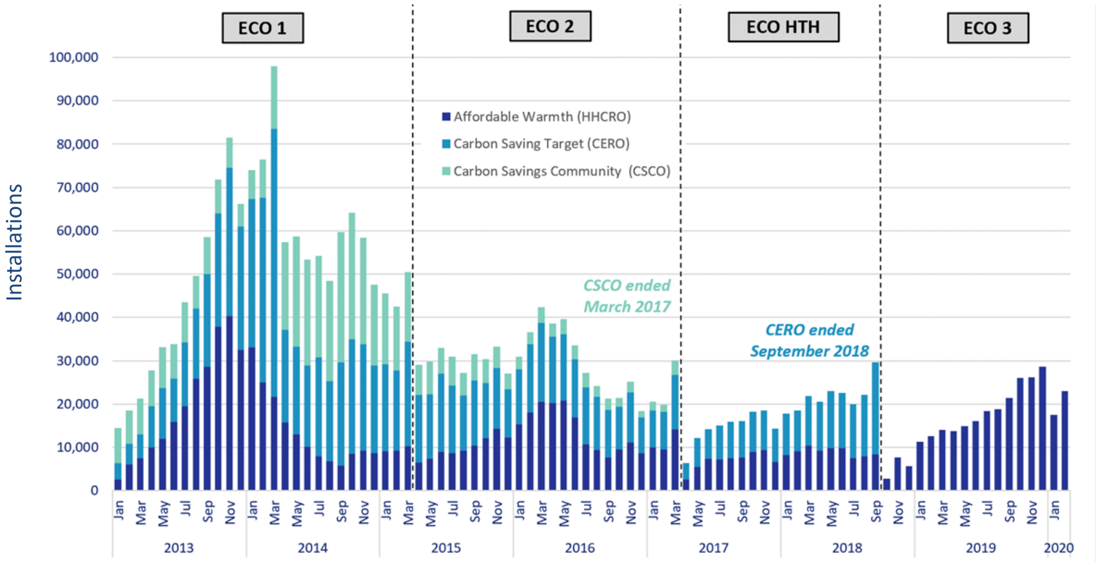


Figure 2.2: Number of ECO installations per month, 2013-2020

As of December 2019, 2.7 million measures had been installed across 2.1 million homes through ECO. Figure 2.2, produced by the office for National Statistics, shows how the installation of these measures has declined over time. This is predominantly a result of the scrapping of the CSCO and CERO in 2017 and 2018 respectively. This plot highlights the need for new policy incentives for energy efficiency upgrades to be cancelled out since the uptake is slowing with each year. Moreover, the 2.1 million homes to receive ECO installations account for less than 10% of the homes in the UK. Clearly, to achieve the rollout of widespread energy demand reduction measures, a new policy direction is necessary.

2.2 ‘Do deep low carbon domestic retrofits actually work?’ (Gupta and Gregg, 2016)

This 2016 study set out to assess the energy performance of two deep energy retrofits conducted in the UK on a Victorian solid wall house and a cavity wall house built in the 1990’s. Both the performance of the thermal envelope and the behaviour of the occupants were analysed before and after the retrofit. The retrofits were conducted as part of the government-sponsored ‘Retrofit for the Future’ (RfF) programme. The scheme was introduced in 2009 and was underpinned by the UK’s new emissions target of an 80% reduction by 2050. Over 200 different projects were awarded £20,000 to design a ‘whole-house’ strategy to reduce household CO_2 emissions by 80%. 86 of these projects were subsequently awarded £150,000 to realise these designs. The standardised emissions reduction target was 17 kg/m^2/year of CO_2 savings for each house.

Air permeability tests were also performed both pre- and post-retrofit, as well as a thorough post-retrofit monitoring strategy to understand how the energy use of the building and it’s occupants had changed. The energy reduction retrofit measures included cavity wall insulation, triple glazing and improvements to the air tightness of both buildings. The low-carbon measures added afterwards included a high efficiency boiler, efficient appliances, LED lighting and finally the installation of solar PV and solar thermal panels.

Pre-retrofit, the Victorian house was found to use significantly less energy than was modelled using the SAP methodology. This was attributed to the occupants’ concerns over cost and the ineffectiveness of the current heating system given the leaky thermal envelope. The modern cavity wall house was far closer to the predicted value.

Post-retrofit, both houses failed to meet the air infiltration reduction target set out. It was suggested that this was due to errors in the work carried out to plug the holes and gaps in the external envelope. This displays how difficult it is to reduce the air permeability of a building. In terms of emissions, the Victorian house saw a 75% decrease in CO_2 emissions whilst the cavity wall property saw a smaller reduction of 57% compared to their respective baseline emissions. This was partially due to the air permeability rates not reaching the low target. However thermal imaging work showed that there was significant heat loss where there were connections between materials. This thermal inconsistency was highlighted by U-value measurements that saw localised U-values double that of the material's specification in some cases. Occupancy behaviour was also highlighted by the post-retrofit monitoring as a key factor in the disparity between the 80% reduction target that had been designed to, and the reality. Specifically, the residents were openly unwilling to learn how to get the most out of their new heating system, preferring to use a simple timing system which often led to overheating. The occupants of the modern home also bought an unrated freezer, increased their use of the tumble dryer and purchased two reptile tanks with heat lamps (Gupta and Gregg, 2016).

This study, whilst simple in its scope, provides good insight into the energy-saving potential of retrofits. Perhaps more importantly however, it offers a very grounded discussion around the reasons for the gap between simulations and real-world performance.

2.3 'Energy-led domestic retrofit: impact of the intervention sequence' (Simpson *et al.*, 2015)

This journal paper centres around the investigation of the influence of the sequencing of energy retrofits, and how different measures work when applied as a complete package versus being installed in stages. Five different sequences are defined, each installing up to five retrofit measures over a 25-year simulation period. The sequences are derived from the differing priorities that may be in play, whether that be aesthetics, energy savings, or a boost to the value of the property.

The results, simulated using IES Virtual Environment, showed that wall insulation and installation of double glazing had the largest impact on energy consumption, with ground floor insulation offering the least improvement. The study evaluated the cumulative CO_2 emissions of each scenario over the 25-year period and found that the timing of each installation was by far the biggest factor. For example scenario A, characterised as wealthy homeowners, were able to invest early on in relatively expensive measures like double glazing and wall insulation. Scenario A saw the lowest cumulative emissions at 149.6 tonnes of CO2. Whereas other scenarios that resulted in greater final reduction in annual energy demand after 25 years, saw up to 50 tonnes more emissions over the period as the measures were installed far later. This is a key consideration given the strong evidence that the earth has an inherent ‘carbon budget’ whereby once the cumulative global ghg emissions go beyond a certain point, permanent damage to the environment will be incurred.

The authors noted that the same retrofit measures performed slightly differently in different houses. The efficiency of the boiler system in place was cited as the most explicit reason for the discrepancy. Logically, a building with an old, inefficient boiler will save more energy than a similar building installing the same measures, but with a new, efficient boiler. In conflict with this statement is the fact that the double glazing installed in house A before the boiler replacement was less effective than the same installation in house B that was carried out with a new boiler already installed. For house B the reduction in energy demand was 14% greater than that of house A. For house A, the double glazing was the first installation. Whereas for house B, wall, ground floor and loft insulation had already been put in place alongside the efficient boiler. Further inspection found that adding the double glazing in combination with these measures reduced the heating load more than double glazing on its own. This manifested itself primarily in the decrease in boiler operation hours. There was a drop of 441h from double glazing in house A and a fall of 1290h in house B (Simpson *et al.*, 2015).

The visual presentation of results is impressive, however there is little detail given on the simulation process. This means that it would be difficult to repeat the investigation. Nevertheless, this kind of study is crucial for furthering the understanding of ‘whole-house’ retrofits and being able to budget and plan large-scale retrofit schemes. It is also of direct relevance to this study as a key touchstone of the investigation is understanding the performance of measures in combination.

2.4 ‘Existing building retrofits: Methodology and state-of-the-art’ (Ma *et al.*, 2012)

This paper takes a holistic approach to deriving solutions to the problem of building efficiency. The authors begin by outlining the ‘generic retrofit problem’, primarily citing the misconceptions around retrofit options, benefits and cost that the paper aims to shed light on. They then introduce a five-phase breakdown of any sustainable retrofit programme. The phases are project setup and pre-retrofit survey, energy auditing and performance assessment, identification of retrofit options, site implementation and commissioning, and finally validation and verification. The details of each phase are all explored in the main body of the report. This phase structure acts as a clear way of simplifying the retrofit process and helps potential investors in retrofit to understand each aspect. The writers proceed to provide the ‘state-of-play’ for each area of retrofit. The reader gains brief overviews of energy audits, economic analysis, verification of energy savings and risk assessments. Brief descriptions of the different schools of thought on each topic are given along with references to further reading. The range of retrofit options are then explored, splitting them into three categories: demand side, supply side and human factors. Again, the grouping of options is helpful in avoiding confusion when later discussing broader retrofit strategies, i.e. demand side vs supply side management. Figure 2.3 below is then used to illustrate the fact that demand side options such as insulation and air-tightness improvements are simultaneously the cheapest of the retrofit options and the most environmentally beneficial. Therefore, the motivations of the investor are particularly important.

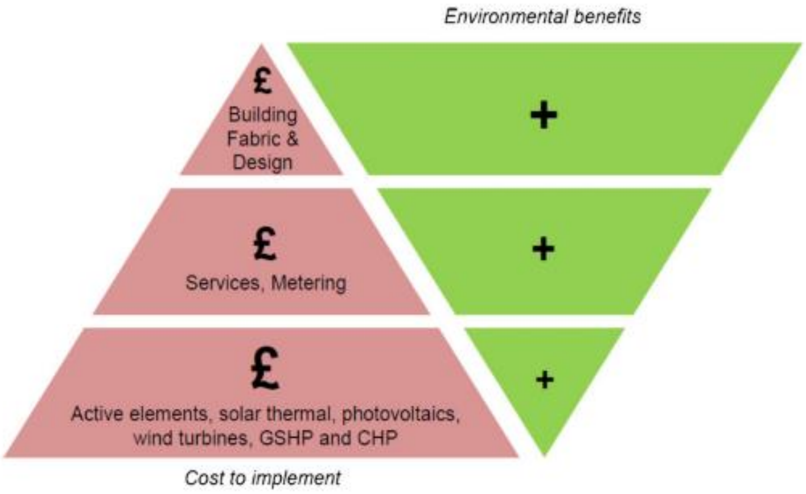


Figure 2.3: Cost versus environmental benefits between types of energy upgrade

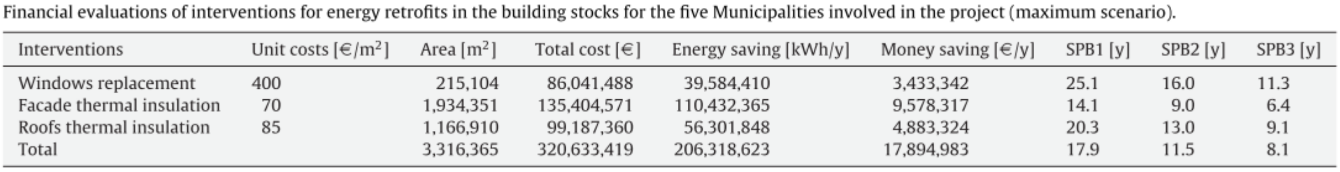
Finally, the report describes a summary of some the retrofit projects carried out for office buildings, residential buildings and other building types. This summary acts as a good overview of a range of basic conclusions garnered from research in the field (Ma *et al.*, 2012).

The key success of this paper are the frameworks that are presented that offer a basic understanding of the holistic retrofit process and its contributing factors. These frameworks serve as a good starting point beyond which a deeper understanding can be gained with more specific reading.

2.5 ‘A methodology for evaluating the potential energy savings of retrofitting residential building stocks’ (Dall’O’, Galante and Pasetti, 2012)

The aim of this report was to create an analysis tool to evaluate the potential energy savings that can be gained by retrofitting a stock of buildings. This tool is applied to five municipalities within the Milanese province in Italy, each of which had committed to a 20% CO2 emissions reduction by 2020 under the Covenant of Mayors Act, 2008.

The methodology begins by describing the methods used to gain a significant amount of contextual information about each building under the remit of a particular retrofit programme. These methods include the use of site maps, photogrammetric surveys, GIS analysis as well as on-site surveys. This all aims to build a more realistic picture of the real potential of each building under retrofit. The outputs are cited to include details on whether refurbishment is required, any previous retrofits completed and any historically sensitive features that may constrain retrofit work. From these investigations, three energy savings scenarios are then set out. The first assumes ‘business as usual’, taking the current policy framework and levels of investment and estimating potential energy savings across the building stock. The second scenario applies the same question of energy saving to a policy landscape that achieves a 20% CO2 reduction compared to a 2005 baseline. The last scenario considers the maximum potential for building efficiency improvements, within the real constraints defined by the prerequisite survey work. This is another distinction from other such papers. Rather than just define a limited target to achieve with least cost for example, this investigation defines the full potential to allow investors to then decide the extent of this potential that represents the best trade-off between cost and carbon mitigation.



Financial evaluations of interventions for energy retrofits in the building stocks for the five Municipalities involved in the project (maximum scenario).

Interventions	Unit costs [€/m²]	Area [m²]	Total cost [€]	Energy saving [kWh/y]	Money saving [€/y]	SPB1 [y]	SPB2 [y]	SPB3 [y]
Windows replacement	400	215,104	86,041,488	39,584,410	3,433,342	25.1	16.0	11.3
Facade thermal insulation	70	1,934,351	135,404,571	110,432,365	9,578,317	14.1	9.0	6.4
Roofs thermal insulation	85	1,166,910	99,187,360	56,301,848	4,883,324	20.3	13.0	9.1
Total		3,316,365	320,633,419	206,318,623	17,894,983	17.9	11.5	8.1

Figure 2.4: Cost evaluation for retrofits within the building stocks of the municipalities involved in the study

Figure 2.4, shows the results of the resulting analyses performed on the five municipalities in Italy. The key figures are the simple pay-back periods (SPBs) at the right-hand side. The three figures represent three different government incentive scenarios. First is no incentive, second is a 36% tax reduction and third is a 55% tax reduction. These figures show that the façade improvements offer the quickest return on investment, followed by roof insulation and window replacement.

The method used to calculate the benefits of each retrofit solution were limited. The savings of each type of retrofit measure, i.e. roof insulation, wall insulation and windows, were calculated in isolation. The use of a multi-flow integrated modelling tool would have provided more accurate results but require more time to complete the analysis. Additionally, for the wall insulation, only an external wall option is considered. This means that for 7 of the 11 building types, wall insulation was deemed not to be viable. This is disregarding significant energy saving potential that could be added to these building types using either cavity wall or internal wall insulation. The roof insulation was also only considered for those roofs over 30 years old as anything younger was deemed not to be cost-effective. Whilst its certainly likely that these options that have been omitted from the analysis would have been more costly and/or technically difficult, it is still important as a potential investor to see the full picture (Dall'O', Galante and Pasetti, 2012).

Lastly, the methodology only includes so-called 'demand-side' improvements to the thermal envelope of the buildings. Therefore, the use of low-carbon heating technologies or PV panels as well as upgrades to the internal control systems are not considered as carbon-mitigation options. Moreover, the thermal envelope improvements that are included are only the most readily available, mature technologies. This narrow scope of options potentially misses options that could provide cheaper or deeper carbon mitigation than those proposed.

The focus on the unique characteristics of the building stock is an important distinction from other bulk modelling methodologies. However, the lack of options analysed raises the question as to whether the resources and time spent gathering detailed information on the building stock would be better used in bolstering the analysis performed.

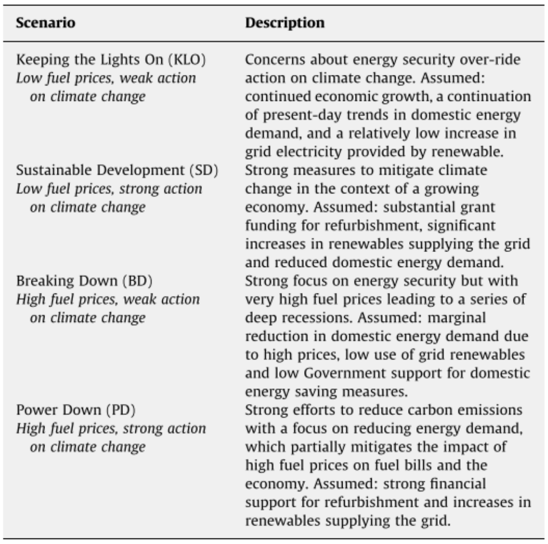
2.6 ‘Modelling the potential to achieve deep carbon emission cuts in existing UK social housing: The case of Peabody’ (Reeves, Taylor and Fleming, 2010)

This paper uses the case study of Peabody, a UK Housing Association that manages 18,000 homes in London, to demonstrate the issues and challenges involved in assessing the carbon-saving potential of a large group of homes.

Only physical home improvements and energy supply system changes are considered. Factors such as occupancy patterns and behaviour are discounted since they are outside the remit of a housing association or other retrofit investor.

The impact of the stock refurbishment was simulated using the purpose-built ‘Peabody Energy Model’. The energy usage was assimilated for 189 individual housing estates from the year 2006 until 2030. The first 4 years of simulated retrofit measures were driven by the then-planned work to satisfy the Decent Homes standard. However, after 2010, four different retrofit scenarios were examined. The primary focus was on the average annual CO_2 emissions per dwelling that was calculated for each estate. The ‘base’ approach is essentially an extrapolation of the then-current Decent Homes strategy. The ‘fabric’ scenario represents an all-in-one package of improvements including external wall insulation, double-glazing, thermostatic radiator valves and installing gas boilers in place of electric storage heaters amongst other measures. The ‘communal’ and ‘renewable’ scenarios introduce district heating connections and PV panel installations respectively.

The modelling assumptions such as energy demand and fuel conversion factors are introduced and explained well. Aside from the four modelled retrofit approaches, a further four scenarios are introduced. These scenarios are intended to demonstrate the impact of factors such as government support for renewable technologies and fuel prices on carbon mitigation. Figure 2.5 shows the written description of each scenario below.



