Department of Mechanical and Aerospace Engineering

Strategic Approach to Retrofitting Scottish Housing Stock towards Net Zero Carbon

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Signed: Shannon Murray Date: 23rd August 2019

Abstract

The main aim of the project is to recommend a suitable approach for retrofitting the current Scottish housing stock to achieve net zero carbon by 2050, by upgrading the building fabric and heating systems, along with installation of solar PV systems. The Climate Change Plan aims to reduce overall carbon dioxide emissions by 80% by 2050, and proposes that all buildings should be close to net zero carbon as possible by this time. Since space heating uses the most energy in a domestic building, and hence, will contribute the greatest carbon emissions from the dwelling, it is essential that Scottish housing stock is retrofitted in order to reduce emissions to reach 2050 target. The housing stock is comprised of a diverse range of dwellings, and one retrofit measure applied to two different types of dwellings may not produce the same results, therefore, a strategic approach as to how percentages of the stock can be retrofitted is analysed.

The Housing Energy Upgrade (HUE) tool was used to apply energy efficiency measures in different scenarios to an estate built to represent the most common houses in the Scottish housing stock. The scenarios explored applying each type of retrofit individually and then combining together in order to achieve greater reductions in space heating demand. It was found that only a small percentage of the whole housing stock can be retrofitted to net zero carbon emissions through the implementation of building fabric upgrades combined with low carbon technologies. However, the approaches adopted in the scenarios still produced substantial savings in space heating requirements and subsequent carbon dioxide emissions. So, even though net zero carbon emissions were not achieved for majority of the stock, the housing stock can still reach near zero carbon emissions using the approaches adopted in this project.

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Challenges of Retrofitting Homes

1.1. Domestic Energy Use and Carbon Dioxide Emissions in Scotland

Heating is responsible for using over half of Scotland's energy consumption, using double the energy required for transport and electricity. (Scottish Government, 2018) This is depicted in the pie chart in Figure 1.

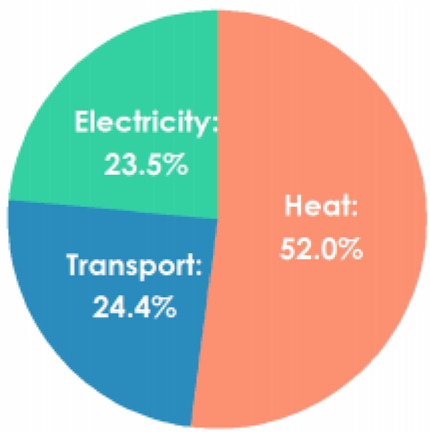
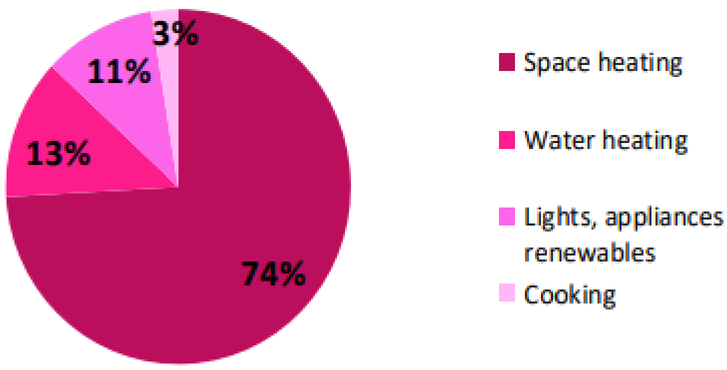


Figure 1: Energy Consumption by Sector in Scotland

In 2018, domestic energy consumption accounted for 42% of Scotland's total energy consumption, and with population expected to increase, this will only be expected to increase. This has encouraged the development of government policies and targets to improve the energy performance of the built environment. Scotland's Climate Change Plan sets out Scotland's aim of buildings being near zero carbon by 2050. However, over 85% of homes standing today will still be here in 2050, thus, it is essential that these dwellings are retrofitted to meet government targets. Installing energy efficiency measures and low and zero carbon technologies will have a significant effect on the energy consumption, and most importantly, carbon dioxide emissions of the Scottish housing stock.

There are various factors that contribute to the energy efficiency of a building and affects how well it performs. Mainly, the building fabric and when the building was built have significant effects on the energy performance, and most notably for this study, the improvement potential of a dwelling. For example, it will be more difficult to improve the building fabric and heating system of an older house than it will a more recently built house, which was built to meet a higher building standard. Also, the type of house can impact the energy efficiency, for instance, a detached dwelling has more exposed areas to the external environment than a terraced house (which has a house on either side of it). So, the detached house is more likely to lose heat quicker than the terraced type. Additionally, the floor area contributes to how energy efficient a home is. Larger homes, like detached homes, require more energy to heat and thus cost more to heat. These types of homes are most in need of retrofitting as they are essentially more difficult to heat and occupants are more vulnerable to increase in fuel prices, and hence, more at risk to suffer from fuel poverty. (Scottish Government, 2018)

Although many recently built homes comply with the Scottish Building Regulations Part L, thus making them the least challenging to retrofit towards net zero, older buildings built before the introduction of Scottish Building Standards in 1982 (Scottish Government, 2017), have few measures installed to improve energy efficiency.



(Scottish Government, 2018)

Figure 2: Average Household Energy Consumption by End Use (2016)

As shown in Figure 2, the main components that contribute to the overall energy demand of a dwelling are space heating (74%), water heating (13%), lighting (11%) and cooking (3%). (Scottish Government, 2018) Since the seasonal weather and corresponding external temperatures have been fairly consistent in Scotland over recent years, it would be expected that space heating of dwellings would also remain constant since it primarily depends on the outdoor temperature. However, since the 2005-07 baseline, domestic energy consumption has reduced by 20% due to increasing improvements in energy efficiency of the Scottish housing stock over the years. (Scottish Government, 2018) The desired outcome of installing energy efficiency measures is to essentially reduce the amount of heat required to heat a dwelling, as heating makes up the majority of energy consumed in a dwelling. For that reason, it is essential that residential buildings and space heating are focussed on in order to achieve greatest reductions in energy. It is evident that improving homes in Scotland is an important part of reducing energy use and action must be taken to continue to improve the efficiency of the housing stock.

It is widely accepted that carbon dioxide emissions and energy use are interlinked, yet the trends in carbon dioxide emissions differ slightly to that of energy use in buildings. This is largely due to the fact different types of fuel used to heat homes have varying carbon dioxide emissions associated with them. Therefore, it is likely that space heating emits the most significant carbon dioxide emissions in the built environment. So, retrofitting of existing homes should primarily focus on reducing these two sources to create substantial savings in energy consumption and carbon dioxide emissions of the housing stock. The current housing stock could be demolished and more energy efficient homes could be built instead, however, demolishing buildings would contribute more landfill waste and requires a large investment of money, making it less environmentally friendly and less cost effective than just retrofitting the current stock to achieve the same outcome. (Salem, et al., 2018)

This project researched this issue by modelling different upgrade scenarios using a tool based on dynamic simulation models of the Scottish housing stock. These scenarios investigated how homes can be retrofitted to a net zero carbon standard, particularly that which matches the Zero Carbon Hub's (ZCH) definition of net zero carbon homes. The housing stock will be upgraded with an emphasis on improving building fabric and heating systems and installing low to zero carbon technologies to meet reduced energy demand. The analysis software used throughout the project was the Housing Energy Upgrade (HUE) tool. (Clarke, et al., 2008) The scope of the study is limited to the retrofitting of a typical housing estate and examining its operational (kWh/yr) and environmental ($kgCO_2$/yr) performance, and so, costs of upgrades will not be analysed when selecting the most appropriate solution to upgrading the dwellings.

1.2. Project Aims

The aim of the project is to recommend a suitable approach for retrofitting the current Scottish housing stock to net zero carbon by 2050, and to explore current technologies to determine which combination of energy efficiency measures have the greatest potential to create significant reductions in space heating requirements and carbon dioxide emissions of the Scottish housing stock.

A software tool based on dynamic simulation models was used to build a housing estate model consisting of 500 homes representing the most common types in the Scottish housing stock and building fabric and heating systems upgrades applied, along with photovoltaic (PV) panels to quantify the impact this has on the overall space heating demand and carbon dioxide emissions associated with this demand.

The rates at which these retrofit measures will be applied in the forthcoming years to 2050 was also investigated in order to analyse the feasibility of the Scottish housing stock reaching net zero carbon standards by 2050. The aim of the project is to develop a systematic approach to house retrofit planning to assist policy makers to take action for retrofitting homes towards net zero emissions, in order for Scotland to meet its climate change targets.

1.3. Project Objectives

The primary objectives of the project to achieve this aim are:

- build an estate model that is representative of the Scottish housing stock using the HUE software;
- use HUE to examine alternative approaches to retrofitting in terms of energy use and emissions reduction;
- assess the rates at which these retrofits can be carried out; and

- assess feasibility of installing solar photovoltaic (PV) panels to cover additional energy needs after installation of retrofit measures to reach net zero carbon target.

1.4. Methodology

The estate under study consists of 500 homes and represents the most common house types found in Scotland today. The estate includes the following types of dwellings:

- Detached homes built pre-1919 and post 1982
- Terraced houses built between 1945-1982
- Semi-detached dwellings built between 1945-1982
- Tenement flats built pre-1919 and post 1982 (Scottish Government, 2018)

The exact percentage of these homes in the stock and number in made up estate can be in Chapter …, Section … (SHCS) As shown, there is a variety of dwellings with varying age bands in the estate, therefore, a strategic approach will have to accommodate the retrofit of all these dwellings individually in order to achieve the best outcome.

Since this study is exploring retrofitting of the Scottish housing stock and not just an individual dwelling, a suitable software was utilised. While a dynamic simulation tool like ESP-r (Energy Systems Research Unit, 2002) would have been a suitable choice, simulating several different types of homes repeatedly with various different upgrades applied each time rendered the approach unsuitable given the resources available in the project. Nevertheless, it is recognised that dynamic simulation is more realistic than steady-state models such as embedded in the Standard Assessment Procedure (SAP) procedure. An intermediate approach was therefore adopted via the use of the HUE with its underlying models based on the pre-simulation of architype models. (Clarke, et al., 2008)

The HUE tool was designed specifically to analyse housing estates and formulate an upgrade strategy. The software is based on dynamic simulation and has pre-simulated results for an array of thermal models available in the tool to give instantaneous energy, carbon and cost results for any upgrade applied to a dwelling. Weather data for several locations in the UK are embedded in the tool along with fabric and system parameters. (Clarke, et al., 2008) As each improvement is applied to the dwellings under study, the outcome of the energy consumption and carbon dioxide can be readily analysed.

Another benefit of using HUE over other dynamic simulation tools is its ease of use as it does not require extensive data input. A base case model of the individual dwelling or estate is first defined, allowing the user to compare the results of improvements added to the original dwelling/estate. The two key parameters that can be improved in the tool are building fabric and heating system parameters either individually or in combination, allowing the user to identify the most suitable combinations of measures to achieve a desired outcome. Figure # below shows the interface of the HUE tool.

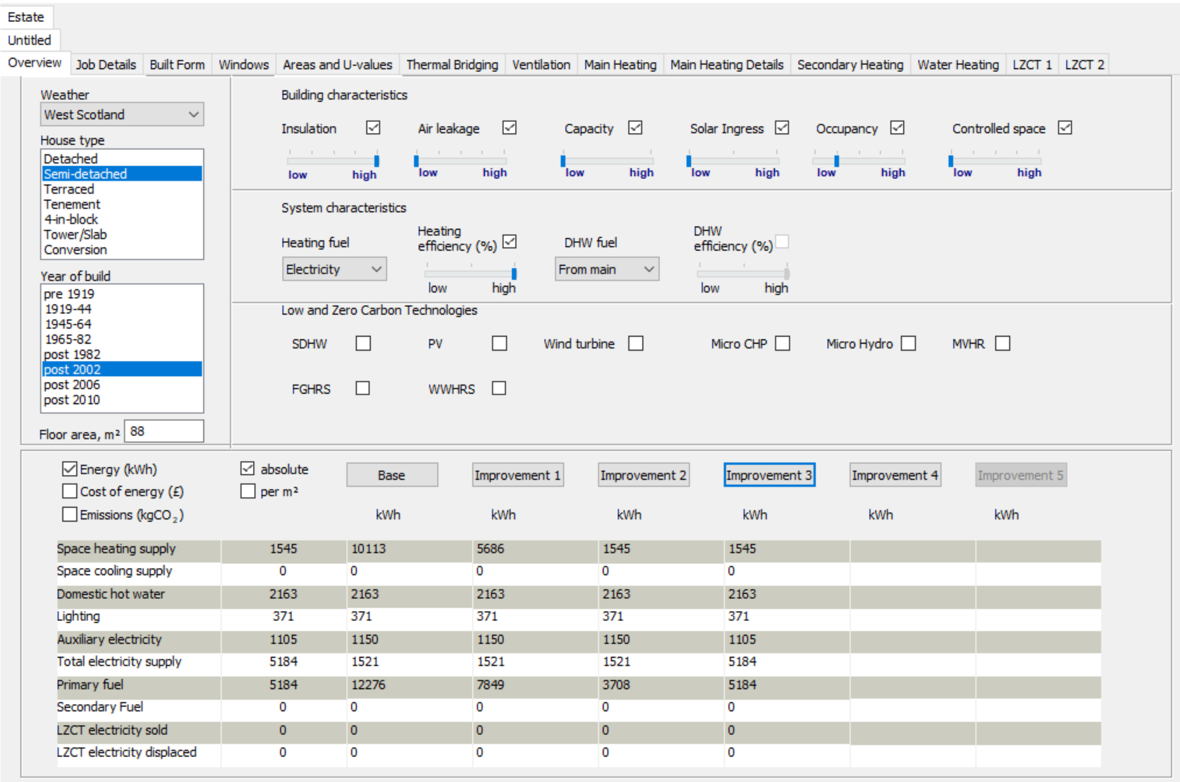


Figure 3: Example of a HUE retrofit analysis.

In this study, the main fabric upgrades that were implemented were:

- insulation;

- air tightness; and
- glazing type.

The heating system upgrades included primary heating fuel (natural gas) being changed to electricity. These measures were implemented individually, then combined to analyse effects on the estate's energy and carbon dioxide emissions.