Scenario	Description
Keeping the Lights On (KLO) *Low fuel prices, weak action on climate change*	Concerns about energy security over-ride action on climate change. Assumed: continued economic growth, a continuation of present-day trends in domestic energy demand, and a relatively low increase in grid electricity provided by renewable.
Sustainable Development (SD) *Low fuel prices, strong action on climate change*	Strong measures to mitigate climate change in the context of a growing economy. Assumed: substantial grant funding for refurbishment, significant increases in renewables supplying the grid and reduced domestic energy demand.
Breaking Down (BD) *High fuel prices, weak action on climate change*	Strong focus on energy security but with very high fuel prices leading to a series of deep recessions. Assumed: marginal reduction in domestic energy demand due to high prices, low use of grid renewables and low Government support for domestic energy saving measures.
Power Down (PD) *High fuel prices, strong action on climate change*	Strong efforts to reduce carbon emissions with a focus on reducing energy demand, which partially mitigates the impact of high fuel prices on fuel bills and the economy. Assumed: strong financial support for refurbishment and increases in renewables supplying the grid.

Figure 2.5: Written descriptions of each modelling scenario

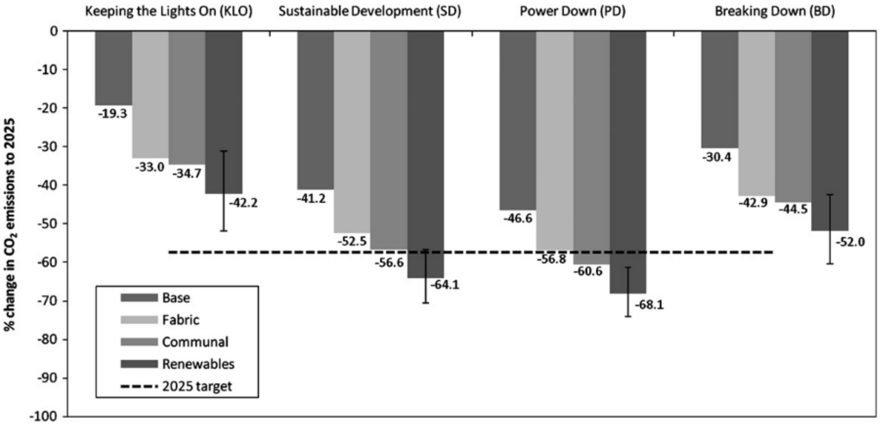


Figure 2.6: Emissions reduction for each scenario against 2025 target

Figure 2.6 shows how the combinations of retrofit approach and policy/fuel-price scenario stack up against the Greater London Authority’s target of reducing emissions by 60% by 2025 with respect to a 1990 baseline. It can be seen that this target is only met when there is a combination of strong action on climate change (sustainable development or power down scenarios) and the inclusion of district heating and/or renewable microgeneration in the measures implemented. This figure therefore indicates that it is critical that the government takes action to increase the availability of renewable technologies and offers financial support for retrofit measures (Reeves, Taylor and Fleming, 2010).

This investigation provides good and thorough theoretical grounding for the analysis that is carried out. However, since the model was only run through to 2030, some of the conclusions and discussion points are outdated at the time of writing. For example, the conclusion that including district heating and PV panels are the best way to meet a 2025 target is likely true, however arguably short-sighted as in 2020 most of the relevant discourse now surrounds the UK’s 2045 net-zero target. If 2045 is taken as the target date, then there is an argument that these supply-side measures become increasingly less valuable in carbon-mitigation terms because the electricity network’s carbon intensity falls towards zero as we approach 2045. Instead, the debate turns to how best to achieve net-zero in the buildings sector which prompts any solution to be considered over a longer period of time. the trade-off between implementing deep fabric retrofit measures to reduce the energy demand on fossil-fuel heating systems before the inevitable switch to a low-carbon alternative

In conclusion, this investigation implements a rigorous and valid modelling methodology, however the questions asked of the model in question are no longer as relevant as they were in 2010.

2.7 ‘Retrofitting social housing in the UK: Home energy use and performance in a pre-Community Energy Saving Programme (CESP)’ (Elsharkawy and Rutherford, 2015)

This report addresses and discusses the results of a survey completed by residents involved in a pilot Community Energy Saving Programme (CESP) in Aspley, UK. CESP is introduced within the context of previous government initiatives such as the Carbon Emissions Reduction Target (CERT) and Renewable Heat Incentive (RHI). CESP is intended to help low-income households and the barriers to installation of retrofit measures that they face. These include absence of funding, low awareness of the benefits and split-incentives between landlord and tenant. A ‘whole-house’ approach is employed by the CESP initiative. This means they aim to install a number of insulation measures alongside other improvements like replacing old boilers and installing modern kitchen and bathroom fittings. [P. Richards, D. Hough, Energy Efficiency Schemes, House of the Commons Library, London, 2012] These measures are installed with involvement from local authorities, housing associations, energy companies and community groups, this aims to ensure positive community engagement. The ‘rebound effect’ is then introduced. This is a behavioural phenomenon which can manifest itself in several ways. In this case, energy and cost savings gained from fabric improvements to a home may be partially offset by less stringent use of home heating for example. This is the driving argument behind a block of discussion that suggests that simply addressing the physical issue of building efficiency does not maximise the emissions reductions. In reality, there must be concurrent focus on understanding occupational patterns, lifestyles and habits in order to design control systems and educate people to maximise the energy savings.

The relationship between building efficiency, actual usage and consumption patterns is at the core of the methodology for this investigation. The primary objective is to formulate recommendations to help guide future domestic building efficiency policy initiatives. However, instead of modelling the benefits, the CESP pilot programme is used to perform a ‘before and after’ analysis. A questionnaire was devised to collect the required information both before and after the retrofit measures had been installed. The survey included questions on current problems with homes, heating patterns, monthly bills, energy performance and also lifestyle and behavioural questions. The responses to the initial questions about their installed heating systems showed that 38% of households said that they had only one heating control, the boiler thermostat. However, Nottingham City Homes suggested that most homes in Aspley are also fitted with a wall thermostat and thermostatic radiator valves. This strongly suggests a lack of awareness of the controls available. The report then declares a ‘moderate’ correlation between the 32% of homes that ‘always heat occupied rooms only’ and homes that ‘always use heating controls’. This correlation is used to suggest again that there is a majority that need more advice and training on how to use their heating controls.

It is difficult to take any strong conclusions about energy awareness from the lifestyle questions that were asked. Whilst the inferences that were made may well be correct, the majority of the questionnaire offers little that can be taken forward as genuine research. However, the question regarding advice received about saving energy did result in interesting discussion. 72% of residents said they had never had advice about managing their energy (Elsharkawy and Rutherford, 2015). This was compounded with a reference to a 2013 study that suggested 40% of those who have received energy advice considered it useless (Huebner, Cooper and Jones, 2013). This is fairly conclusive that there is a significant gap in knowledge that needs to be addressed. This investigation offers little that can be repeated with a software-based methodology, however there are key issues introduced that must be tackled by any organisations devising bulk retrofit strategies.

3. Methodology

3.1 Modelling objectives & scope

The primary aim of this investigation is to understand the value proposition of different retrofit measures that are commonly employed to improve the energy efficiency of homes in the UK. To produce a complete picture of this value proposition, we must understand firstly the energy saving associated with each installation, but also the cost of the materials and labour. Once the energy-saving potential and cost of each retrofit measure has been established, the analysis will turn towards assessing which measures, in combination, would enable a home to be declared as ready for ‘net-zero’. This section will explain the rationale behind each step of the investigations in question.

3.2 Choice of software

ESP-r was used to carry out the energy flow simulations for this investigation. ESP-r is an open-source multi-flow energy modelling software designed by researchers at the University of Strathclyde. It allows users to simultaneously analyse the thermal, electrical and acoustic performance of building geometries that can be realised within the graphical interface. The energy flows are calculated explicitly over a time-period defined by the user. Energy balances are calculated for each zone that is defined (usually representing a room). These calculations are driven predominantly by construction properties, heat gains (casual and weather-driven) and heating control schemes(Allison *et al.*, 2018). The software is well-suited to this investigation as there is a large database of materials as well as a powerful results module that allows for an in-depth examination of the model in question. ESP-r has been long-established in the energy research community and is the recipient of numerous validation efforts. Strachan, Kokogiannakis and Macdonald, (2008) have summarised the majority of this validation work.

3.3 Base Model configuration and assumptions

A key part of the validity of this study is the quality of the model used to answer the questions asked of it. However before introducing the model, the aims and intentions of the model must first be established. The aim of the base model is to represent a typical post-war UK home that is at the lower end of the government’s EPC rating system. It is true that many homes have already installed at least one of the retrofit measures that will be examined shortly as shown by figures 2.1 and 2.2. However in order to capture the relative benefit of each addition, the model must begin with little to no retrofit measures installed.

It was assumed that the building is heated using a natural gas boiler with an average operational efficiency of 70%.

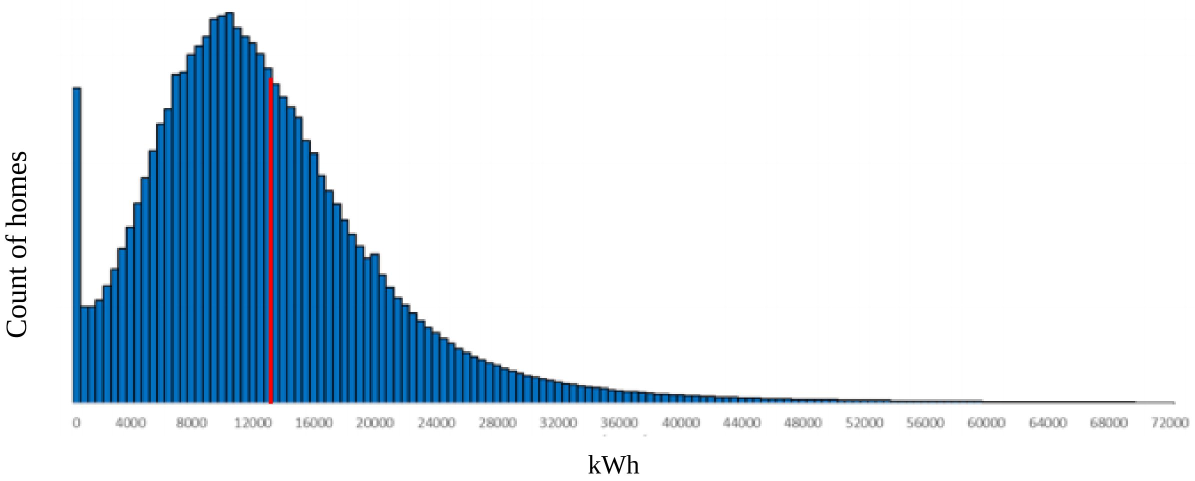


Figure 3.1: Histogram distribution of domestic natural gas consumption per meter in 2019, UK

Figure 3.1 displays a histogram distribution of natural gas consumption for all available gas meters in the UK, produced by the department for business, energy and industrial strategy (National Statistics, 2019). The mean value is 13,236 kWh. This report is concerned with only space heating demand, which according to the 2013 UK housing fact file, makes up 65% of total gas consumption (Palmer and Cooper, 2013). Therefore, considering an average gas boiler system efficiency of 70%, this leaves the average space heating demand per household at 6022 kWh per home. This will act as the minimum energy demand target in order to validate the base model in terms of energy usage as the uninsulated base model should be representative of an ‘energy hungry’ home.

3.3.1 Model geometry

A semidetached house was selected as the basis of the model as it represents the largest proportion of UK homes by type as shown by figure 3.2 from the UK housing fact file (Palmer and Cooper, 2013). It also sits in a median position in terms of size, allowing any conclusions to be applied to larger detached homes or generally smaller terraces, bungalows or flats.

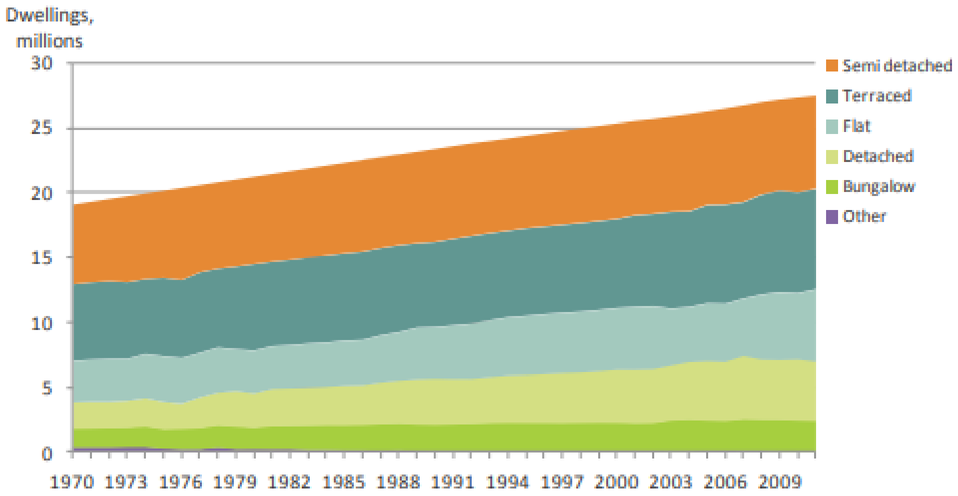


Figure 3.2: UK housing stock by building type

The building model matches the common ‘two-up two-down’ configuration. Figure 3.3 shows the wireframe view of the entire model geometry, along with its orientation. The west-facing side of the house is modelled as being attached to an adjacent building, either the other half of a two-home block or the first of a terraced row. In terms of the boundary conditions of the model, this means that the surfaces on this west-facing side are assumed to be connected to another surface of similar temperature. Conversely, the east-facing side of the building is modelled as being exposed to ambient weather conditions along with the north and south-facing sides.

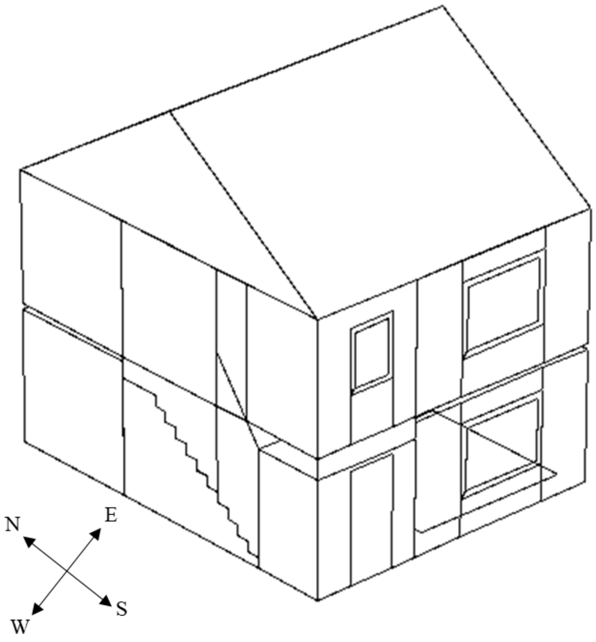


Figure 3.3: Wireframe view of the model geometry

Figure 3.4 below shows the plan view of each of the downstairs rooms, including the locations of doors and windows. It can be seen that the front door leads into the hall, whilst there is a back door leading out from the kitchen.

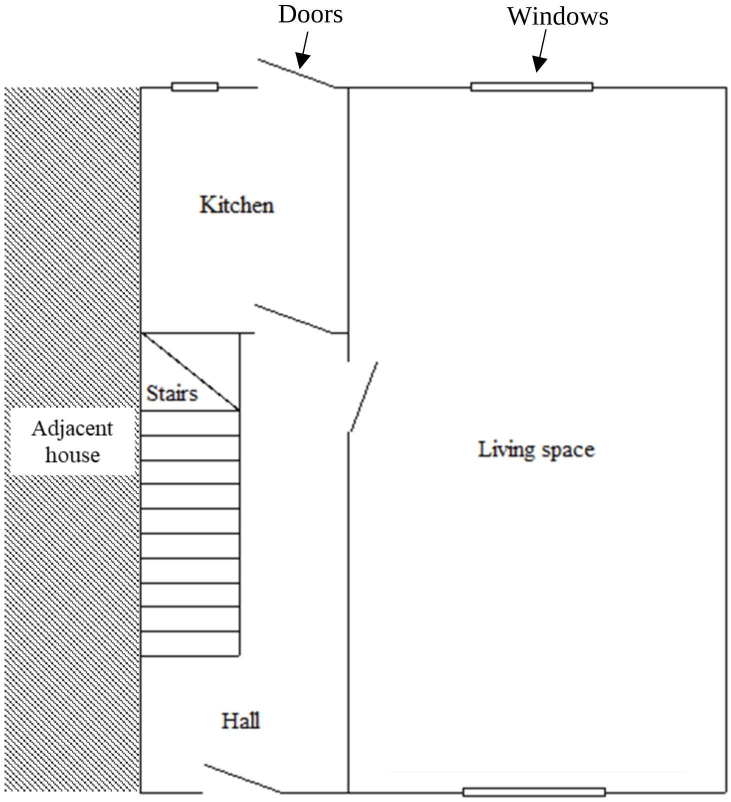


Figure 3.4: Plan view of ground floor

Similarly, figure 3.5 shows the layout of the upper floor. Note that each of the named rooms or spaces represent one of the nine zones defined within ESP-r to allow for calculation of energy flows. The only zone not shown in the figures below is the 'roof' zone which represents the empty loft space at the top of the building.

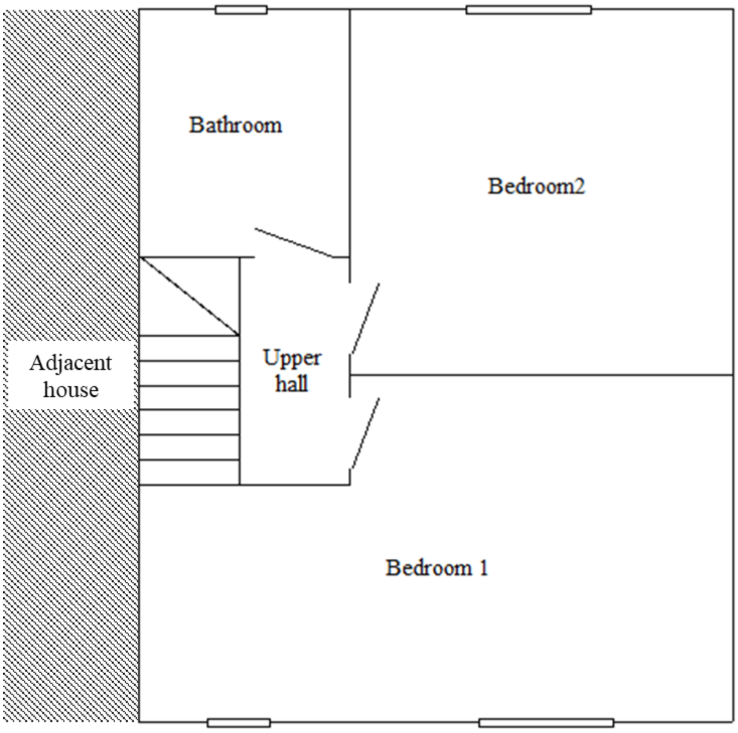


Figure 3.5: Plan view of upper floor

3.3.2 External conditions

External weather conditions can have a significant effect on the energy balance of a home. The ambient temperature, incident solar radiation and the direction and speed of the wind are prominent factors in determining the heating load required at any given time. A weather file for Birmingham was used during the simulations as it was deemed to be representative of average UK weather conditions.