2. Literature Review

2.1. Scottish Housing Stock

According to the Scottish House Conditions Survey (Scottish Government, 2018), there are approximately 2.5 million homes in Scotland at the present time, with the average home producing 7 tonnes of carbon dioxide annually. It is unlikely Scotland will meet its climate change targets of 80% reduction in overall CO2 emissions by 2050 without drastic change. The Scottish housing stock is diverse and Table 1 shows the proportion of dwellings categorised by age band and type in terms of percentage of whole housing stock.

Table 1: Scottish dwellings by type and age.

	Type of Dwelling					
Age of dwelling	Detached	Semi-Detached	Terraced	Tenement	Other flats	**Total**
Pre-1919	4%	3%	3%	7%	2%	**19%**
1919-1944	2%	3%	1%	2%	4%	**12%**
1945-1964	2%	6%	8%	4%	3%	**22%**
1965-1982	5%	4%	7%	3%	2%	**21%**

Post-1982	10%	3%	3%	8%	2%	**26%**
Total	**22%**	**20%**	**22%**	**24%**	**13%**	**100%**

(Scottish Government, 2018)

These data reveal that almost 75% of dwellings were built prior to 1982, before the need for energy efficiency measures was introduced. This emphasises the challenge associated with retrofitting Scottish homes, and this project will investigate the effects of upgrading these older dwellings. Table 2 lists eight predominant Scottish house types as a proportion of the overall stock:

Table 2: Proportion of dwelling types in the Scottish housing stock.

Type of Dwelling	Age of Dwelling	Percentage of whole stock
Detached	Pre-1919	4%
Tenement flat	Pre-1919	7%
Detached	Post-1982	10%
Tenement flat	Post-1982	8%
Terraced	1945-1964	8%
Terraced	1965-1982	7%
Semi-detached	1945-1964	6%
Semi-detached	1965-1982	4%
Total		**54%**

(Scottish Government, 2018)

From these data it is evident that the problem of upgrading homes is complex due to the variations in house types and different options available for upgrading each of these. Furthermore, the most common houses make up just over half of whole building stock, therefore, retrofitting of these homes will cause great reductions in energy demand and CO_2 emissions of the whole stock.

The primary fuel used in a dwelling can have a significant effect on the energy efficiency of the dwelling and the amount of carbon dioxide it emits annually. It can also have an opposing effect on the cost of energy, and thus, increases the risk of occupants suffering from fuel poverty. According to the Scottish House Condition Survey (Scottish Government, 2018), 79% of Scottish homes use mains gas for heating, 12% use electricity, 6% use oil, 1% use communal heating and the remaining 1% use biomass. The dwellings in Scotland which were found to have the lowest carbon dioxide emissions were flats built post-1982 (4 tonnes of carbon dioxide per year), which is almost half of the average 7 tonnes per year. As expected, detached homes were found to produce the highest carbon dioxide emissions due to their large floor area and high exposure to the external environment. (Scottish Government, 2018)

Scotland has implemented programmes such as the Home Energy Efficiency Programme for Scotland and Warmer Homes Scotland, which both aim to improve insulation levels in dwellings. However, with space heating consuming 74% of energy in homes, there is certainly an opportunity to reduce this demand as identified elsewhere. (Scottish Government, 2015) The percentage of homes with loft insulated to 100mm or more remained at 94% in 2017, with only 30% of lofts insulated to a high standard (300mm or more). In terms of wall insulation, 75% of homes have cavity wall insulation whereas the percentage of solid walls with insulation is only 18%. Moreover, it is evident that more needs to be done in order to improve the energy efficiency of the Scottish housing stock as a whole. (Scottish Government, 2018)

2.2. Net Zero Energy Buildings

The UK Government previously established a policy that all new homes should be built to net zero standard by 2016, however, this policy has now been cancelled. Although this standard was proposed mainly for new homes, the concept still applies when upgrading current homes to net zero carbon. In order to give the building industry a clearer idea of the definition of zero carbon homes, the government developed a definition based on hierarchical approach to attaining zero carbon buildings, described in Figure 2 below:

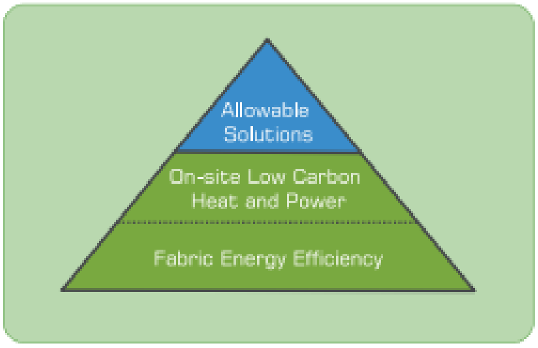


Figure 4: Three Steps of the UK Government's Approach to Net Zero Homes.

The first step of the Zero Carbon Hub's (ZCH) definition, referred to as the minimum Fabric Energy Efficiency Standard (FEES), involves implementing high levels of energy efficiency through the building fabric in order to minimise the energy demand that the low-to-zero carbon (LZC) technologies will have to provide. Furthermore, concentrating on updating the building fabric helps reduce the need for more expensive and complex retrofit measures being applied at a later time. Once these fabric measures have been installed, the home must perform to the recommended levels of energy use per m^2 for each type of dwelling. (Zero Carbon Hub, 2013) These values are summarised in Table 3.

Table 3: Recommended levels of energy use.

Type of Dwelling	Fabric Energy Efficiency Standard (FEES) (kWh/m^2/yr)	Carbon Compliance Limit ($kgCO_2/m^2/yr$)
Detached	46	10
Semi-detached	46	11
End of terrace	46	11
Mid-terrace	39	11
Apartment blocks (up to 4	39	14

storeys)		

(Zero Carbon Hub, 2013)

These values are independent of fuel type and considered to be the most appropriate units to use to estimate the energy performance of a dwelling. Also, these values represent the maximum energy required for space heating and cooling. This allows a specific level of performance to be attained by the building which is beneficial for the industry. (Zero Carbon Hub, 2009) Once these metrics have been achieved by the building, LZC technologies can then be installed to further reduce carbon dioxide emissions, and ultimately provides the building with the required energy it needs in order to balance out carbon emissions, hence the building can be described as being net zero carbon. Like the minimum Fabric Energy Efficiency Standard metrics, the ZCH has also provided a maximum permitted amount of carbon dioxide emissions from space heating and cooling, hot water use, lighting and ventilation. This is known as the Carbon Compliance target and each type of dwelling has a different limit, which can be viewed in Table 3 below. (Zero Carbon Hub, 2013)

The third step of achieving net zero carbon standard is Allowable Solutions. This is when developers can either pay into a carbon fund or invest in carbon savings projects which are associated with their own specific projects. The main example of this is investing directly into the extension of an already existing district heating network. However, since ZCH's net zero approach is no longer government policy, allowable solutions are not explored within this project. However, there are three strategic approaches which can be applied to a home in order to achieve net zero carbon emissions: a balanced approach, extreme fabric approach or extreme low carbon technology approach. (Zero Carbon Hub, 2013)

Applying a balanced approach to a home involves achieving a fabric performance almost at the FEES level and installing low carbon technologies in order to achieve overall emissions at or below the Carbon Compliance level. The extreme fabric approach includes a fabric performance at the equivalent of Passivehaus levels or better and installing little, if any, low carbon technologies in order to achieve Carbon Compliance limit. This approach is beneficial as the majority of the overall emissions are being achieved through building fabric performance and it also achieves significant reductions in primary energy usage. The previous approaches rely on the use of Allowable Solutions to reduce carbon emissions to zero. However, the extreme low carbon technology approach aims to attain net zero standard using just fabric and low carbon technologies. The fabric performance will be significantly greater than FEES, maybe even beyond Passivhaus standards, and on-site low carbon energy technologies must be used to their maximum potential in order to reduce carbon emissions beyond the Carbon Compliance level. This approach could be scaled up easily as once the fabric upgrades have been installed, the capacity of technologies installed can simply be increased. Nevertheless, this approach is more likely to cost more money than the other two approaches and some locations may not be suitable for such an approach. (Zero Carbon Hub, 2013) An approach similar to the extreme low carbon technology approach will be explored in this project.

2.3. Retrofitting Homes

As outlined in the previous section, Scotland's homes are in need of energy efficiency improvements. Retrofit means refurbishing existing homes to make them more energy efficient, for example, by insulating the walls and loft to keep heat in. It can also involve upgrading the heating system from a standard combi-boiler to an air source heat pump. Measures fitted will vary from house to house as will depend on what is appropriate and cost-effective in each case. (Homes that don't cost the earth) The majority of houses in Scotland were built before 1982, when the relationship between energy usage and climate change was not yet realised. Since 2012, there has been a rapid decline in installation of domestic energy retrofits in Scotland, which is due to the lack of energy efficiency policies. Therefore, to avoid this problem of low rates of domestic retrofits, domestic energy policies need to be re-evaluated by the government. (Trotta, 2018)

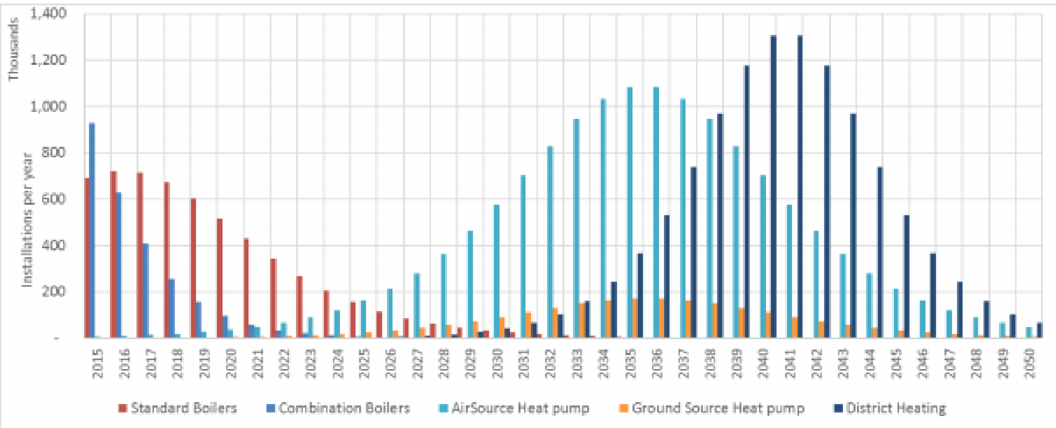
As a result, there has been an increase of policies and programmes that aim to improve building energy performance standards. The Scottish Government has set long term programmes in place in order to increase the efficiency of the Scottish housing stock, and also, to reduce fuel poverty which is a major problem at the moment. (Scottish Government, 2018) For Scotland to achieve its climate change ambitions, buildings must greatly reduce their energy and any energy which is consumed should come from low carbon sources, wherever feasible. Energy Efficiency Scotland's Route Map (Scottish Government, 2018) sets out how this will be achieved; this is a 20 year programme containing a set of actions aimed at making Scotland's existing homes near zero carbon by 2050. The Climate Change Plan has set out objectives of reducing overall carbon dioxide emissions by 80% in Scotland, and specifically reducing domestic buildings heating demand by 23%. Also, it aims to have homes insulated to the maximum appropriate level and space heating provided by low carbon technologies. (Scottish Government, 2018) It is suggested that this is completed in phases, as different homes have different starting points and should be upgraded at varying paces. (Institution of Engineering and Technology, 2018) Policies that deliver a one size fits all approach will prove unsuccessful as energy efficiency measures will need to be modelled in a way that treats each property individually. (UK Parliament, 2019) However, even though the Scottish Government has taken measures to encourage building upgrades, there is still much to do in order to reach overall net zero targets.

In order to reach these ambitious climate change targets, the scale and depth of retrofit needs to be improved. The German Government, which has similar climate change targets to the UK and Scotland, aims to retrofit 2% of building stock per year. (Neuhoff & Amecke, 2011) However, at this rate it would take 35 years to tackle half the housing stock, assuming there are sufficient funds available. Therefore, Scotland should aim for a higher retrofit rate than this in order to achieve its ambitious climate change targets. In the past though there were times when domestic upgrades were being installed at a considerable rate in Scotland. The UK Government Carbon Emissions Reduction Target (CERT) scheme delivered approximately 411,000 loft insulation measures between 2008 and 2012 in Scotland, with a further 60,000 installed between 2013 and 2017 by its successor scheme, the Energy Company Obligation (ECO). (Scottish Government, 2018) Overall, this works out to be an 85% drop in loft insulations since 2012 and is estimated going from a 4% per year retrofit rate with CERT to only a 0.6% retrofit rate with ECO.

Three quarters of dwellings in Scotland have external cavity walls and the remaining dwellings have solid wall or other construction types such as steel or timber frame.

Improving solid walls generally requires more extensive interventions than cavity wall insulation does. CERT scheme installed 218,000 cavity wall insulation in 2012, and the ECO scheme installed 299,000 from 2014 to 2017. (Scottish Government, 2018) Walls constitute a significant proportion of total heat loss from dwellings, thus have historically been a primary target of insulation. History cavity wall insulation rates of 400,000 to 500,000 installations per year. (Morgan & Killip, 2017)

Furthermore, retrofitting the heating system within a dwelling is crucial in achieving low carbon emissions. The majority of homes in Scotland are currently heated using efficient gas boilers, and it is likely that the installation of boilers will continue in the short term, as illustrated in Figure # (brown lines). However, it is assumed there will be a gradual decrease of boiler installation until 2029 and the rate of heat pump installations starts to increase greatly from this time onwards, when it is assumed electricity will be nearly or full decarbonised. Figure # shows that heat pump installations could increase from below 200,000 installation per year in the UK in 2025 to over 1 million installation in 2035 (4% rate per year). Also, this is in line with government plans to supply heating with renewable energy, wherever feasible. Despite these claims, there is still a great uncertainty how heat and electricity will be supplied in the future. (Morgan & Killip, 2017)



(Morgan & Killip, 2017)

Figure 5: Rates of Installation of Heating Systems Upgrade in the UK

As outlined in the previous section, even after the installation of building fabric and heating systems upgrades, there will still be residual carbon emissions from the dwelling. Therefore, solar panels can be installed on the roof to generate energy for a home. The current rate of retrofit of solar panels in the UK is 170,000 per year (0.7% rate per year), however, it is estimated that this number will have to increase to 1.6 million installations in 2032 (7% rate per year) in order to reach 2050 climate change targets. (Morgan & Killip, 2017)

In Scotland, energy efficiency measures have been installed in homes without any strategic thought process as to which homes should be retrofitted and how, but rather, installations were carried out in homes which volunteered to have retrofitting completed. Therefore, to conclude the literature review, there are good aspirations in Scotland to increase energy efficiency and reduce carbon emissions but weak evaluation capability shown as how to carry this out, a situation that this project seeks to remedy.