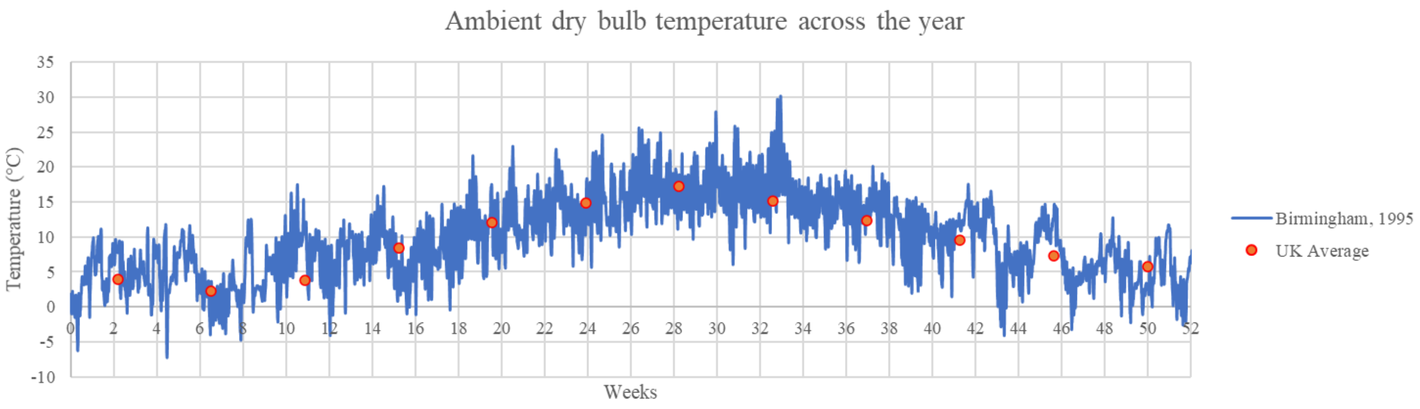


Figure 3.6: Dry bulb ambient temperature across the year

Figure 3.6 above displays the ambient temperature across the year that was applied to the model. The red dots represent the average UK temperature for each month as stated by the Royal Meteorological Society's 'State of the UK Climate' report in 2018 (Kendon *et al.*, 2019). The plot above clearly indicates that this particular weather file is representative of expected UK temperatures.

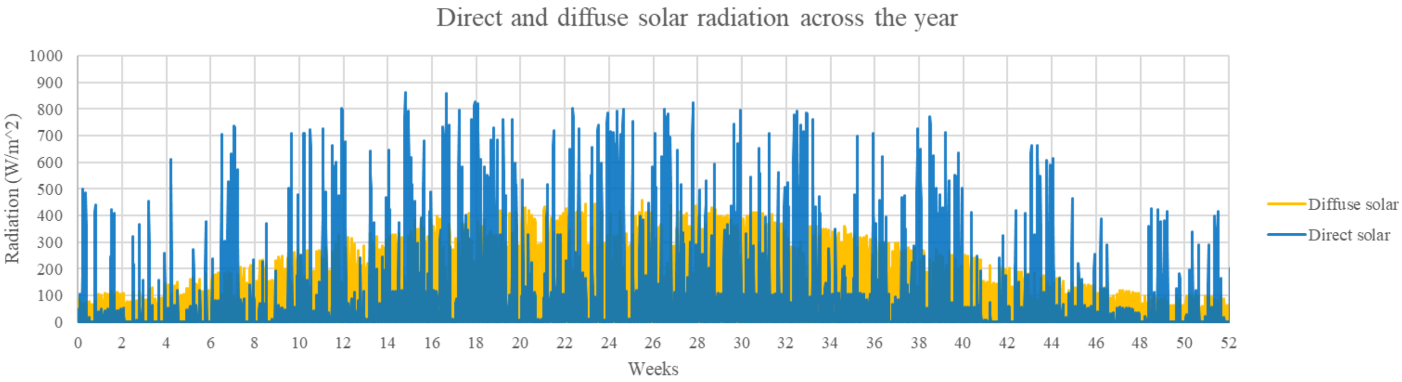


Figure 3.7: Direct and diffuse solar radiation across the year

Figure 3.7 exhibits the direct and diffuse solar radiation incident on a horizontal surface. Direct solar radiation refers to that which travels mostly unobstructed between the sun and the earth's surface, on days with clear skies for example. Whereas diffuse solar radiation has been scattered by molecules in the atmosphere before reaching the earth's surface. Diffuse radiation is most prominent on cloudy days (Weiss and Norman, 1985). Figure 3.7 shows that levels of both direct and diffuse radiation are seasonal, with significantly more incident radiation in the summer months. This radiation assists in heating building spaces, predominantly through transparent surfaces like windows, but also by absorption by external surfaces before conduction through the material.

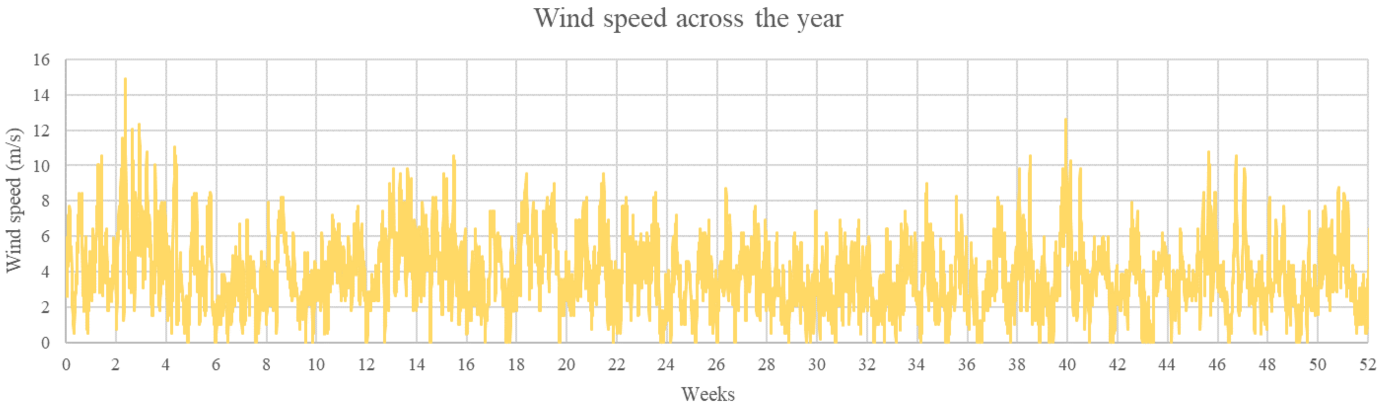


Figure 3.8: Wind speed across the year

The wind speed is an important factor in determining both the rate of convection losses from the external surfaces, and the magnitude of infiltration of air into the building. Figure 3.8 displays the wind speed across the year. It can be seen that there is little to no seasonal fluctuation in wind speeds.

3.3.3 Materials

Table 3.1 shows the materials that make up the base model. Each was selected to represent a standard post-war home with little to no efficiency improvements made.

Table 3. 19 Base model materials

	Construction name	Description	Layers	U-value (W/m^{2}K)
External walls	Wall_EW_1975	Standard brick cavity wall	Brick, gap, brick, plasterboard	1.086
Internal walls	int_part	Plasterboard over stud partition wall	Gypboard, gap, gypboard	2.144
Ground floor	grnd_floor	Uninsulated carpeted floor over chipboard	Wilton, chipboard, gap, concrete, gravel, earth	0.699
Mid-floor	cpt_flr2cel	Carpeted wood floor with underlay	Wilton, underlay, plywood, gap, gypboard	1.458
Loft floor	susp_ceil	Uninsulated plaster ceiling	Plaster	4.976
Glazing	single_glazing	Single glazing, 6mm thick glass	Glass (6mm)	5.691
Window frames	sash_fr55mm	Wooden sash window frame, 55mm thick	Softwood	1.686
External doors	door	Solid oak external door	Oak	3.316
Internal doors	int_doors	Solid oak internal door	Oak	3.316
Roof	tile_rfcold	Uninsulated tiled roof	Tiles, gap, bitumen paper, plywood	2.143

3.3.4 Infiltration & air flows

Air infiltration is defined as the unintended exchange of outdoor air with a building's indoor air through openings and cracks in a building's external envelope, due to natural or artificial pressure differences (ASHRAE, 2009). It has been shown to make up a significant portion of heat loss from a building. It is of particular importance in the winter months when the ambient air temperature is consistently 15-20°C colder than the temperature of air indoors.

This temperature difference enhances the ‘stack effect’ which is one of the primary air infiltration mechanisms. The disparity in temperature causes variation in air density between internal and external air masses. This in turn encourages air to travel down the pressure gradient and exfiltrate through openings and cracks in the building. This effect is particularly significant in high-rise buildings; however it still plays a significant role in 2-storey buildings (Younes, Shdid and Bitsuamlak, 2012).

Air pressure is also linked to the second major driver of air infiltration, wind pressure. Wind pressure is a function of wind speed, air pressure, and the external geometry of the building in question. Similar to the stack effect, when the wind pressure is such that there is a negative pressure gradient between inside and out, internal air will exfiltrate.

The net energy loss is two-fold. When the cold outdoor air infiltrates, it reduces the temperature of a given room/space and therefore requires the heating system to supply more heat to meet the temperature set point. However this infiltration also helps to force the warm indoor air to exfiltrate, resulting in a loss of energy used to heat that air initially. So whilst convention refers to this form of heat loss as infiltration, it is actually the resulting exfiltration of heated air that represents the direct heat loss (Bobenhausen, 1994).

Air infiltration can be split into two distinct types. Firstly, ‘concentrated’ infiltration that occurs directly through openings and large cracks around a building envelope. This is predominantly seen around doors, windows and at junctions between walls, floors and ceilings. ‘Diffuse’ infiltration refers to air that travels laterally through small cracks in walls for perhaps a few metres before making it to the interior (Younes, Shdid and Bitsuamlak, 2012). It is also referred to as ‘heat recovery’ since there is heat exchanged between the air walls. This results in a shift in the temperature distribution profile across the wall from linear to a curved distribution. It also slows the rate of heat loss through infiltration in winter as the warm outgoing air passes heat to the walls. (Anderlind, 1985).

Infiltration through windows, has been found to be determined mostly by the type and usage of the windows, rather than their age or condition (Weidt, Weidt and Selkowitz, 1979).

Similarly, when considering the changes in infiltration in each zone due to individual retrofit measures, a common-sense approach was applied.

Table 3.2 shows the estimated breakdown of this total contribution.

Table 3. 20 Contribution to total air infiltration rate by feature

Route	Average Contribution (%)
Walls	35
Ceiling details	18
Forced-air/cooling systems	18
Windows & Doors	15
Fireplace	12
Passive vents	5

Table 3. 21 Contribution to air infiltration, corrected for model features

Route	Average contribution (%)
Walls	51
Ceiling details	27
Windows & Doors	22

The building model in this investigation does not have any cooling systems, fireplaces or passive vents. Therefore, table 3.3 shows the revised contributions for the remaining features that are present in the building model.

In terms of evaluating the total air infiltration rate occurring within the building model, it would be difficult to assess empirically within ESP-r and have it regarded as representative of a standard UK home. This is because there is little data available on exact crack sizes, particularly for the diffuse infiltration routes through walls for example. This would be very difficult to accurately capture and represent in an empirical air flow model. Therefore it is more reliable to look at information available on air infiltration rates generated through physical testing done on UK homes.

The UK's building research enterprise (BRE) has a database of 471 buildings of varying age, size and type that have undergone airtightness testing. Whilst this sample is not large enough to be truly representative of the UK's housing stock, it is currently the largest database of airtightness information on UK homes and offers a good insight into the sort of figures that can be expected. The buildings tested ranged between 9.9 and 16.5 Ac/h with an average of 13.2Ac/h (Johnston *et al.*, 2004). It is important to note that this figure refers to the infiltration seen under test conditions at 50Pa. This can be considered as the peak infiltration rate that a building would experience. This peak value is useful for sizing heating systems, however is not suitable for use as an average rate of infiltration.

Instead, the CIBSE environmental design guide defines average infiltration rates based on air permeability which is the volume of infiltrating air per unit surface area per hour (m^3/m^2 h) at peak infiltration (CIBSE, 2006).

Table 3. 22 Air infiltration characteristics of building model

Peak infiltration (Ac/h)	Total volume of building	Peak infiltration rate (m^3/h)	Total surface area of envelope (m^2)	Air permeability (m^3/m^2 h)
10	264.48	3491.1	224.48	**15.6**

Given a peak infiltration of 13.2 Ac/h, and a total building volume of 264.48 m^3, this gives us a peak infiltration rate of 3491.1 m^3/h. The total surface area of the external building envelope (ground floor, walls and roof area) is 224.48m^2. This therefore equates to an air permeability of 15.6 m^3/m^2 h. These values are displayed in table 3.4. The air permeability figure places the building model in the 'leaky' category as defined in the CIBSE guide and outside of the UK's regulation for airtightness in new buildings which specifies a maximum air permeability of 7 m^3/m^2 h. Average air infiltration for 'leaky' buildings is stated as 1 Ac/h. However, this is for a building with a volume of 220m^3 per storey. The per-storey volume of the model in this investigation is 106.5m^3; roughly half 220m^3. Therefore, the infiltration value of 1 Ac/h must be doubled to 2 Ac/h to account for this difference in volume.

An air infiltration of 2 Ac/h was applied to each of the zones in the base configuration of the model. An alternative approach would be to alter the infiltration rate by the area of wall, ceiling and window surfaces in each zone to represent the difference between say the small bathroom with one window and the larger living space with two windows. There would be an increase from bathroom to living space in infiltration rate in terms of air velocity (m^3/s). However, when converting back to Ac/h, the infiltration in the two zones would converge back together due to the difference in volume. Since it is difficult to evaluate the difference in the size of cracks and openings between zones, this exercise would be rendered no more legitimate than simply applying zone-to-zone consistency.

Note that the external doors are assumed as being always closed. Meanwhile the internal doors are modelled as being cracked open, allowing for passive ventilation between rooms at a rate of 0.5 Ac/h. Another significant factor of air infiltration is how exposed the building in question is. In this case, the model is assumed to be situated in a typical suburban landscape. Other homes and light tree coverage obstruct winds mildly, resulting in no scaling up or down of typical infiltration rates being required.

3.3.5 Heating control & casual gains

Again, the heating control scheme employed throughout the following simulations was designed to represent typical occupancy behaviour. The scheme assumes each of the zones is heated apart from the upper hall, stairs and roof. It also assumes a home of three occupants; two in the larger 'bedroom 1' and one in 'bedroom 2'.

Table 3. 23 Weekday heating control schedule

Weekdays		
Time period	**Heating capacity (W)**	**Temperature set point (°C)**
00:00-06:00	0	N/A
06:00-09:00	7000	20
09:00-16:00	0	N/A
16:00-00:00	7000	20

Table 3. 24 Weekend heating control schedule

Weekends		
Time period	**Heating capacity (W)**	**Temperature set point (°C)**
00:00-09:00	0	N/A
09:00-00:00	7000	20

Tables 3.5 and 3.6 show the heating control schedules for weekdays (Monday to Friday) and weekends (Saturday and Sunday). This is based on the assumption that on weekdays, each of the 3 occupants wakes at 7am, leaves the house at 9am and returns from work or school at 5pm. This allows an hour (6am-7am and 4pm-5pm) for the heating system to pre-heat the home before the occupants wake and return from work/school. Please see section 3.5 for further details of the rationale behind the control schedule.

The heating control schedule is also of importance as one of the key outputs of the simulations is the worst-case heat demand. Clearly this peak heat demand would be significantly lower if a pre-heating schedule were to be adopted. However, in order to serve as a gauge of heat-pump readiness, the peak heat demand must represent something close to the greatest load that the heat pump could be reasonably expected to handle. Therefore, assuming the occupants are awake and active from 7am, the 6am heating start allows for an hour to reach the set point temperature.

The (CIBSE, 2006) guide for environmental design sets out the ideal temperature ranges for a number of typical residential spaces in order to achieve satisfactory thermal comfort for occupants. The different residential spaces all fell within an ideal temperature range of between 17°C and 24°C. Therefore 20°C was used as the set point target temperature for the heating system as it satisfies the ideal temperature range of each room type. The size of the heating system was defined as 7000W. In this investigation, the heating system size is not of concern for the base case. This is because it is important to capture the true heat demand of the building based on its occupancy and construction materials. The 7000W size simply ensures there is ample headroom to avoid the delivery of heat being hampered by reaching the load capacity.

3.4 Modelling plan

The primary section of this investigation centres around understanding the impact of adding a range of different retrofit measures to the base model established above. These measures are split into six different types of installation. Namely, these are: roof insulation, loft floor insulation, ground floor insulation, cavity wall insulation, replacement of window frames and glazing and the replacement of external doors. These areas were chosen as together they make up the majority of the thermal envelope of a building and offer significant energy-savings without the need for a change in occupancy behaviour.

The following sub-sections will describe the material properties and reductions in infiltration associated with each type of installation. Each of these constructions were added to the base model before running the simulation to understand the influence the installation has on the annual heating demand. The corresponding air infiltration reduction is then applied (see section 3.4.7) to the relevant zones to understand its relative contribution to the energy savings. This process was then repeated with each of the retrofit measures stated below. Note that each iteration initially only involves one construction at a time that differs from the base model; this ensures that the impact of that measure is captured in isolation.

Following this, two possible combinations of installations, one of each type, were applied simultaneously to the base model. These combinations are defined as ‘A’ and ‘B’ and are defined in section 3.4.8. This was done to examine whether the respective benefits of each measure in isolation would linearly combine with one another to give a total benefit equal to the sum of its parts.