3. Retrofit Strategy Evaluation

The estate under study was made up to represent the most common houses in the Scottish housing stock. After reviewing several similar estates within the Greater Glasgow area, the average number of houses in them was estimated to be 500, therefore, the estate in this project was comprised of 500 homes. Since the number of homes was estimated based on estates in Glasgow, the weather file was chosen as West Scotland in the HUE tool. As stated in the Scottish House Condition Survey (Scottish Government, 2018) in the literature review, these common house types make up 54% of the total stock. Therefore, the number of each type of dwelling in the estate was calculated considering the common housing stock rather than the whole housing stock. Table # shows the number of each type of home in the estate.

Table 4: Number of types of dwellings in estate with age bands

Type of Dwelling	Age of Dwelling	Percentage of estate	Number of dwellings
Detached	Pre-1919	7%	35
Tenement flat	Pre-1919	14%	70

Terraced	1945-1964	14%	70
Semi-detached	1945-1964	12%	60
Detached	Post 1982	19%	95
Terraced	1965-1982	12%	60
Semi-detached	1965-1982	8%	40
Tenement flat	Post 1982	14%	70
Total		**100%**	**500**

The dwellings are rated from worst performing to best performing starting from pre-1919 detached type to post 1982 tenement flats. The estate undergoes four retrofit scenarios in this project:

- Retrofit Scenario 1: fabric upgrades only (insulation, air tightness, glazing)
- Retrofit Scenario 2: heating system upgrade only
- Retrofit Scenario 3: fabric and heating system upgrades combined
- Retrofit Scenario 4: solar PV systems added to retrofitted dwelling to analyse whether net zero carbon standard can be achieved

These scenarios were chosen as it is important to observe the impact of retrofitting measures individually in a dwelling, and also analysing the effect of combining these upgrades together in order to achieve the optimum outcome. Furthermore, these scenarios allow the best approach to be found in retrofitting certain types of dwellings and evaluating which retrofit scenarios work best for each type of dwelling in the estate. Also, these scenarios follow similar approaches developed by the ZCH in order to achieve net zero carbon emissions, outlined in the literature review.

It is unrealistic that all of the stock will be retrofitted by 2050, however, simulation results of retrofitting full estate are shown just to compare to original estate. Certain percentages of the estate are retrofitted each time in order to see effects on retrofitting several different types of houses at same time. The breakdown of these percentages and the types of home included in each are listed here:

- 25% of stock = Detached houses and tenement flats (pre-1919)
- 50% of stock = previous dwellings plus terraced and semi-detached (1945-1964)
- 75% of stock = all previous dwellings plus detached (post-1982) and terraced (1965-1982)
- 100% of stock = all dwellings in estate

3.1. Baseline Scenario

In this section, the 'as built' performance of the estate under study will be investigated in terms of the energy consumption for space heating and the carbon dioxide emissions associated with this, in order to gauge the extent of retrofitting that these homes need. There have been no modifications made to the estate at this point, the following sections will outline the results of the enhancements made to help the dwellings move towards a net zero carbon status.

For the baseline scenario, it is important to note that the model represents the estate as built; most of the dwellings in this estate were built before building regulations were introduced and have little to no insulation installed, leaky facades and single glazed windows with U-values of 5.6 W/m^2K. Therefore, the energy performance of these buildings is poor.

The following parameters are kept constant throughout the retrofit scenarios:

- Weather file kept constant as West Scotland
- Wall, floor, roof U-values of each type of dwelling remains unchanged
- Domestic hot water fuel and efficiency
- Occupancy levels of each dwelling are unchanged
- Capacity (represents high or low thermal mass of dwelling)

The main features of the dwellings that are subject to an upgrade are the insulation and air tightness levels, glazing type and heating system. The baseline scenario shows how far building regulations have come and the performance of homes built over the years from 1919, and also compares the energy consumption of similar types of dwellings.

Space Heating Demand Results

The initial simulation run on the HUE tool for the estate calculates the annual space heating demand of the estate. Table 4 below shows space heating demand associated with each dwelling in the estate.

Table 5: Baseline Estate Annual Space Heating Results

Type of Dwelling	Age of Dwelling	Number of Dwellings	Annual Space Heating Demand (kWh/yr.)
Detached	Pre-1919	35	5,107,192
Tenement flat	Pre-1919	70	4,791,605
Terraced	1945-1964	70	4,670,219
Semi-detached	1945-1964	60	3,662,263
Detached	Post-1982	95	5,634,987
Terraced	1965-1982	60	2,889,143
Semi-detached	1965-1982	40	1,804,884
Tenement flat	Post-1982	70	1,885,354
	Total	500	30,415,648

As expected, houses built prior to 1919 (detached and tenement flats) are the worst performing houses within the stock, especially the detached dwellings. These dwellings have high air leakage, little to no insulation and the boiler installed has a low efficiency. The best performing houses were semi-detached homes built between 1965 and 1982 and the tenement flats built post 1982. Again, this was expected due to the fact they were built in times of higher building standards, therefore have improved boiler efficiencies and better building fabric. From the worst performing to best performing dwellings, the space heating requirements per m^2 ranges from 1028 kWh/m^2 (detached pre-1919) and 442 kWh/m^2 (tenement flat post-1982). Independent of the age band they were categorised into, flats were found to have the lowest energy usage per m^2.

Carbon Dioxide Emissions Results

All of the houses in the estate use mains gas as their primary fuel for space heating. Older homes tend to have boilers with low to medium efficiencies whereas more recently built homes have a higher boiler efficiency of around 90%. Table 6 summarises the individual carbon dioxide emissions of each type of dwelling along with the total for the estate.

Table 6: Baseline Estate Annual CO2 Emissions

Type of Dwelling	Age of Dwelling	Number of Dwellings	Annual CO_2 emissions ($kgCO_2/yr$)
Detached	Pre-1919	35	1,011,224
Tenement flat	Pre-1919	70	948,738
Terraced	1945-1964	70	924,703
Semi-detached	1945-1964	60	725,128
Detached	Post-1982	95	1,115,727
Terraced	1965-1982	60	572,050
Semi-detached	1965-1982	40	357,367
Tenement flat	Post-1982	70	367,360
	Total	500	6,022,298

Each of these homes emits more carbon dioxide than the average of 7 tonnes of CO_2 per year found in the 2017 housing survey, therefore, this shows the extent of retrofitting these houses need and the dramatic reductions that need to be achieved.

Operational and Environmental Performance of Estate in Baseline Scenario

The operational and environmental performance of each dwelling in the baseline scenario is quantified in Table # below. The average kgCO2/m2 of the estates dwellings is estimated to be 130 kgCO2/m2/yr, which is far from the Carbon Compliance limit which ranges from 10 to 14 kGCO2/m2/yr, dependent on the type of dwelling.

Table 7: Operational and Environmental Performance of Baseline Estate

Type of Dwelling	Age of Dwelling	Operational performance of dwelling (kWh/m2/yr)	Environmental performance of dwelling (kgCO2/m2/yr)
Detached	Pre-1919	951	203
Tenement flat	Pre-1919	1058	226
Terraced	1945-1964	688	147
Semi-detached	1945-1964	661	137
Detached	Post-1982	418	83
Terraced	1965-1982	535	106
Semi-detached	1965-1982	513	102
Tenement flat	Post-1982	442	87
	Average	**658**	**136**

3.2. Retrofit Scenario 1

This sections covers the fabric upgrades added to the baseline estate. To reach net zero carbon standards, the insulation and air tightness levels must be upgraded to the best possible option. Furthermore, it was determined from these results whether the dwellings met the minimum Fabric Energy Efficiency Standards outlined by the Zero Carbon Hub. Insulation, air tightness and glazing were all improved individually to see results of each then combined together to all the dwellings to analyse the effects.

Space Heating Demand Results

Table shows the percentage reduction when percentages of the estate were retrofitted individually with insulation, air tightness and triple glazing measures and then all of these combined together.

Table 8: Retrofit Scenario 1 – Percentage Reduction in Space Heating Demand

Type of Retrofit				
Percentage of stock retrofitted	Insulation	Air tightness	Triple glazing	All combined
25%	20%	12%	3%	30%
50%	38%	22%	5%	56%
75%	60%	30%	9%	84%
100%	69%	33%	10%	96%

Carbon Dioxide Emissions Results

Since there was no change of heating fuel in this type of retrofit, the reduction in CO_2 emissions is found to be of the same magnitude as the space heating demand reductions.

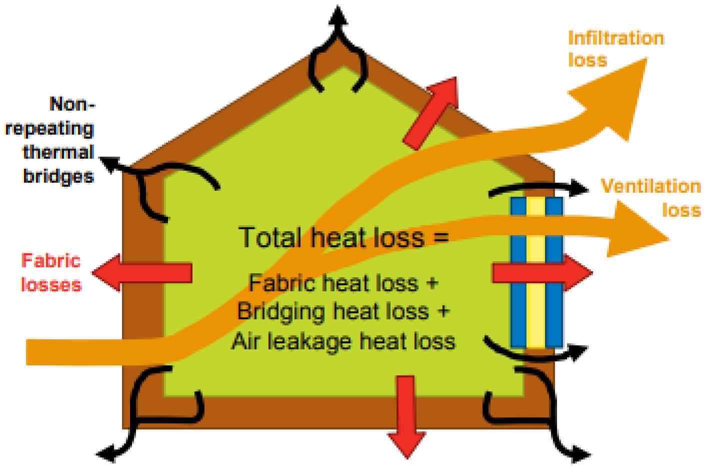
Insulation Upgrade

One of the most effective ways to improve energy efficiency of a dwelling is upgrading or adding insulation to the property. It is expected that an un-insulated dwelling loses a third of all its heat through the walls and a further quarter of heat through the roof. This wasting of energy can have a significant impact on the heating bills of a property, therefore, installing insulation can aid in lowering heating bills and making it more affordable to achieve optimum levels of thermal comfort. Furthermore, insulation is mainly added to a dwelling in loft spaces and by adding materials to the external walls. (Scottish Government, 2018) External wall insulation is considered to be an effective solution to insulating hard to treat properties. This is mainly due to the fact it is not as invasive and disruptive as internal insulation, and also, it is a more feasible option when undertaking the retrofit of several houses. (Energy Saving Trust, 2010)

In the HUE tool, the highest insulation level that could be added is that defined by the AECB Gold standard and Passivehaus guidelines. As can be seen from the results, changing insulation alone to the dwellings is a worthwhile enhancement. Retrofitting 25% of the estate reduces space heating demand and CO2 emissions by almost a quarter. This highlights the impact of changing the worst performing houses of the estate as this reduction comprised of adding insulation only to the dwellings built prior to 1919. In terms of the operational performance achieved by upgrading the insulation of a dwelling, the detached home built pre 1919 went from using 1028 kWh/m2 to 298 kWh/m2, and a better performing home such as a semi-detached built between 1965 and 1982 went from using 513 kWh/m2 to 143 kWh/m2. As more of the dwellings in the estate are retrofitted with high levels of insulation, a reduction of 62% in space heating and associated CO2 emissions is achieved when 75% of the estate is upgraded. In terms of the environmental performance achieved when insulating homes in the estate, the average CO2 emissions per m2 of each dwelling decreases from average of 130 kgCO2/m2/yr in baseline scenario to average of 42 kgCO2/m2/yr once insulation is installed to estate.

Air Tightness Upgrade

Another key area of building energy efficiency that must be considered in order to meet climate change targets is the air tightness of dwellings. It is essential that air leakage is reduced in the building façade in order to reduce overall energy loss and achieve good fabric performance. Air can flow into and out of a property through several ways, which are depicted in Figure 6.



(Energy Saving Trust, 2010)

Figure 6: Energy loss from typical dwelling

Cool external air entering a dwelling is referred to as infiltration, but is most commonly known as draughts. The opposite of this is exfiltration, when warmed internal air leaves the dwelling and is ultimately replaced by the infiltrated cool air. Both of these forms of air leakage causes an increase in space heating demand, and therefore, increases CO_2 emissions. They can occur through gaps and cracks found in the building façade, and unfortunately, they are both uncontrollable and occur continuously. As a result of this, undesired air leakage should be reduced to the lowest possible limit through draught proofing and ventilation with heat recovery. However, draught proofing is more cost effective option out of the two and more suitably applied to the Scottish housing stock. (Energy Saving Trust, 2010)

To upgrade the air tightness of a dwelling, the value used in the HUE tool for low air leakage is 0.6 air changes per hour. As shown in Table #, reducing air leakage alone is not as effective as upgrading insulation alone. To obtain a similar reduction in space heating demand and CO2 emissions, the air tightness has to be upgraded in 50% of the dwellings in the estate compared to only 25% of the dwellings upgraded with high levels of insulation in order to reduce demand by a quarter. Even when applied to the whole estate, only a reduction of 33% is achieved. These low reductions in demand will be due to the fact heat can still be lost through the dwellings' poorly insulated walls. Therefore, it is expected that upgrading insulation and air tightness levels will have a significant impact on the estate's heating demand and subsequent CO2 emissions.

Glazing Upgrade

Heat can be lost through windows, doors and roof of any dwelling, however, by upgrading windows to double or triple glazing, this heat loss can be minimised. Like all building fabric improvements, energy efficient glazing helps retain heat and can contribute to significant energy savings when combined with other building façade upgrades, such as insulation. Therefore, the energy efficiency of double or triple glazing is evaluated in terms of its ability to reduce heat loss through the window pane, and also in terms of how much sunlight and air it allows to pass through the unit. The most important parameter of glazing is the U-value; this value quantifies how the rate of heat transfer through a material. A window glazing with a high U-value indicates that heat passes through the glazing easily and is therefore less energy efficient. (Glass and Glazing Federation, 2019) The ZCH suggests that triple glazing windows be installed to improve energy efficiency, with a U-value of 0.8W/m2K. (Zero Carbon Hub, 2013) So, this is the U-value applied to upgrade the dwellings glazing type in the estate under study.