With each iteration, a set of results was exported for analysis. This included the total energy delivered annually to the building, a representation of the annual heating demand. The rest of the exported results focussed on understanding the most prominent mechanisms of heat transfer within the building. Heating load for each zone and conduction and convection for each key surface was also exported for each iteration. The output period for these exports was limited to the period of 2nd January to 4th January as this was the coldest three-day period in the weather year. This would ensure visibility of the peak heating demand.

Tables 3.7 to 3.13 below show the properties of the material improvements iteratively added to the base model as described above. Note that the U-value refers to that of the entire construction in combination, not just the additional layer of insulation for example.

3.4.1 Roof

Table 3. 25 Roof insulation upgrade properties

	Roof	
1	**Construction** name	Pitch rf1980
	Description	80mm thick glasswool layer
	U-value (W/m^{2}K)	0.413
	Layers	tiles, gap, glasswool (80), plasterboard
2	**Construction name**	Pitch rf2000
	Description	140mm thick glasswool layer
	U-value (W/m^{2}K)	0.257
	Layers	tiles, gap, glasswool (140), plasterboard
3	**Construction name**	Pitch rf2013
	Description	290mm thick glasswool layer
	U-value (W/m^{2}K)	0.131
	Layers	tiles, gap, glasswool (150), glasswool (140), plasterboard

3.4.2 Loft floor

Table 3. 26 Loft floor insulation upgrade properties

Loft floor	
Construction name	ceil_rev
Description	
U-value (W/m^{2}K)	0.333
Layers	glasswool (100), ceiling mineral (10)

3.4.3 Ground floor

Table 3. 27 Ground floor insulation upgrade properties

Ground floor		
1	**Construction name**	floor_cur
	Description	
	U-value (W/m^{2}K)	0.317
	Layers	wilton, concrete, XPS CO_2 foamed, gravel, earth
2	**Construction name**	floor_2013
	Description	
	U-value (W/m^{2}K)	0.151
	Layers	wilton, wool underlay, concrete, XPS CO_2 foamed (100x2)

3.4.4 Cavity walls

Table 3. 28 Cavity wall insulation upgrade properties

Cavity Walls		
1	**Construction name**	Wall_EW_1990
	Description	60mm thick mineral wool layer
	U-value (W/m^{2}K)	0.435
	Layers	brick, gap, mineral wool (60), concrete, gap, plasterboard
2	**Construction name**	Wall_EW_2002
	Description	100mm thick mineral wool layer
	U-value (W/m^{2}K)	0.303
	Layers (W/m^{2}K)	brick, gap, mineral wool (100), gap, plasterboard
3	**Construction name**	brk_blk_2012
	Description	150mm thick mineral wool layer
	U-value (W/m^{2}K)	0.207
	Layers	brick, gap, mineral wool (150), aerated concrete (140), lime plaster

3.4.5 Window frames & glazing

Table 3. 29 Window frame upgrade properties

Window Frames		
1	**Construction name**	PVC_fr_1.0u
	Description	PVC frame with an EDPM thermal break
	U-value (W/m^{2}K)	1.054
	Layers	N/A

Table 3. 30 Glazing upgrade properties

Glazing		
1	**Construction name**	dbl_glz
	Description	Untreated double glazing (6mm glass, 12mm air gap)
	U-value (W/m^{2}K)	2.811
	Layers	glass, gap, glass
2	**Construction name**	tripglz_1.08
	Description	Triple glazing with low-emissivity coating (6mm glass, 12mm air gap)
	U-value (W/m^{2}K)	1.081
	Layers	glass, gap, glass, low-e coating

3.4.6 External doors

Table 3. 31 External doors upgrade properties

External doors		
1	**Construction name**	door_u1.5
	Description	Standard oak door with 36.5mm woodwool insulation layer
	U-value (W/m^{2}K)	1.5
	Layers	oak, woodwool (36.5), oak
2	**Construction name**	door_PH
	Description	Oak door with 90mm woodwool insulation layer and anti-draft membrane
	U-value (W/m^{2}K)	0.832
	Layers	oak, woodwool (90), oak

3.4.7 Air infiltration reduction

After the energy savings had been assessed for each of these installations, they were again applied to the base model but this time with a reduction in infiltration rate also applied to the relevant zones. This was done to ensure the energy savings gained from the improvement in infiltration could be isolated from those gained from a reduction in material U-value. CIBSE recommends a minimum air supply of 10l/s per person, so 30 l/s for the three occupants in the model (Legg, 2017). The minimum infiltration required was calculated at 0.5 Ac/h for the model as this equates to 36.7 l/s for the whole building. This allows some headroom above the minimum recommendation and avoids the need for potentially expensive mechanical ventilation.

Table 3. 32 Infiltration reduction associated with each retrofit measure

Installation	Infiltration reduction (Ac/h)	New infiltration (Ac/h)	Applied to
Cavity Wall insulation	0.765	1.235	All zones
Loft floor insulation	0.127	1.873	Bathroom, Bed 1, Bed 2 & Upper hall
Ground floor insulation	0.127	1.873	Kitchen, Living Space, Hall & Stairs
Roof insulation	0.152	1.848	Loft
Window replacement	0.251	1.749	Bathroom, Bed1, Bed2, Living space, Kitchen
External door replacement 1	0.0395	1.9605	Hall & Kitchen
External door replacement 2	0.079	1.921	Hall & Kitchen

Table 3.14 shows the infiltration reductions associated with each retrofit measure. These values were achieved by splitting the 1.5 Ac/h difference between 2 and 0.5 Ac/h between the walls, ceilings/floors and windows/doors using the ratios in table 3.3. These values were further distributed by the relative surface area affected by the retrofit measures. For example, of the 22% of total infiltration attributed to windows and doors, a greater proportion of this fraction was attributed to windows as they have a larger total surface area than the external doors in the model.

3.4.8 Installations in combination

Once each of the retrofit measures has been assessed in isolation, it is important to then understand how they will work in combination with each other when a group of measures is installed simultaneously. The two groups of materials used are ‘A’ and ‘B’. Group A contains each of the upgrade measures with the lowest U-values from sections 3.4.1 to 3.4.6. Meanwhile, group B is generally made up of the constructions with the next lowest U-values. Tables 3.15 and 3.16 show the breakdown of the installations in each group.

Table 3. 33 Installations in combination group A

Group A

	Upgrade number	Description	U-value (W/m^2K)
Loft floor	1	100mm thick glasswool	0.333
Roof	3	290mm thick glasswool	0.131
External walls	3	150mm thick mineral wool	0.207
External doors	2	Oak door with 90mm insulation layer	0.832
Ground floor	2	200mm thick polystyrene foam	0.151
Glazing	2	Triple glazing with low-e coating	1.081
Window frames	1	PVC frame with thermal break	1.054

Table 3. 34 Installations in combination group B

Group B

	Upgrade number	Description	U-value (W/m^2K)
Loft floor	1	100mm thick glasswool	0.333
Roof	2	140mm thick glasswool	0.257
External walls	2	100mm thick mineral wool	0.303
External doors	1	Oak door with 36.5mm insulation layer	1.5
Ground floor	1	100mm thick polystyrene foam	0.317
Glazing	1	Double-glazing	2.811
Window frames	1	PVC frame with thermal break	1.054

3.5 Post-simulation analysis

The following two subsections will set out the theory and information behind the additional analyses performed on the data collected from ESP-r. They are designed to give greater context and value to the results produced.

3.5.1 Costing of retrofit measures

Firstly, Spon's architects' and builders' price book was used to obtain costs for each of the retrofit measures involved in the study. The compendium has long been a trusted resource for professional cost-evaluation of building projects and installations. The book includes discrete prices for materials, labour and any other plant that may be required to complete an installation. Since it contains a broad range of specific material configurations for each type of installation, it was possible to find priced entities that closely represented those under evaluation in this study. Thus ensuring a good level of accuracy in terms of costing (AECOM, 2018).

Table 3. 35 Estimated cost of each retrofit measure

	Construction	**Size (m2)/Quantity**	**Labour (£/m^2)**	**Materials (£/m^2)**	**Total (£/m^2)**	**Total price (£)**
Wall insulation	1	119.77	1.98	3.70	5.68	679.80
	2	119.77	2.24	5.74	7.98	955.74
	3	119.77	2.54	7.59	10.13	1213.24
Loft floor insulation	1	42.52	1.43	1.80	3.23	137.34
Roof insulation	1	51.00	1.26	1.80	3.06	156.06
	2	51.00	1.57	2.48	4.05	206.35
	3	51.00	2.88	7.18	10.06	513.06
Windows (glazing and frame)	1	7.86			206.93	1626.06
	2	7.86			333.12	2617.66
External doors	1	2 pcs			113.48	226.96
	2	2 pcs			199.51	399.02
Ground floor insulation	1	42.52	10.21	14.83	25.04	1064.49
	2	42.52	10.21	23.67	33.88	1440.58

Table 3.17 displays the cost breakdown of each of the retrofit measures for this particular building. Note that many of these prices assume that materials are bought in bulk; these prices are more accurate for a potential government upgrade scheme, for example. Individual

homeowners can expect to see slightly higher prices than presented here. Nevertheless, the mark-up is likely to be consistent across the different installations, therefore conclusions about the relative value proposition of each measure would remain valid. The cost also does not include any delivery charges that may be incurred.

3.5.2 Net-zero readiness: low-temperature radiators

Next, to further contextualise the results, it was important to consider the energy savings with regards to net-zero. Specifically, the question being posed is what does it mean for a house to be net-zero ready.

In order for the domestic building stock to become classified as net-zero, the method used to heat each home must be decarbonised. Since natural gas cannot be combusted without releasing CO_2, heat pumps are expected to become the primary home heating system. Therefore, once the electricity supply network has been decarbonised, heat pumps will become a net-zero option for heating homes. However, due to the thermodynamic characteristics of heat pump systems, they can only feasibly supply hot water up to temperatures of around 50°C. Temperatures significantly higher than this would cause a significant drop in the coefficient of performance; making sustained supply uneconomic. Traditional thermal radiator units are designed for water supply temperatures of roughly 80°C. These radiators are small by design as an 80°C surface temperature creates a large temperature gradient with respect to the bulk air mass of the room. This drives a high rate of heat transfer per unit surface area of the radiator. Therefore, reducing this surface temperature to 50°C lowers the rate of heat transfer per unit area; often resulting in heat pumps being unable to meet peak heat demands in winter.

There are three options that would allow heat pumps to meet these peak demands. Firstly, other heating systems, a free-standing convection heater or an in-series resistive heater could be used to supplement the central heating or ensure that radiators are supplied with water at 80°C. This option is far from ideal as these supplementary systems are inefficient in comparison to heat pumps, resulting in higher heating bills and more strain on the electricity network. The second option is to increase the surface area of the radiator units. This would involve the installation of new radiators at considerable expense. The last option is to reduce the peak heat demand by improving the energy performance of the thermal envelope. This would allow the heat requirements of a given space to be met using the current standard radiator units at the lower temperature of 50°C. In order to understand how low the heat demand must be to be met, calculations were made to determine the maximum theoretical rate of heat emission from a low temperature radiator.

Radiators predominantly emit heat through both convection and radiation. The following calculations quantify the relative contribution of each type of heat transfer before summing for a total rate of heat transfer.

Firstly, the radiation fraction of the heat transfer:

$$\dot{Q}_{\mathrm{Rad}} = \varepsilon * C_S * A * \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad (1)$$

Where ε can be derived from figure 3.9 since $\varepsilon_n = 0.925$ for radiator paint. Reading off the plot and rearranging for ε gives **ε** = 0.888.

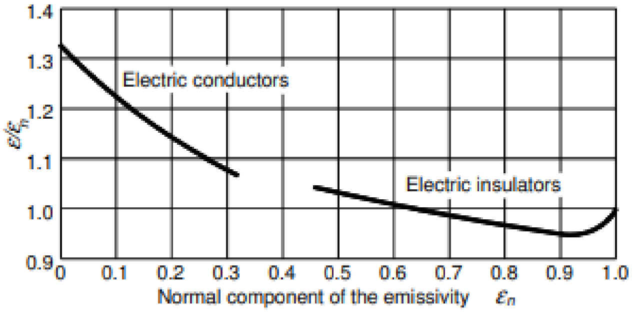


Figure 3.9: Plot to determine the emission coefficient of a radiative surface

Assuming a standard radiator is 1.5m long and 0.7m tall, with a thickness of 0.03m. This gives a surface area of A= 2.23m^2 since both the front and back surfaces must be considered.

If the surface temperature of the radiator is equal to the input temperature of the working fluid, this gives T_1 = 323K (50°C)

Lastly, assuming the wall temperature is equal to the desired bulk air temperature, T_2 = 293K (20°C).

Therefore revisiting equation (1):

$$\dot{\mathrm{Q}}_{\mathrm{Rad}} = 0.888 * 5.67 * 2.23 * \left[\left(\frac{323}{100}\right)^4 - \left(\frac{293}{100}\right)^4\right] = \mathbf{394.96W}$$

Now onto the convection portion:

$$\dot{\mathrm{Q}}_{\mathrm{Conv}} = \mathrm{A} * \alpha * (\theta_1 - \theta_0) \qquad (2)$$

Properties of air at 20°C:

$\lambda = 0.02569$; $\mathrm{Pr} = 0.7148$; $\nu = 0.00001535\ \mathrm{m}^4/\mathrm{s}^2$

In order to find the heat transfer coefficient, α, we must first find the Nusselt number associated with the convective air flow off the radiator:

$$Nu = \left[0.852 + 0.387 * Ra^{1/6} * f_1(\mathrm{Pr})\right]^2 \qquad (3)$$

Where:

$$\mathrm{Ra} = \mathrm{Gr} * \mathrm{Pr} = \frac{\mathrm{g} * \mathrm{h}^3 * (\theta_1 - \theta_0)}{\mathrm{T}_2 * \nu^2} * \mathrm{Pr} \qquad (4)$$

$$\mathrm{Ra} = \frac{9.81 * 0.7^3 * (50 - 20)}{293 * 0.00001535^2} * 0.7148 = 104.52 * 10^7$$

Since Ra satisfies $0.1 < \mathrm{Ra} < 10^{12}$:

$$f_1(\mathrm{Pr}) = (1 + 0.671 * Pr^{-9/16})^{-8/27} \qquad (5)$$

$$f_1(\mathrm{Pr}) = (1 + 0.671 * 0.7148^{-9/16})^{-8/27} = 0.8387$$

Inserting Ra and f_1(Pr) into equation (3):

$$Nu = \left[0.852 + 0.387 * 104.52 * 10^{7^{1/6}} * 0.8387\right]^2 = 124.66$$

Now finding the heat transfer coefficient between the radiator surface and surrounding air:

$$\alpha = \frac{Nu * \lambda}{h} \qquad (6)$$

$$\alpha = \frac{124.66 * 0.02569}{0.7} = 4.58\, W/m^2K$$

Now returning to equation (2)

$$\dot{Q}_{\mathrm{Conv}} = 2.23 * 4.58 * (50 - 20) = 306.34\, W$$

Finally:

$$\dot{Q}_{\mathrm{Tot}} = \dot{Q}_{\mathrm{Rad}} + \dot{Q}_{\mathrm{Conv}} \qquad (7)$$

$$\dot{Q}_{\mathrm{Tot}} = 394.96 + 306.34 = \mathbf{701.3W}$$

Equations (1) to (7) and figure 3.9 are taken from (von Bockh and Wetzel, 2012).

This figure describes the rate of heat that can be emitted to a room from this low-temperature radiator. This result effectively means that a radiator of this size will be able to manage the heating load of a room if it is lower than 701.3W. Table 3.18 shows the target values of the peak heating demand for each of the model zones. Note that since bedrooms 1, 2 and the living space are significantly larger than the other zones, they are assumed to each have two radiators installed. The other heated zones are taken as having a single radiator.

Table 3. 36 Target peak rate of heat demand for each heated zone

Zone	No. of radiators	Target peak heat demand (W)
Bath	1	701.3
Bed1	2	1402.6
Bed2	2	1402.6
Hall	1	701.3
Kitchen	1	701.3
Living	2	1402.6

The following chapter will present and discuss the results of the investigation set out in this section.

4. Results and Discussion

This chapter will introduce the results of the investigations introduced in the methodology. Note that this is not a full disclosure of each results set obtained, but rather a display of the most relevant and significant results. Sections 4.2 to 4.7 cover the benefits of each retrofit measure in isolation, firstly without, then with the associated air infiltration reduction applied. The following sections then observe the impact of applying multiple measures in combination and assess how best to ensure net-zero readiness for the building. Please see appendix A for results in tabular form.

4.1 Base case

Before assessing the impact of each of the retrofit measures, the energy performance of the base scenario introduced in section 3.3 must first be quanitfied.

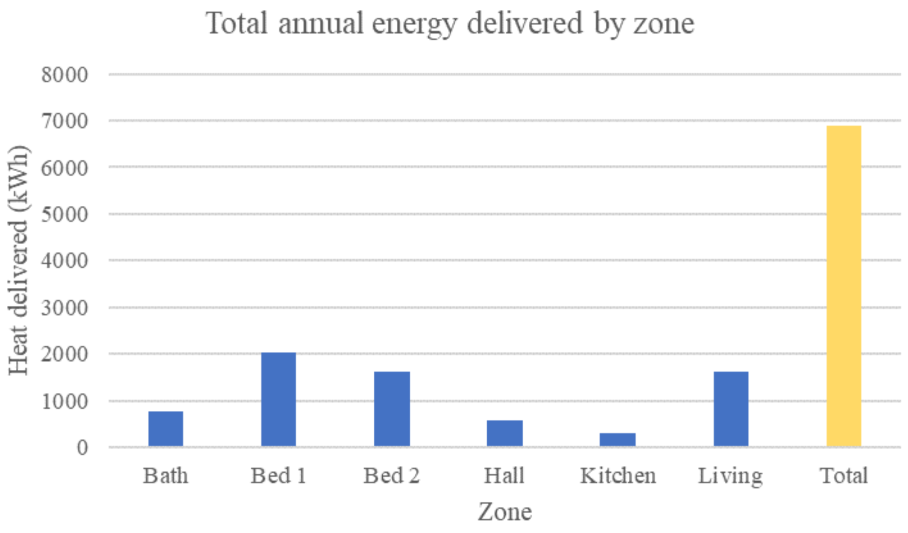


Figure 4.1: Base scenario, total energy delivered by zone

Figure 4.1 shows the total heat delivered to each zone over a 12-month period. This is the space heating demand of the building. The total value is 6897.4 kWh. The average for UK homes was found to be 6022kWh in section 3.3, this higher value is to be expected as the thermal envelope of building represented in the model is less efficient than the average home. As for the distribution of energy demand by zone, the pattern is driven largely by the size of the zone. The reason for the discrepancy between the equally sized kitchen and bathroom is two-fold. Firstly, the kitchen receives significant casual gains each day as the oven is used in the evening (and at lunchtime at weekends). This removes some of the load from the heating system. Secondly, the bathroom is subject to significant conductive losses to the roof space. Over the three-day period from 2nd Jan to the end of 4th Jan, the bathroom lost 10,993W through conduction via the ceiling into the cold loft space. In comparison, the kitchen lost just 1320W of heat through conduction via the ground floor.