The older dwellings in the estate have single glazing windows with a U-value or 5.6 W/m2K, whereas the more recently built homes have a U-value of 3.4 W/m2K, indicating double glazing windows. From Table #, it is observed that changing glazing from double to triple has no significant effect to the overall estate, ranging from reduction of 3-10% in space heating requirements. This will also be because in the older dwellings, heat will continue to be wasted through the building fabric and leaky façade, therefore, upgrading to triple glazing windows will not be worthwhile without improving the building fabric as well. Furthermore, the cost of upgrading insulation and air tightness levels are lower than cost of installing triple glazing windows to a dwelling, therefore, it is not cost effective to install triple glazing without improving building fabric also.

Combining Insulation, Air Tightness and Glazing Upgrades

It was found that combining all fabric measures in detached and tenement homes built before 1919 in the estate caused a 30% decrease from baseline estate in space heating requirements and CO_2 emissions. This shows just by changing the worst performing fraction of the stock, a moderate reduction can be made. However, insulation correlates well with increased air tightness and when combined together, along with triple glazing windows, a significant improvement is made to the overall energy consumption of the estate. When half of the stock is retrofitted with all three fabric measures there is a 56% decrease in space heating energy consumption and its associated carbon emissions.

However, when all measures are combined together, significant improvements to the estates overall energy performance is observed. In terms of kWh/m2 of each dwelling and the minimum Fabric Energy Efficiency Standard (FEES) that must be met in order to progress with net zero carbon status, all of the dwellings met this standard except from the ones built before 1919. However, even though they do not necessarily meet the minimum fabric standards to be considered net zero, they originally emit the highest CO_2 emissions and are therefore a priority to retrofit. Moreover, even though the tenement flat built prior to 1919 did not meet FEES standards, it still reached a very low heating demand of 64 kWh/m2.

Rate of Installation

The best outcome of this scenario is an 84% reduction in the estate's space heating demand and associated CO2 emissions when over 75% of the estate (390 homes) are retrofitted with improved insulation, air tightness and glazing. If these retrofits are carried out at a 2% rate (10 homes in estate per year), it will take 39 years to reach 75% target.

If completed at a faster rate of 5%, this means 25 houses in estate will be retrofitted each year and it will only take approximately 16 years to complete retrofits and achieve 84% reduction in demand and CO2 emissions. Hypothetically, if these retrofits began in 2020, retrofits will be completed well before 2050 targets and allows time for other retrofit measures to be installed until 2050.

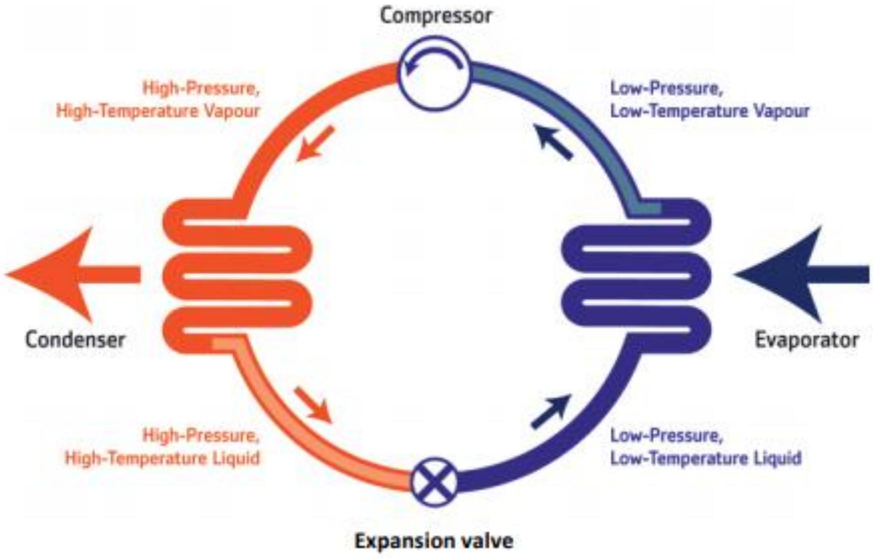
3.3. Retrofit Scenario 2

This section outlines the results of upgrading the heating systems of dwellings in the estate. Air source heat pumps were chosen and input into the HUE estate at medium and high efficiencies. Medium efficiency heat pumps were not worth installing due to very low reductions in energy, and since most of the older dwellings had medium efficiency boilers, it made no difference to the heating demand in most cases. Therefore, only the results of installing high efficiency heat pumps are reported in this study. Furthermore, the tenement flats in the estate are excluded from this investigation as it is unrealistic that heat pumps will be installed in individual flats. As a result, the types of homes broken down into percentages of stock are as follows:

- 25% of stock = detached (pre-1919) and terraced (1945-64)
- 50% of stock = previous dwellings plus semi-detached (1945-1964) and detached (post 1982)
- 75% of stock = all of the previous dwellings plus terraced and semi-detached (1965-1982) (in this scenario this equates to 100% of the stock since the tenement flats are not being considered)

Heat pumps extract low temperature heat from the air outside a building and convert it to higher temperature of air using electricity. It is expected that heat pumps will play a key role in achieving a low carbon future, mainly due to the fact the prospect of a decarbonised electricity supply in the future, possibly from 2030 onwards. Therefore, in this scenario, using electricity to power the heat pump will be one of the lowest carbon heating options available. (Fawcett, 2011)

Many future predictions of reductions in carbon emissions from the housing stock involve implementing LZC technologies which will utilise electricity to provide space heating. Heat pumps, specifically air source heat pumps, use electricity to extract heat from outside air and convert it to higher temperature air which can be used to heat homes. This technology fully utilises the fact that when liquids evaporate, they take in a vast amount of energy (specific latent heat of vaporisation), so when the vapour condenses back into a liquid, all of the energy is released again. Figure # shows the operation of a heat pump in more detail.



(Fawcett, 2011)

Figure 7: Diagram of operation of a heat pump

The efficiency of a heat pump is referred to as the coefficient of performance (COP); this specifies the amount of heat that can be produced per unit of electricity used by the heat pump. (Fawcett, 2011) It is estimated that for every unit of electricity input, heat pumps can potentially produce 4 to 5 units of heat. (Leonardo energy) Actual COP values of air source heat pumps in the UK range from 2.2 to 3. (Narec Distributed Energy, 2013)

Space Heating Demand Results

Table 9 shows the percentage reduction in space heating requirements of estate when heat pumps are installed.

Table 9: Retrofit Scenario 2 – Percentage Reduction of Space Heating Demand

	Type of Upgrade
Percentage of stock retrofitted	Heat Pump

25%	8%
50%	10%
75%	11%
100%	11%

CO_2 Emissions Results

Table 10 outlines the percentage change in CO2 emissions when heat pumps are installed to estate.