4.2 Roof insulation

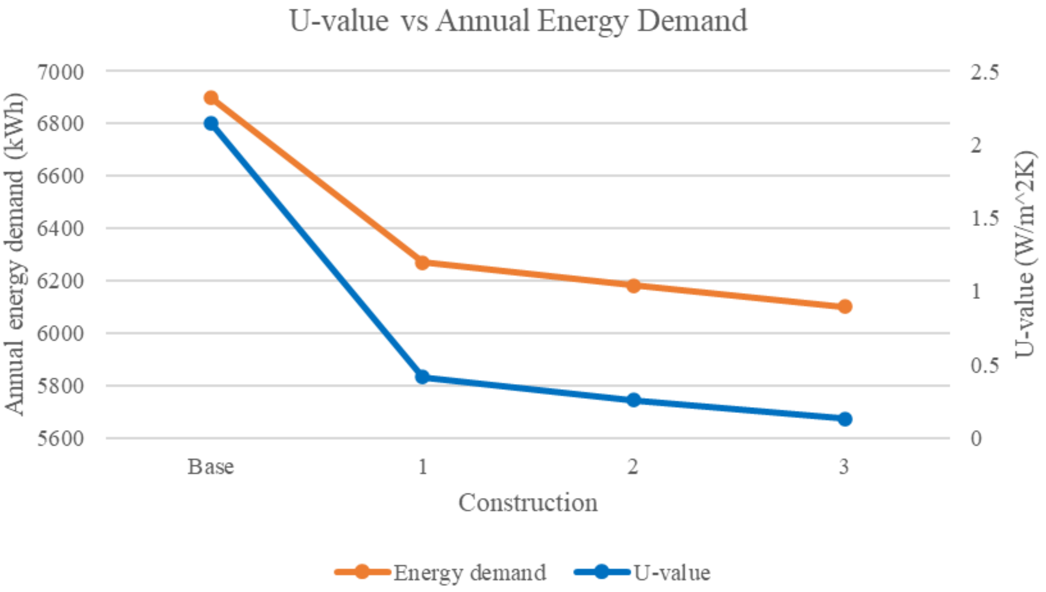


Figure 4.2: Roof insulation, U-value vs annual energy demand

Figure 4.2 shows the relationship between the U-value of each construction and the annual energy demand of the building. It is observed that as the U-value of the constructions applied falls with ever-thicker insulation, the energy demand of the house also falls linearly.

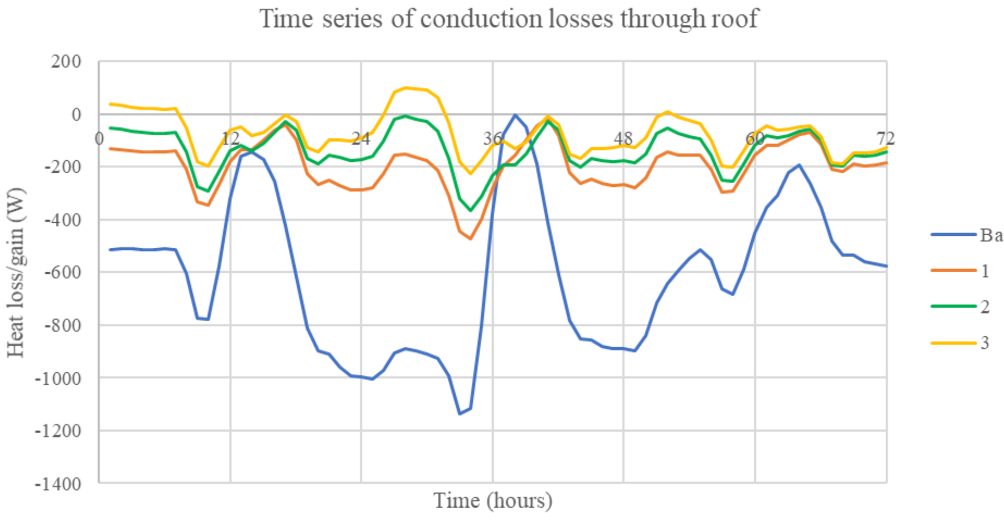


Figure 4.3: Roof insulation, conductive heat loss through roof, Jan 2nd-Jan 4th

The majority of this reduction in energy demand can be attributed to the reduction of conductive losses through the roof. Figure 4.3 shows how these losses are reduced with each material iteration. Again, the proportional reduction is in broadly line with the drop in U-value at each step. The U-value of upgrade no. 3 (0.131 W/m^{2}K) is 6% of the U-value of the base construction (2.143 W/m^{2}K). The net heat transfer via conduction over the 3-day period in January was a loss of 5263 W with upgrade 3 installed. This is 11% of the net conductive heat transfer with the base construction (44019 W). This disparity between the percentage reductions of U-value and net heat transfer result from the fact that whilst the constructions with the lower U-values significantly reduce the conductive losses to the colder ambient air, they also limit the conductive gains seen as the ambient temperature and solar radiation rise in the daytime. This can be seen in figure 4.3 as the peaks displayed by the base construction are truncated in each of the 3 upgrade cases.

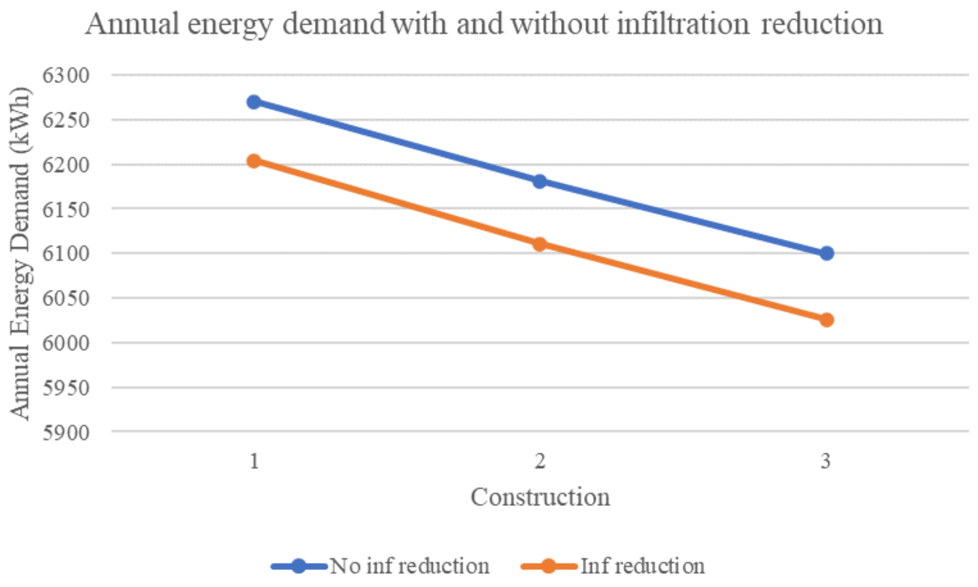


Figure 4.4: Roof insulation, energy demand with and without infiltration reduction applied

Figure 4.4 displays the change in building energy demand when the infiltration rate reduction set out in table 3.14 is applied. There is a fall in energy demand of approximately 70 kWh, this delta is consistent at each of the three constructions. This small reduction is seen as the reduced infiltration into the roof space leads to lower convection losses from the loft floor as the air mass is moving slower and thus cannot remove quite as much heat from the loft floor through convection.

4.3 Loft floor insulation

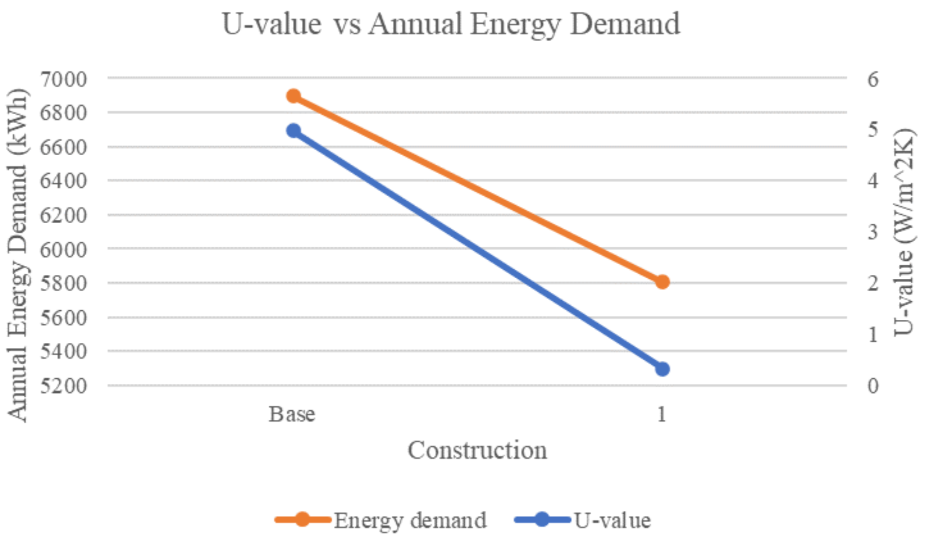


Figure 4.5: Loft floor insulation, U-value vs annual energy demand

Figure 4.5 shows that there is a strong, almost linear correlation between the reduction in U-value of the loft floor construction and the fall in the building's energy demand. Note that with a higher U-value (0.333 W/m^{2}K) than roof insulation construction 3 (0.131 W/m^{2}K), this loft insulation upgrade results in a greater overall energy saving (1093kWh as opposed to just 798 kWh). This is because the mechanism that drives the building energy demand reduction is lowering the heat loss from the heated zones on the upper floor. Insulating the roof in isolation still allows heat to escape through the two brick gable-ends, whereas the loft floor insulation reduces the heat loss to the loft space in the first place.

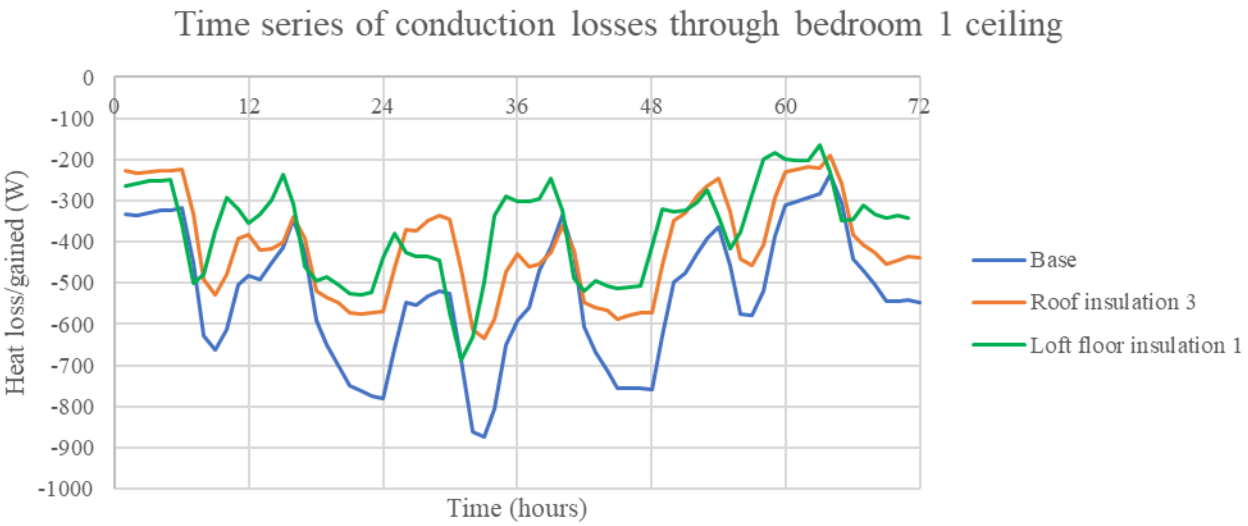


Figure 4.6: Conductive heat loss through bedroom 1 ceiling, Jan 2nd-Jan 4th

Figure 4.6 supports the above statement as the loft floor insulation results in lower conduction losses from the heated bedroom 1 to the comparatively cold loft space when compared to the thicker roof insulation. The total net loss with the thickest roof insulation is 29582 W whilst the figure with the loft floor insulation is 26380 W. For comparison, the value with the base configuration is 38096 W. This kind of reduction in conductive losses is common across the ceilings of each of the zones on the upper floor.

When applying the infiltration reduction associated with the installation of loft floor insulation, the annual energy delivered to the building falls to 5653 kWh. This is a drop of 151 kWh over the year. This is a larger reduction than that seen with the roof insulation because the similar infiltration reduction is applied across each of the upper floor zones rather than just the loft space.

4.4 Ground floor insulation

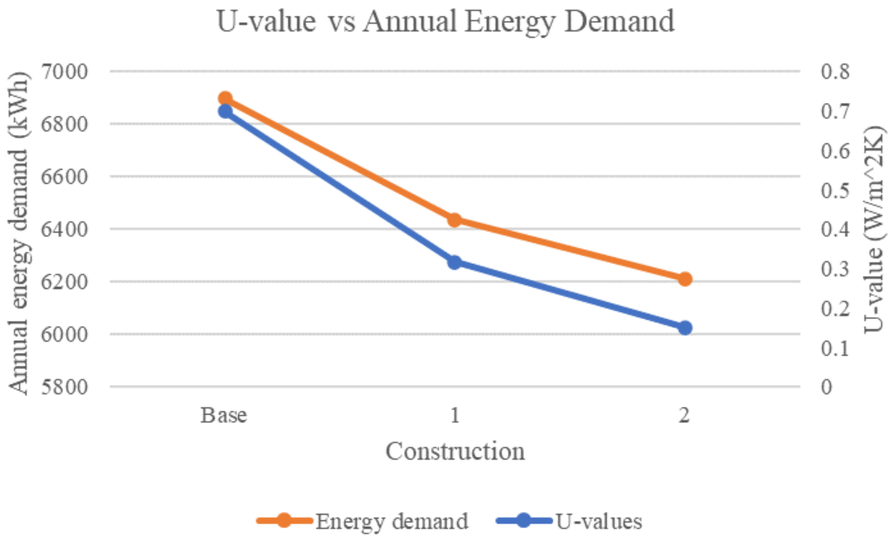


Figure 4.7: Ground floor insulation, U-value vs annual energy demand

Figure 4.7 again displays the link between U-value and building energy demand. The fall in demand from the base scenario to the second upgrade is 684 kWh. This is comparatively lower than the 1093 kWh saved annually by installing the loft floor insulation, despite the second ground floor construction having a lower U-value than that of the loft floor construction. This is because the base ground floor construction already had a relatively low U-value of 0.699 W/m^{2}K. Therefore, the ground floor was not as significant a heat loss interface as the loft floor was prior to the retrofit measures being installed.

Figure 4.8: Conductive heat loss through kitchen and living space ground floors, Jan 2nd-Jan 4th

Figure 4.8 furthers this argument as only a small reduction in losses via conduction through the ground floor is observed.

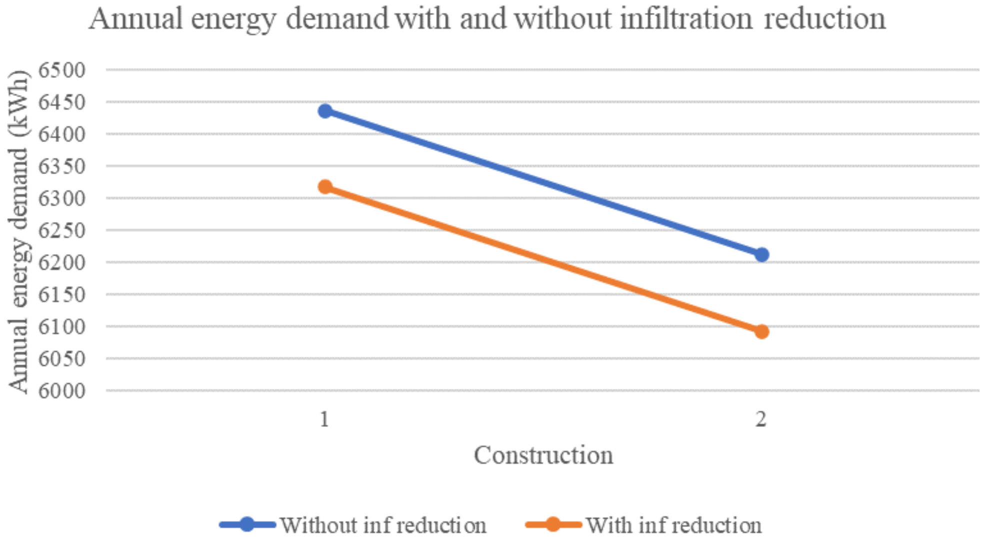


Figure 4.9: Ground floor insulation, energy demand with and without infiltration reduction applied

The data presented in figure 4.9 shows a consistent magnitude of energy demand reduction across the two ground floor upgrades. In both cases, the energy demand falls by around 120kWh annually. This is less than the 151kWh reduction observed with the loft floor installation. Both the loft floor and ground floor upgrades result in an equal reduction in air infiltration rate over zones that sum to the same volume. Therefore, it may be expected that the resulting energy demand reduction would be equal. However, the disparity can be attributed to the fact that in the base scenario, the total convection losses for the ground floor zones are 77686 W for the three-day cold period, whereas the losses for the upper zones are 117787 W. This discrepancy in losses indicates that any fall in infiltration rate in the upper zones would be more effective than an equal drop in the lower zones.

4.5 Cavity Wall insulation

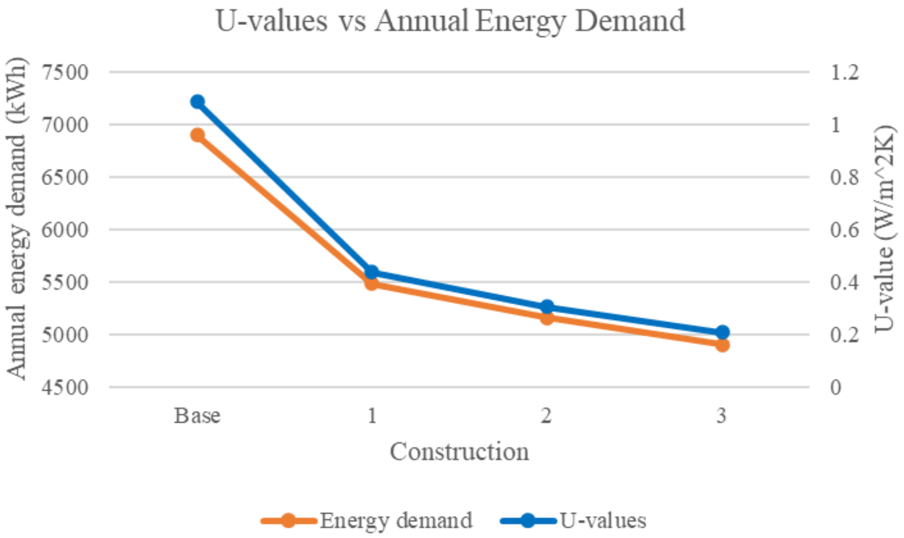


Figure 4.10: Cavity wall insulation, U-value vs annual energy demand

Figure 4.10 shows the continued parallel relationship between the fall in U-value and the equivalent proportional drop in annual energy demand. The 3rd upgrade option of 150mm thick mineral wool sees an energy demand reduction of 1995.6 kWh over 12 months. This is a significantly larger saving than those observed with the previous installations. This is expected as the external walls represent a large proportion of the thermal envelope of the building.

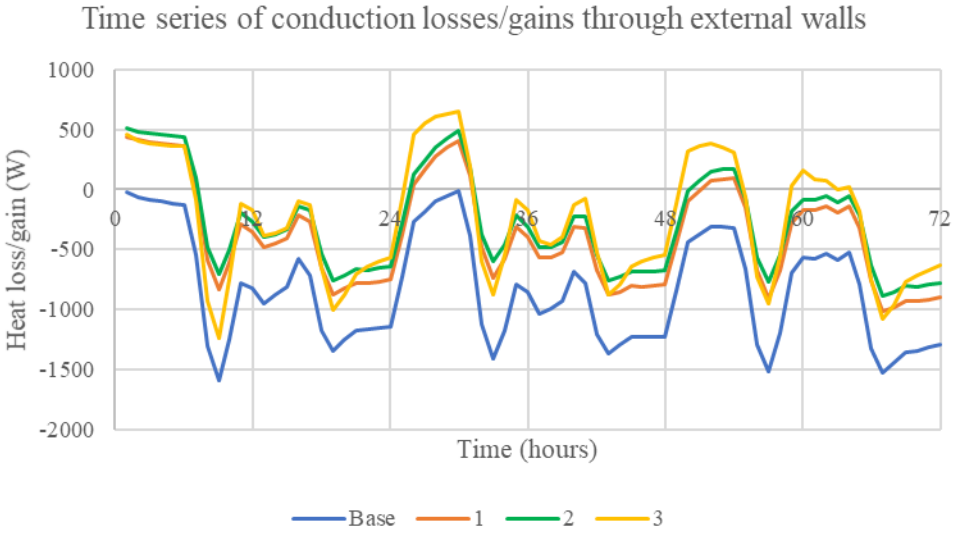


Figure 4.11: Conductive heat loss through external wall surfaces, Jan 2nd-Jan 4th

Figure 4.11 shows a time series summation of conductive heat transfer through all of the external wall surfaces in the building model over 72 hours between Jan 2nd and 4th. The total net loss through conduction via the external walls for this period fell from 60619 W for the base scenario to 18664 W for construction 3. This is a significant decrease that largely accounts for the reduction in annual energy demand shown in figure 4.10.

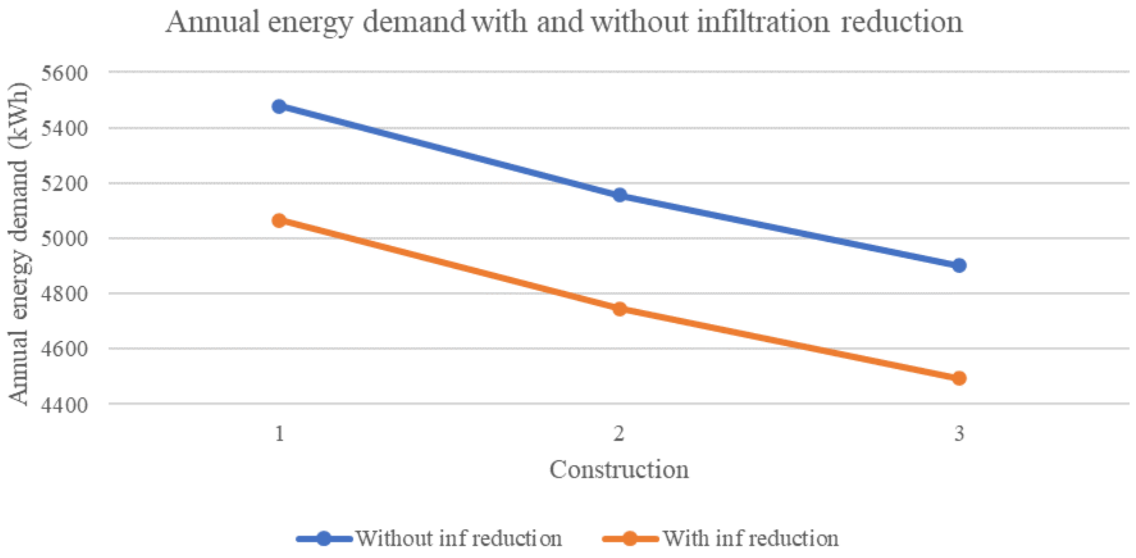


Figure 4.12: Cavity wall insulation, energy demand with and without infiltration reduction applied

Figure 4.12 displays the decrease in annual energy demand as a result of applying the 0.765 Ac/h infiltration reduction that is associated with the installation of cavity wall insulation. The decrease is consistent across the 3 different insulation thicknesses, with a mean annual fall of 411 kWh. This is the largest such reduction in energy demand. This is because the infiltration decrease linked with the cavity walls is the largest (see table 3.14) but also because this reduction is applied across all zones. When only a selection of zones experience a drop in infiltration rate, the passive air flow between zones results in an increase of air flow between adjacent zones with differing rates. Those zones with higher rates will pass more air to those with lower rates as there is now a pressure gradient. This effect works to slightly dull the positive impact of the infiltration reductions in particular zones. However, when a reduction is applied across all zones, the equilibrium means that this effect does not occur. Therefore, as observed in figure 4.12, the building sees a significant fall in annual energy demand.

4.6 Door replacement

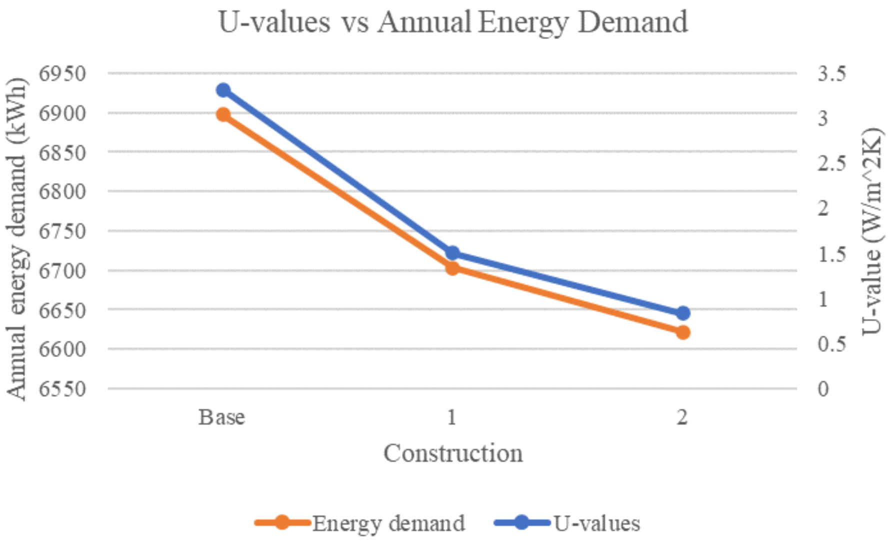


Figure 4.13: Door replacement, U-value vs annual energy demand

Figure 4.13 shows the impact that the reduction in U-value with each type of door had on the annual energy demand of the building. The two doors of increasing insulation thickness caused the demand to fall by 194 and 275.7 kWh respectively. This is a modest reduction in energy demand; however the two external doors are responsible for a small area of the building’s thermal envelope.

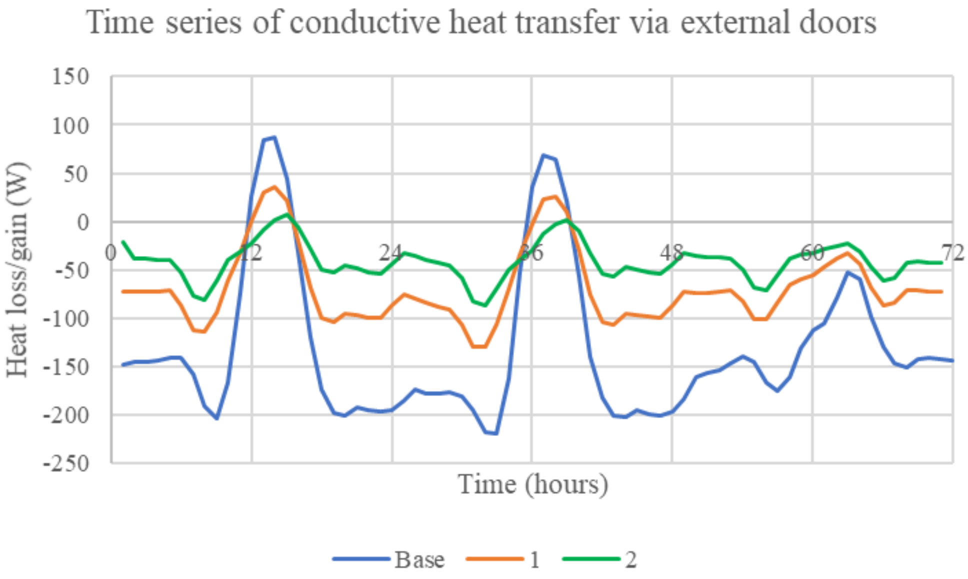


Figure 4.14: Conductive heat loss through external doors, Jan 2nd-Jan 4th

Figure 4.14 shows how the installation of each door type affects the conductive heat transfer through the door surface over the 3-day cold period. The net conductive losses through the doors falls from 9426 W with the base construction to 4865 and 2911 W for upgrades 1 and 2 respectively. Whilst this is a significant proportional reduction of losses through the door surface, it becomes less substantial within the context of the whole building, hence the modest annual demand reduction.

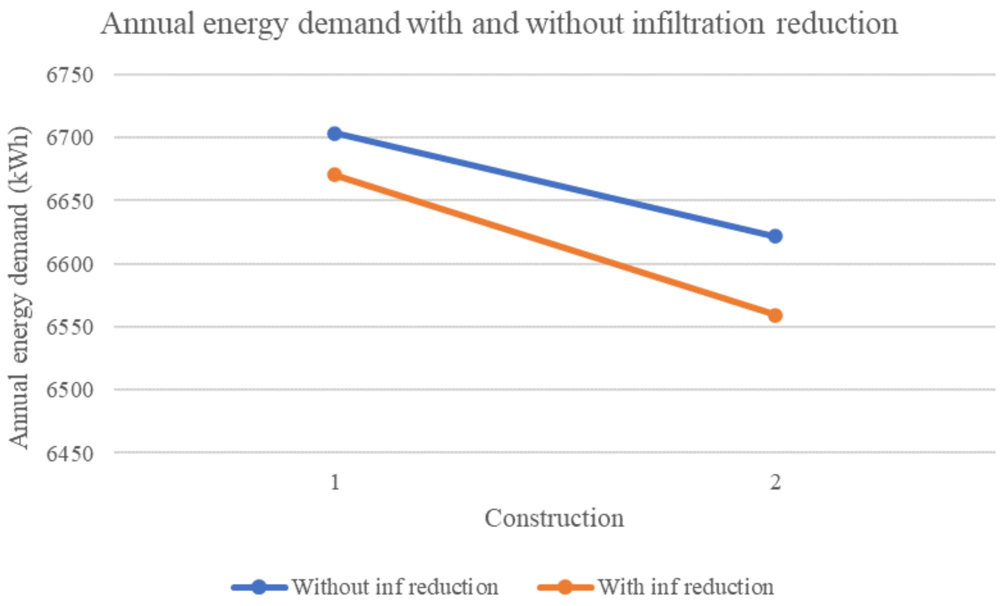


Figure 4.15: Door replacement, energy demand with and without infiltration reduction applied

Figure 4.15 shows the difference in annual energy demand when the infiltration reductions linked to the installation of new external doors is applied. Note that in this case, the infiltration reduction is greater for door upgrade 2 than it is for 1. This is because the second door upgrade consists of a draft-reduction membrane whereas the first upgrade simply ensures a well fitted door compared to the base case. This is why the drop in energy demand is larger for the second construction at 62 kWh rather than 33 kWh for construction 1.

The magnitude of the impact of the infiltration reduction is small as it is applied to only the hall and kitchen zones. This will bring the previously discussed effect into play as the adjacent living space zone is operating at a greater infiltration rate and will be acting to restate the pressure balance between zones by increasing airflow into the hallway. Thus, the positive impact of the infiltration reduction is limited.

4.7 Window replacement

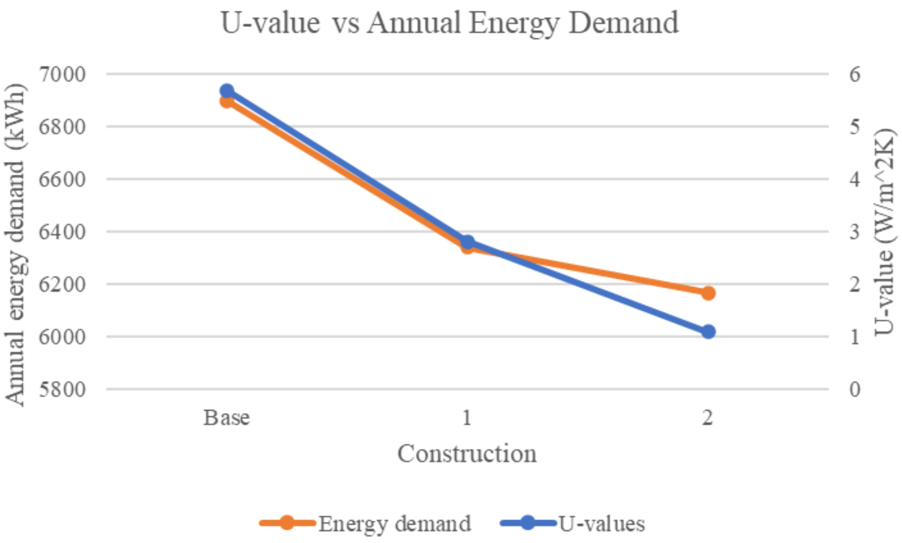


Figure 4.16: Window replacement, U-value vs annual energy demand

Figure 4.16 plots the annual energy demand of the building model alongside the U-values associated with the glazing upgrades. There is a decoupling of the correlation between energy demand and U-value between the 1st and 2nd upgrade. This is because the U-values shown are for the glazing only, however the energy demand is a result of upgrades to both the window frames and glazing. The 1st glazing upgrade aligns with the switch from wooden sash windows (1.686 W/m^{2}K) to PVC frames (1.054 W/m^{2}K). However, the 2nd glazing upgrade is applied alongside the same PVC frame, hence the diversion of the energy demand trendline away from the U-value trendline in figure 4.16.

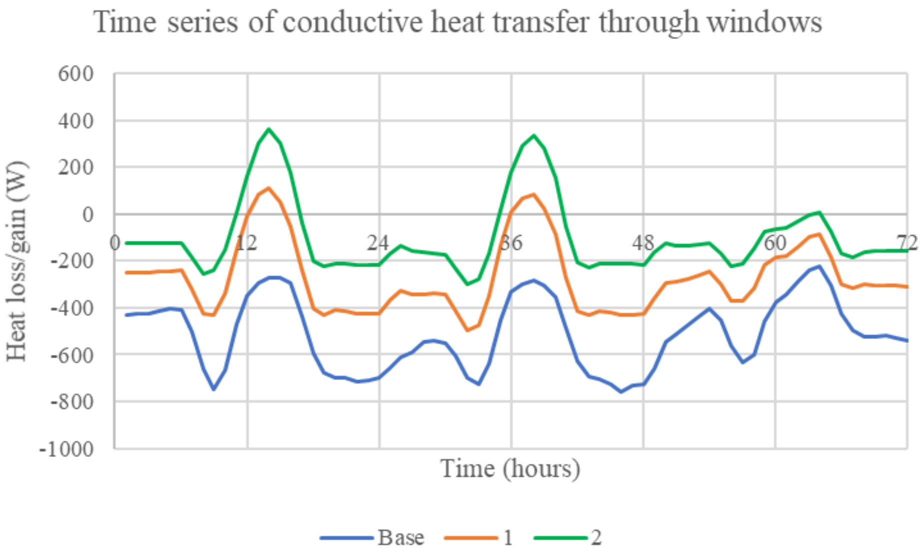


Figure 4.17: Conductive heat loss through windows, Jan 2nd-Jan 4th

Figure 4.17 shows the time series of conductive heat transfer through both the glazing and frames. The data is a summation at each time step of each of the 7 windows in the building model. A significant reduction in heat loss is observed at each upgrade increment. The majority of this decrease is driven by the glazing as total conduction through the glazing over the cold period fell from 33,331W for the base case to just 4,795W for construction 2. Whereas conduction through the frame structures started at 3646W and fell to 2278W. Since the heat loss through the frames is minimal to start with, the key is ensuring a sound fitting to avoid unwanted air infiltration and avoiding the introduction of thermal bridges.

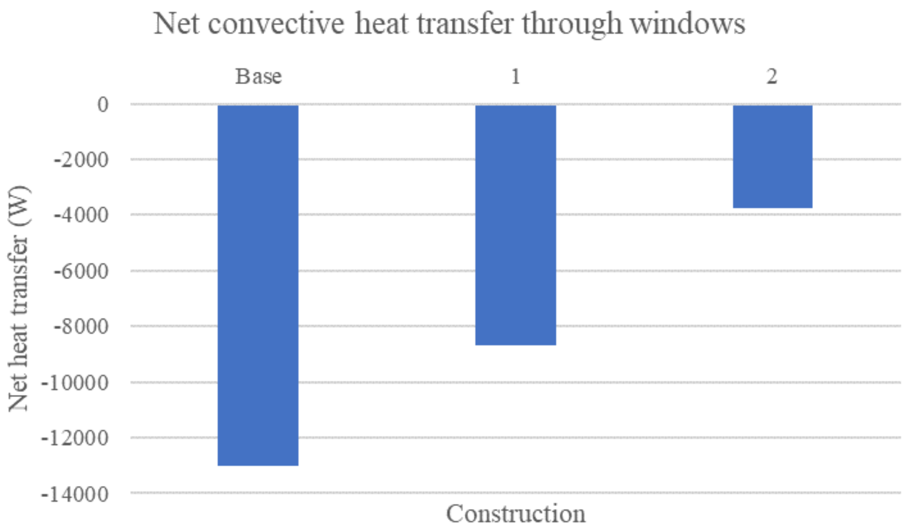


Figure 4.18: Total convective heat loss through windows, Jan 2nd-Jan 4th

Figure 4.18 shows that the window upgrades have a similarly reductive impact on heat transfer via convection.

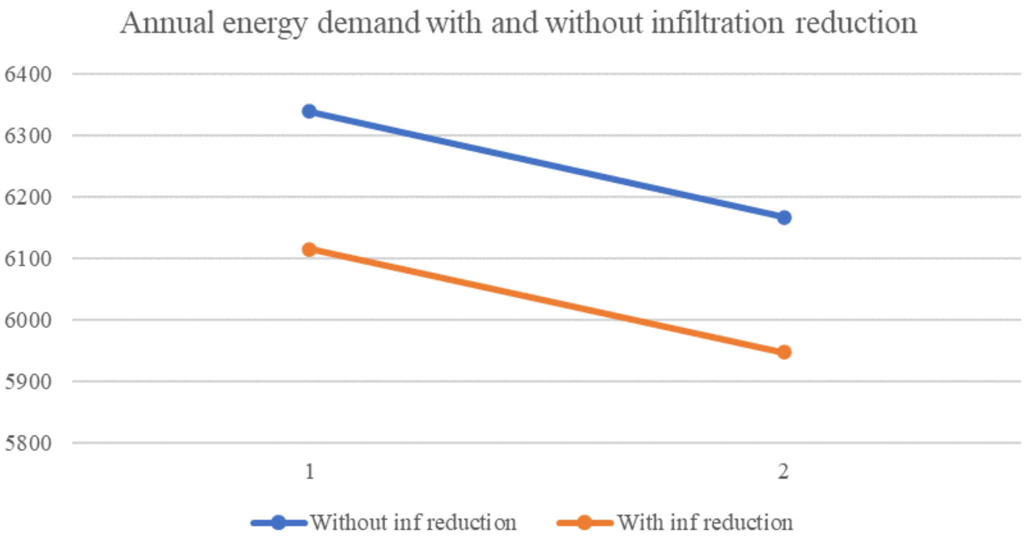


Figure 4.19: Window replacement, energy demand with and without infiltration reduction applied

Figure 4.19 displays the change in annual energy demand due to the infiltration rate reduction associated with the replacement of the building's windows. For the double glazing (upgrade 1), there is a further energy saving of 219.7 kWh and the triple glazing (upgrade 2) sees a decrease of 223.5 kWh over the year. The characteristics of this decrease due to infiltration is similar to that seen with the cavity wall insulation in section 4.5. There is a relatively large decrease in infiltration, and the hall is the only heated zone to which the reduction does not apply. These are the principle reasons for the size of the energy demand decrease.

4.8 Cost assessment

Table 4. 4 Summary of cost per kWh saving for each retrofit measure

	Construction	Total price (£)	Energy saving (kWh)	Cost per kWh saving (£/kWh)	Rank
Wall insulation	1	679.80	1831.9	0.37	3
	2	955.74	2151.2	0.44	
	3	1213.24	2405.2	0.50	
Loft floor insulation	1	137.34	1243.8	0.11	1
Roof insulation	1	156.06	693.6	0.23	2
	2	206.35	786.5	0.26	
	3	513.06	871.2	0.59	
Windows (glazing and frame)	1	1626.06	782.8	2.08	6
	2	2617.66	950.2	2.75	
External doors	1	226.96	227	1.00	4
	2	399.02	337.9	1.18	
Ground floor insulation	1	1064.49	579.5	1.84	5
	2	1440.58	804.5	1.79	

Table 4.1 uses the cost information first provided in section 3.5.1 and combines it with the energy savings associated with each of the different retrofit measures. This allows for an assessment of the value-proposition of each installation. Note that the energy savings figures used in the table are those seen with the relevant infiltration reduction applied to each retrofit measure. The ranking on the right side of table 4.1 is based solely on the relative cost per kWh of energy saved over a 12-month period for each type of retrofit measure. The loft insulation is ranked top with a cost per kWh saving of £0.11; whereas the windows rank last with an average cost of £2.42 per kWh saving. Clearly, the energy saving potential does not capture the full utility of each installation. Other benefits such as moisture control, security

and soundproofing also provide value for homeowners, however these benefits are more difficult to empirically quantify.

If a flat rate of 5p/kWh is assumed for the continued price of natural gas, it is possible to assess the payback period for each of the installations under investigation. This is displayed in table 4.2. It also makes use of the assumption that the natural gas boiler that is providing the building with space heating, is operating at 70% efficiency. This enables the calculation of the amount of fuel that is needed to satisfy the space heating demand.

Table 4. 5 Payback period for each retrofit measure

	Construction	Energy demand reduction (kWh)	Natural gas demand reduction (kWh)	Annual cost saving (£)	Payback period (years)
Wall insulation	1	1831.9	2617.0	130.9	5.2
	2	2151.2	3073.1	153.7	6.2
	3	2405.2	3436.0	171.8	7.1
Loft floor insulation	1	1243.8	1776.9	88.8	1.5
Roof insulation	1	693.6	990.9	49.5	3.2
	2	786.5	1123.6	56.2	3.7
	3	871.2	1244.6	62.2	8.2
Windows (glazing and frame)	1	782.8	1118.3	55.9	29.1
	2	950.2	1357.4	67.9	38.6
External doors	1	227	324.3	16.2	14.0
	2	337.9	482.7	24.1	16.5
Ground floor insulation	1	579.5	827.9	41.4	25.7
	2	804.5	1149.3	57.5	25.1

The pattern of value is the same as in table 4.1 above, with the loft insulation paying for itself in 1.5 years, whilst the windows will have to provide energy savings for an average of 33.85 years. Clearly, this analysis does not account for the fact that it is both likely and necessary that homes switch to a low-carbon heating system in the near future. However, the value proposition of each installation relative to the others still stands, regardless of the heating system.

4.9 Assessment of measures in combination

This section observes the impact on the building's energy demand when a set of installations, one of each type, are applied to the model in unison. Two groups of installations are investigated, group A and group B. Section 3.4.8 outlines the particular measures that are included in each of these groups.

Summing the energy saving associated with each installation in isolation (set out in sections 4.1 to 4.7) before subtracting from the base demand of 6897 kWh gives a demand of 1321 kWh for group A. The same calculation with the constructions in group B gives an annual energy demand of 2133 kWh.

However, when applying each of the relevant constructions to the building model within ESP-r, the simulated output is different from this summed estimation. For group A, the simulated annual demand is 1668 kWh and for group B the value is 2530 kWh for the year.

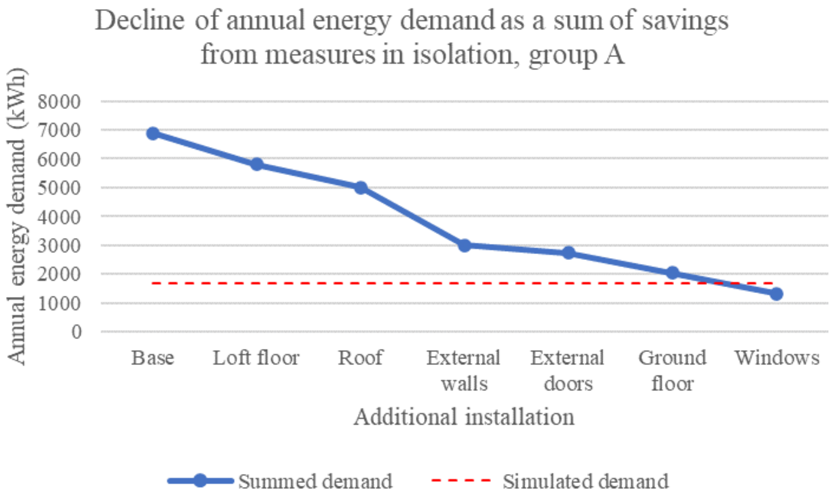


Figure 4.20: Group A, summation of isolated energy savings and actual simulated demand

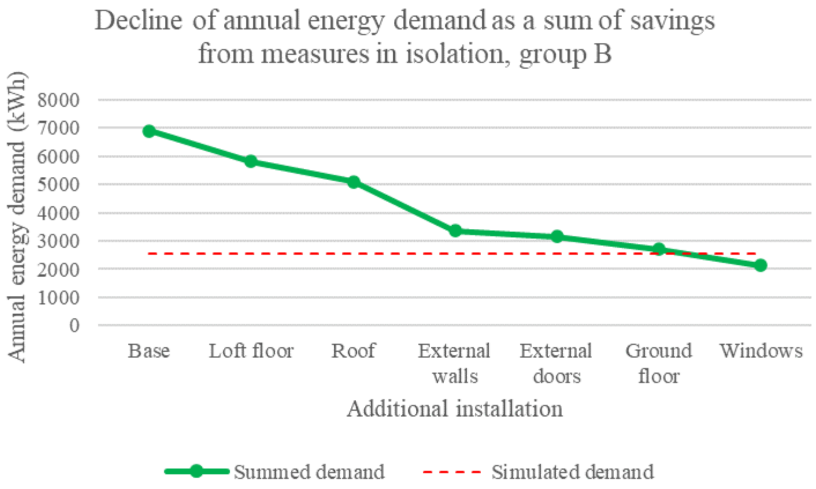


Figure 4.21: Group B, summation of isolated energy savings and actual simulated demand

Figures 4.20 and 4.21 show how the energy demand falls with each installation that is added, assuming that the demand reduction at each step is equal to that seen when the installation is examined in isolation. The figures also illustrate how, in both cases A and B, the summed demand reduction overshoots the actual simulated reduction in energy demand. For group A, the overshoot is 347 kWh, whilst 397 kWh is the equivalent figure for group B. This suggests the existence of a diminishing-returns effect. Whereby with each installation that is added, and as the energy demand tends toward zero, the energy benefit becomes increasingly smaller than expected.

4.9.1 Assessment of diminishing-returns

In order to assess the potential diminishing-returns effect, the simulated energy demand is required at every step as each new retrofit measure is installed. For the purposes of this sub-investigation, the measures are installed in order of cost per kWh saving, cheapest to most expensive. This is also the order set out in figures 4.20 and 4.21 above.

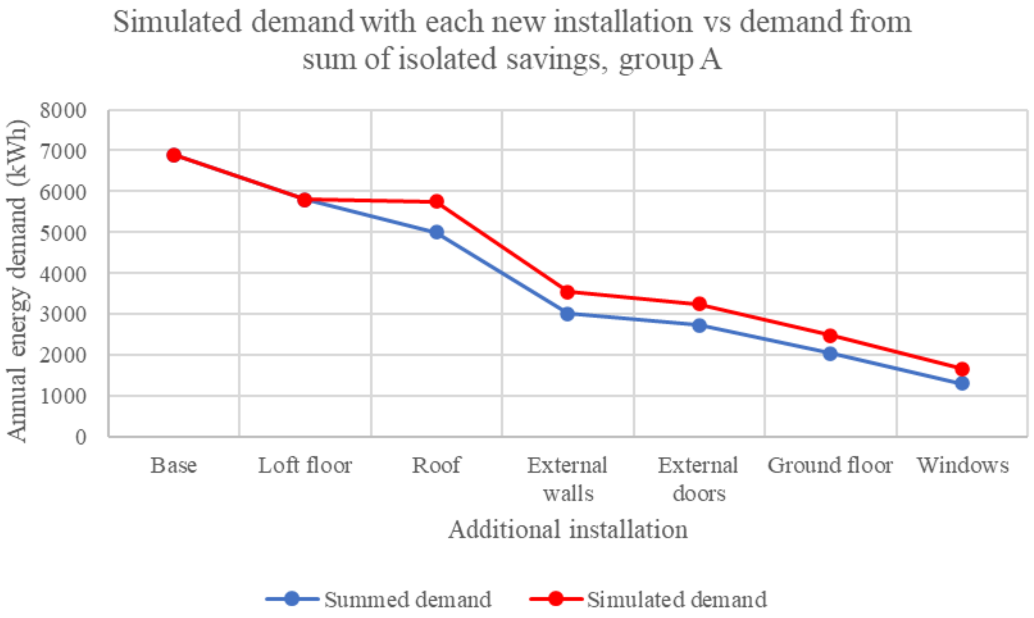


Figure 4.22: Group A, summation of isolated energy savings vs actual simulated demand at each step

Figure 4.22 shows how, for each step, the simulated demand differs from the demand derived from simply summing the demand reductions associated with each installation in isolation. The difference between the two series after all of the measures are installed is the same as shown in figure 4.20 above; 347kWh for group A. However, it is how the delta between the series changes at each step that is of interest.

It is clear that having already installed the loft floor insulation, the addition of roof insulation barely reduces the energy demand of the building. The demand falls by just 52.6 kWh over 12 months compared to the 797.5 kWh of demand reduction that was seen when examining the impact of the roof insulation upgrade 3 in isolation. This indicates that both the roof insulation and loft floor insulation are essentially performing the same job. Both installations ultimately work to reduce the heat transfer through the loft floor and into the heated zones below. Indeed, when removing the roof insulation, but retaining the rest of the group A retrofits, the final energy demand is increased by only 63 kWh. Therefore, the addition of roof insulation, at a cost of £513.06 for the 290mm thick insulation used in group A, suddenly becomes very cost-inefficient.

From the installation of cavity wall insulation onwards, rather than displaying a diminishing return, each individual addition actually reduces the energy demand by more than it did when examined in isolation. The cavity wall insulation reduced demand by 199 kWh more than expected, 29 kWh for the doors, 88 kWh for the ground floor and 83 kWh for the windows. In each case, the magnitude of the ‘overshoot’ is consistently about 10% of the expected demand reduction. This enforces the findings of Simpson *et al.* (2015) who observed a 14% overshoot when applying double glazing to a combination of measures compared to the same double glazing in isolation. This additional benefit can be largely attributed to the reduction of hours required for the boiler to be operating as shown by figure 4.23.

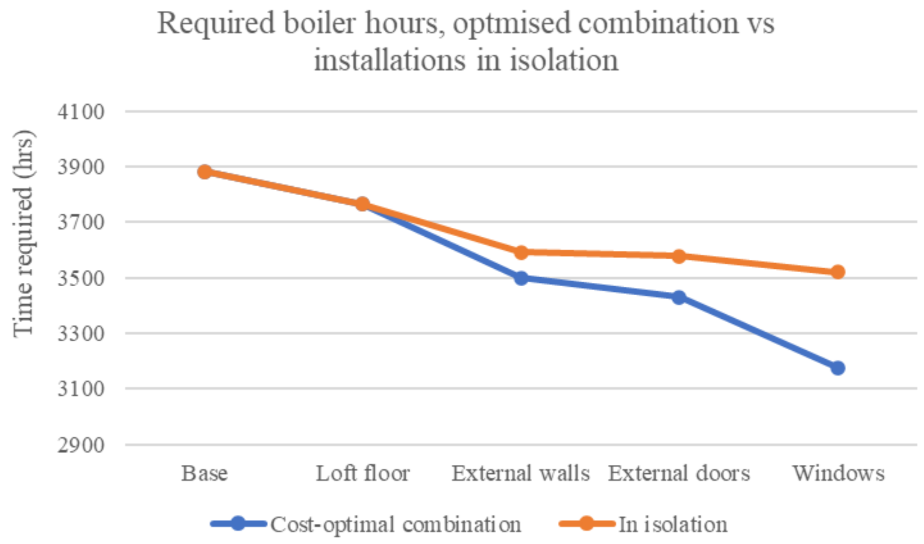


Figure 4.23: Comparison of boiler hours required when applying measures in cost-optimal combination vs in isolation

Adding measures to a pre-existing combination of installations significantly increased the reduction of boiler hours when compared with installing the same measure in isolation. The disparity also became greater as more measures that were installed. For the installation sequence in figure 4.23, the cavity wall insulation saw a 1.86 times increase whilst the window replacement had a 4.27 times rise.

Conducting this sub-investigation for the installations that make up group B brings the same observations and conclusions that have been presented for group A.

4.10 Peak heat demand (net-zero readiness)

When considering the installation of a range of retrofit measures, it is important to understand the energy demand reduction target for a given building. In this case, the target is for each zone to be able to be heated by a low-temperature radiator within a heat pump system. The target peak heat demand for each zone is given in section 3.5.2. The key point of observation is the peak heat demand during the 3-day cold period in January for each zone, and whether this worst-case demand is able to be met by low-temperature radiators operating at 50°C. The peak heat figures are taken from simulations where the relevant air infiltration reductions are applied for each retrofit measure.

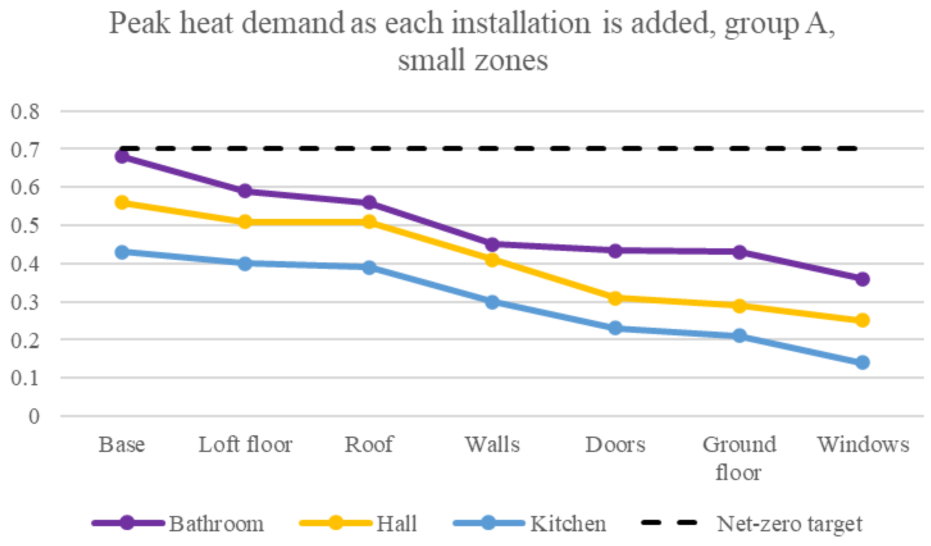


Figure 4.24: Small zones, simulated peak heat demand by zone as each installation is added, group A

Firstly, considering only the smaller zones with one radiator. Figure 4.24 shows that even before any upgrades, the base constructions are sufficient to allow a single low-temperature radiator to heat these zones. This is not unexpected however as these three zones are particularly small; the kitchen and bathroom are volumetrically 5.2 times smaller than the living space.

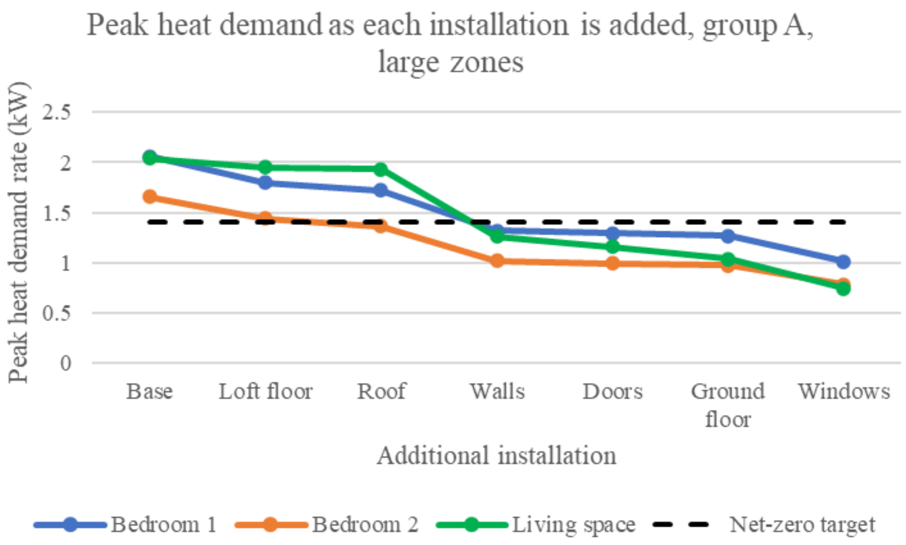


Figure 4.25: Large zones, simulated peak heat demand by zone as each installation is added, group A

Moving on to the three larger zones that require two radiators. Figure 4.25 shows the decrease in peak heat demand for the three large zones as each installation in group A is added. The target is shown by the dashed black line. It is observed that after the cavity wall insulation is installed, the peak rate of heat demand for the building lies below the target rate of 1.402 kW. However, it is not until the triple-glazed windows are installed that the two bedrooms are reasonably distanced from the rate of heat emission limit for low-temperature radiators.

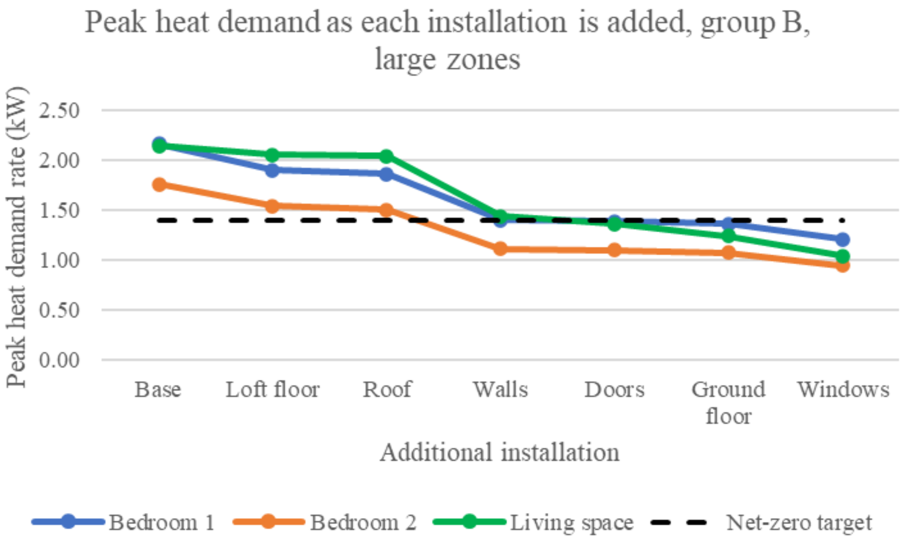


Figure 4.26: Large zones, simulated peak heat demand by zone as each installation is added, group B

Now considering the same plot for the group B installations. Figure 4.26 illustrates that with this set of materials, it is not until the final installation of the double-glazed windows that each of the large zones is comfortably under the peak rate of heat demand target. Clearly, a homeowner is not restricted to installing each of the materials in these groups.

For any homeowner looking to achieve this net-zero rate of heat demand target, the focus will likely be on finding the most cost-effective combination of retrofit measures that still meets this target. For this building model to meet the target, it can be observed from figures 4.25 and 4.26 that it is a necessity to have both the cavity wall and window installations. The window options investigated in this report were declared as the least cost-effective in terms of cost per kWh saving. However, the magnitude of their energy saving and importantly, the large impact they have on the reduction of the rate of heat demand for each zone make them a requirement to meet the net-zero specification. Next down the line of cost-effectiveness is the ground floor insulation, and the roof insulation since when applied in combination with the loft floor insulation, it has little benefit. It would make financial sense to remove these two installations if possible.

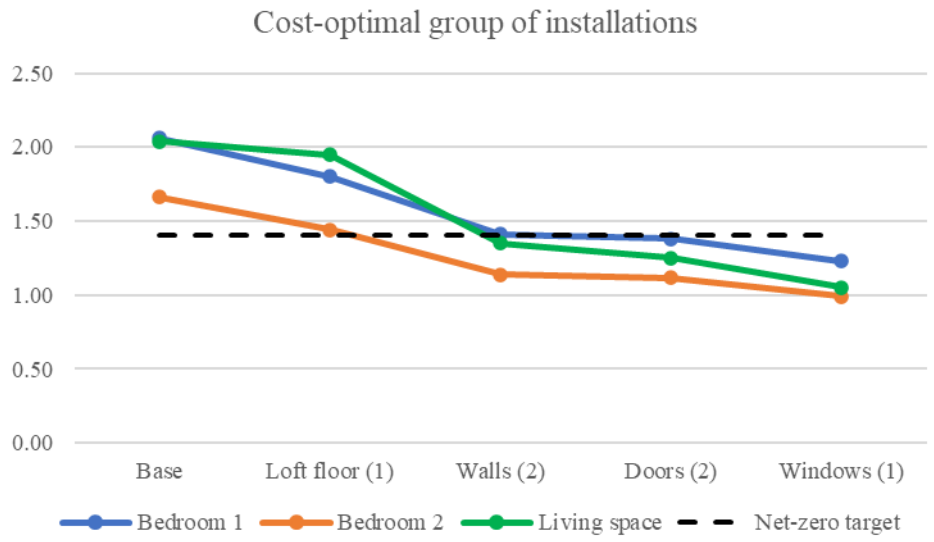


Figure 4.27: Peak rate of heat demand for cost-optimal set of constructions

Figure 4.27 shows the result of testing different combinations of installations to give the cost-optimal group of measures that keep each zone below the net-zero target. Not only is it possible to remove the roof and ground floor measures, but also using the cheaper wall and window constructions from group B maintains each zone's position below the heat rate limit.

Table 4. 6 Cost-optimal set of retrofit measures that achieve net-zero heat rate target

	Upgrade number	Description	U-value (W/m^2K)	Cost (£)
Loft floor	1	100mm thick glasswool	0.333	137.34
Cavity walls	2	100mm thick mineral wool	0.303	955.74
External doors	2	Oak door with 90mm insulation layer	0.832	399.02
Glazing	1	Double-glazing	2.811	1626.06
Window frames	1	PVC frame with thermal break	1.054	
			Total	**3118.16**

Table 4.3 makes note of the materials that make up this cost-optimal set of constructions, as well as their cost. The simulated output with these constructions, including the associated infiltration reductions, gives an annual energy demand of 2840 kWh. This constitutes an annual demand reduction of 4057.4 kWh compared to the base case. With a heating system efficiency of 70%, this corresponds to 5796.3 kWh of natural gas that is no longer used each year. At the current UK average spot price for natural gas of 3.75p/kWh, this energy saving corresponds to an annual cost saving of £217.36 (National Statistics, 2020b). Taking a

conservative price of 5p/kWh for natural gas over the coming years, this energy saving each year would result in a payback period of 10.76 years for each of the four measures in the optimised group.

The results sections above have provided empirical evidence that building retrofits have significant energy and cost saving benefits over the long-term. However, the broad challenge, having established the theoretical position, is how to drive the widespread installation of building retrofit measures. Previous government retrofit schemes have had moderate success, but it is likely that a far more aggressive scheme of incentives is required.

Publicly demonstrating and breaking down the benefits of retrofit and otherwise educating the population is also key. In the post-retrofit questionnaire discussed in section 2.7, 72% of residents declared they had never had any advice on managing energy in the home. However perhaps more damning was the fact that 40% of those that did get advice did not consider it useful (Huebner, Cooper and Jones, 2013; Elsharkawy and Rutherford, 2015). Moreover, lack of understanding of home heating systems makes up a large part of the rebound effect.

5. Concluding remarks

5.1 Limitations of the study

It is key to understand the practical limitations of the assumptions made in the modelling exercise. Firstly, when modelling buildings, the simulated potential savings often aren't fully realised in practice. This is for a number of reasons. Firstly, within ESP-r for, building materials are taken as being in perfect condition when applied to a geometry. However, in reality, each material is laden with imperfections in its fabrication which leads to localised increases in U-value such as those seen in the study by Gupta and Gregg (2016). There are also often mistakes made during the installation process. In short, the practical average U-value of each material is likely higher than that stated in this report. Additionally, the rebound effect is well documented and plays a major role in the actual energy demand of a home after efficiency upgrades. It suggests that once a home is retrofitted to become more efficient, the behaviour of the occupants will become less energy-savvy. A number of papers have quantified the rebound effect and suggest that the benefits of thermal upgrades can be between 10-35% less than the simulated predictions due to the rebound effect(Galvin, 2015; Galvin and Sunikka-Blank, 2016).These limitations were taken into account when curating the optimal set of retrofit measures to achieve 'net-zero-readiness' as care was taken to ensure a moderate delta between the modelled peak heat rate and the target limit. This was done to allow for the conclusions to remain valid even with a margin of error present.

Limitations specific to this investigation would include the fact that just one house type was used. Whilst a semi-detached building is as representative of a broader range of homes as possible, testing using a terraced house may have given different conclusions regarding the benefits of certain measures. For example, if there had been homes adjacent to each side of the terraced house, then it is likely that the cavity wall insulation would be less effective as there is more heat loss through exposed external walls.

Additionally, this study has only considered fabric measures for the reduction of energy demand. It is likely that a significant amount of energy could be saved by modifying the heating schedule. Installing thermostats on each radiator would also allow for greater control of the heat network and provide extra savings. However, these changes are dependent on the behaviour of occupants which is unreliable and difficult to represent in a model. Instead, the focus was on tackling the performance of the thermal envelope of the building, something that will be crucial for the permanent reduction of the UK’s domestic heat demand.

5.2 Recommendations for future work

In order to build on the findings in this study, a similar investigation including a wider variation of building types would provide greater representation of the UK’s housing stock. Experiments using detached, terraced, flat and bungalow models would capture the majority of the homes in the UK. A study focussing on modelling other demand reduction methods would also be of value. Simulations could explore different heating schemes and mimic a variation of occupational behaviour to capture the contribution this would have towards reducing energy demand.

Additionally, focussing on domestic net-zero, research could be carried out into the long-term benefits of first reducing the energy demand of a building before installing smaller heat pumps. The alternative position would be to skip the widespread installation of retrofit measures, saving money in the short-term and simply incentivise the installation of heat pumps in each home as soon as possible. This study could focus on the cost to homeowners over the period to 2045 for example, as well as the load on the electricity network with and without the widespread retrofits in place.

Finally, there would be significant value in the evaluation of potential policy schemes in order to devise the optimal policy solution in order to drive the widespread uptake of energy retrofits.

5.3 Conclusion

A building model representing a semi-detached house was monitored for its energy performance as six different types of retrofit measures were applied both in isolation and in combination with each other. Having completed this investigation, the following can be concluded.

Simulating the energy demand reduction with each retrofit measure in isolation allowed for a clear observation of the benefits specific to each installation. The results showed that the cavity wall insulation, loft floor insulation and the replacement of windows resulted in the highest reductions in annual heating demand. The external door replacement and ground floor insulation saw the lowest reductions. However, when considering the cost of each installation, the measures with the lowest cost per kWh reduction were the loft floor insulation, roof insulation and cavity walls. Meanwhile, the window replacement and ground floor insulation offered the worst value-proposition.

The measures were then analysed for their performance when installed in combination with other measures. This assessment showed that having already installed the loft floor insulation, the addition of insulation to the roof was of little benefit. The annual demand reduction was 52.6kWh, just 6.6% of the value observed in isolation. However, the proceeding installations all outperformed their isolated equivalents in terms of annual energy demand reduction. They offered a demand reduction consistently around 10% greater than that seen for each measure in isolation.

Lastly, the simulated peak rate of heat demand for each zone was evaluated against the net-zero target. The target was driven by the rate of heat transfer that a heat-pump-powered radiator could produce at a surface temperature of 50°C. The cost-optimal set of retrofit measures that ensured the heat rate target was met included loft insulation, cavity wall insulation, replacement of the external doors and double glazing. The total cost came to £3118.16.

The findings of this investigation provide insight into the specific behaviour of retrofit measures in combination with each other. So called ‘whole-house’ retrofits are becoming increasingly necessary as the need to reduce carbon emissions both drastically and quickly from homes becomes greater. Therefore, an understanding of the synergistic properties of retrofit measures is of great significance both for homeowners and policy designers alike.

The next challenge to tackle is how best to drive the widespread installation of energy efficiency retrofits around the UK. Government policy has been moderately successful at capturing the early adopters, however more aggressive incentives are required for the majority of homeowners to invest and ensure that homes emit net-zero emissions by 2045.

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Appendix A: Tabulated results

Table A. 1 Loft floor insulation energy savings

Loft Floor		
Base	**Description**	Suspended ceiling construction, no insulation
	U-value (W/m^{2}K)	4.976
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	100mm thick glasswool layer
	U-value (W/m^{2}K)	0.333
	Annual energy delivered (kWh)	5804.6
	Energy saving vs base (kWh)	-1092.8

Table A. 2 Roof insulation energy savings

Roof		
Base	**Description**	Tiled roof, no insulation
	U-value (W/m^{2}K)	2.143
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	80mm thick glasswool layer
	U-value (W/m^{2}K)	0.413
	Annual energy delivered (kWh)	6270.1
	Energy saving vs base (kWh)	627.3
2	**Description**	140mm thick glasswool layer
	U-value (W/m^{2}K)	0.257
	Annual energy delivered (kWh)	6181.2
	Energy saving vs base (kWh)	716.2
3	**Description**	290mm thick glasswool layer
	U-value (W/m^{2}K)	0.131
	Annual energy delivered (kWh)	6099.9
	Energy saving vs base (kWh)	797.5

Table A. 3 Cavity wall insulation energy savings

Cavity Walls		
Base	**Description**	Standard brick cavity wall, no insulation
	U-value (W/m^{2}K)	1.086
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	60mm thick mineral wool insulation
	U-value (W/m^{2}K)	0.435
	Annual energy delivered (kWh)	5478
	Energy saving vs base (kWh)	-1419.4
2	**Description**	100mm thick mineral wool insulation
	U-value (W/m^{2}K)	0.303
	Annual energy delivered (kWh)	5156.2
	Energy saving vs base (kWh)	-1741.2
3	**Description**	150mm thick mineral wool insulation
	U-value (W/m^{2}K)	0.207
	Annual energy delivered (kWh)	4901.8
	Energy saving vs base (kWh)	-1995.6

Table A. 4 External door replacement energy savings

External Doors		
Base	**Description**	Standard solid oak door, no insulation
	U-value (W/m^{2}K)	3.316
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	Oak door with 36.5mm of woodwool insulation
	U-value (W/m^{2}K)	1.5
	Annual energy delivered (kWh)	6703.4
	Energy saving vs base (kWh)	-194
2	**Description**	Oak door with 90mm of woodwool insulation and anti-draft membrane
	U-value (W/m^{2}K)	0.832
	Annual energy delivered (kWh)	6621.7
	Energy saving vs base (kWh)	-275.7

Table A. 5 Ground floor insulation energy savings

	Ground floor	
Base	**Description**	Uninsulated ground floor
	U-value (W/m^{2}K)	1.086
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	100mm thick layer of extruded polystyrene insulating foam
	U-value (W/m^{2}K)	0.317
	Annual energy delivered (kWh)	6436.5
	Energy saving vs base (kWh)	-460.9
2	**Description**	200mm thick layer of extruded polystyrene insulating foam
	U-value (W/m^{2}K)	0.151
	Annual energy delivered (kWh)	6213
	Energy saving vs base (kWh)	-684.4

Table A. 6 Window replacement energy savings

	Windows	
Base	**Description**	Single glazing, 6mm thick glass
	U-value (W/m^{2}K)	5.691
	Annual energy delivered (kWh)	6897.4
	Energy saving vs base (kWh)	N/A
1	**Description**	Double glazing, 6mm glass, 12mm gap
	U-value (W/m^{2}K)	2.811
	Annual energy delivered (kWh)	6338.1
	Energy saving vs base (kWh)	-559.3
2	**Description**	Triple glazing, 6mm glass, 12mm gaps, low-emissivity coating
	U-value (W/m^{2}K)	1.081
	Annual energy delivered (kWh)	6166.9
	Energy saving vs base (kWh)	-730.5