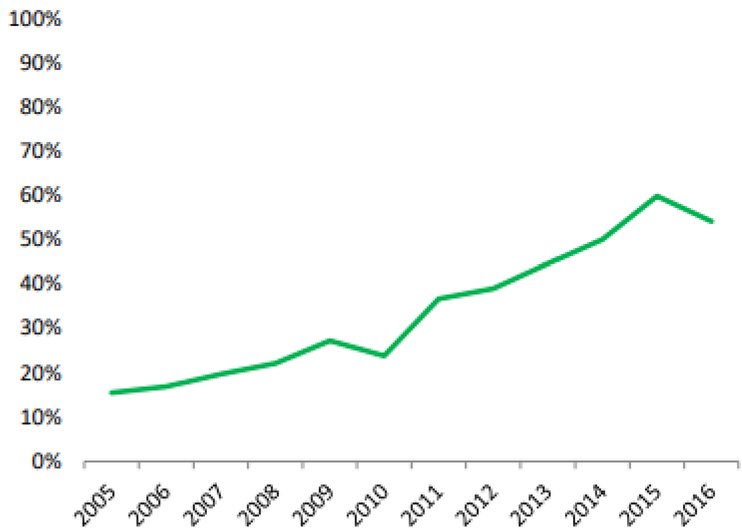
Table 10: Retrofit Scenario 2 – Percentage Reduction in CO2 emissions

	Type of Upgrade
Percentage of stock retrofitted	Heat Pump
25%	-30%
50%	-74%
75%	-95%

When applied to 25%, 50% and 75% of stock, only a reduction of energy by 6%, 7% and 9% in space heating demand is achieved, respectively. Improving heating system without improving insulation and air tightness amounts to wasted energy and capital because heating system will be working at its optimal level but the building fabric will not be able to retain the heat. Furthermore, since the HUE models electricity being generated from the gas grid, there is a surge in CO_2 emissions, shown by the minus values of reductions in Table #. Therefore, the installation of heat pumps will only be beneficial when electricity is totally decarbonised. In order to obtain benefits from heat pump installation, they will need to be installed with fabric measures and installed after 2032, when it is more likely that the grid is decarbonised.

Rate of Installation

From the literature review, heat pump installations are more likely to become prominent after 2030, when it is more likely that the electricity grid has been decarbonised. Figure 8 shows the gross electricity consumption from renewable sources in Scotland between 2005 and 2016. The highest consumption was reached in 2015 (almost 60%) and decreased to 54% in 2016. This shows a rising trend in electricity produced from renewable energy sources.



(Scottish Government, 2018)

Figure 8: Share of renewable electricity in gross electricity consumption in Scotland, 2005 to 2016

Also, it was estimated from the literature review that the rate of installation of air source heat pumps in the UK will be approximately 4%, meaning it will take almost 15 years to install heat pumps to more than half the estate. Since installing heat pumps to 50% of the estate only causes a 10% reduction in space heating requirements, the 2050 climate change targets will not be met utilising heat pumps alone, even though they could theoretically be installed before 2050.

3.4. Retrofit Scenario 3

This section investigates the effects of combining fabric measures with a heat pump system. Again, flats were not included in this scenario therefore the same fractions of stock retrofitted are the same as the previous sections. It is determined from these results whether the dwellings in the estate meet their associated Carbon Compliance limits outlined by the ZCH. The combinations are based on the results found previously when upgrading the fabric and heating system and three scenarios were chosen to be investigated:

1. insulation upgrade with heat pump installation;
2. insulation and air leakage upgrading with heat pump installation; and
3. insulation, air leakage and window triple glazing upgrading with heat pump installation.

Space Heating Demand Results

Table 11 outlines results when combinations of fabric and heating system upgrades are applied to the estate under study.

Table 11: Retrofit Scenario 3 – Percentage Reduction in Space Heating Demand

Type of Upgrade			
Percentage of stock retrofitted	Insulation and heat pump retrofit	Insulation, air tightness and heat pump retrofit	Insulation, air tightness, triple glazing and heat pump retrofit
25%	27%	30%	30%
50%	46%	60%	61%
75%	58%	75%	76%

CO_2 Emissions Results

Table 12 highlights associated CO_2 emission reductions when combinations of upgrades are applied to the estate.

Table 12: Retrofit Scenario 3 – Percentage Reduction in CO2 Emissions

Type of Upgrade

Percentage of stock retrofitted	Insulation and heat pump retrofit	Insulation, air tightness and heat pump retrofit	Insulation, air tightness, triple glazing and heat pump retrofit
25%	11%	30%	30%
50%	21%	57%	58%
75%	27%	71%	72%

Insulation combined with Heat Pump

It is observed from the results that substantial energy savings can be produced by installing this retrofit combination to 50% and 75% of the estate. However, the CO_2 emission reductions are half of the space heating demand reductions; even though high reductions were observed when insulation only was applied to the estate in Retrofit Scenario 1, the high CO2 emissions from using electricity from gas grid simulated by HUE cancel out the benefits of adding insulation. The environmental performance of the dwellings ranges from 50 $kgCO_2/m^2$ (best performing dwellings) to over 100 $kgCO_2/m^2$ (worst performing dwellings), and therefore, do not meet the Carbon Compliance limit.

Insulation, Air Tightness and Heat Pump

Including high air tightness levels to insulation and heat pump combination triples the reduction in CO_2 emissions across the estate. For this combination, only two of the types of dwellings in the estate reach their associated Carbon Compliance limit – detached home built post 1982 and terraced house built between 1965 and 1982. Most recently built dwellings benefit more from this combination than the older houses in the estate, as there is only a 26% reduction in space heating demand when applied to dwellings built prior to 1919 and only 10% reduction in estate CO_2 emissions. When 50% of stock is retrofitted, 60% reduction in energy demand is achieved along with 57% reduction in CO_2 emissions. If this was applied to whole Scottish housing stock, it would be very beneficial.

Insulation, Air Tightness, Glazing and Heat Pump

The results of this combination of upgrades differs only by approximately 0.3% from previous results stated, for both space heating demand and CO2 emissions of estate. Therefore, it can be concluded that adding triple glazing in this situation will not be cost effective in this situation and the impact of installing triple glazing windows is negligible when combined with other energy efficiency retrofits.

Rate of Installation

Similar to previous results, fabric upgrades must be installed at rate of 5% from now until approximately 2035, then heat pumps installations must be installed after 2030 at rate of 4%, in order to reach 2050 reduction targets in time.

3.5. Retrofit Scenario 4

This section investigates the feasibility of the estate reaching net zero carbon emissions by implementing a solar photovoltaic (PV) panels on the roofs. The extreme low carbon technology approach outlined by ZCH which aims to reach net zero carbon standard through the use of only fabric and LZC installations is applied here. The optimum result of combination of retrofits is chosen and solar PV is applied to each dwellings retrofitted to assess whether there is enough roof area to generate the dwellings required space heating demand. The retrofit scenario chosen for solar PV installation is combining insulation, air tightness and heat pump retrofits to 50% and 75% of the stock. This was chosen as it produces the greatest reduction in space heating and CO2 emissions from the above scenarios.

Most domestic solar PV installation involve adding several solar panels to a south facing roof, ranging from 2 to 16 panels depending on the size of the roof area and the energy demand of the dwelling. (Energy Saving Trust, 2015) In the UK, it is expected that 1 kW of PV panels can produce between 700 and 900 kWh of electricity per year. However, as expected with UK weather conditions, it is not sunny all the time, therefore, the energy generated by the panels will be lower on cloudy days, when there is little direct sunlight. (Centre for Alternative Technology, 2019) Most domestic properties have solar panel systems ranging from 1 kW to 4 kW capacity in the UK, and again, the size of system required is dependent on roof area of dwelling and energy demand.

Table 13 is a sizing guide for domestic solar PV systems in the UK applied to types of dwellings.

Table 13: Solar PV System Sizing Guide

House Type	Typical suitable roof area (m2)	Appropriate number of panels	Power rating (kW)
Period mid-terrace or end terrace	16.5	10 panels (16m^2)	2.2
Average semi-detached house	20	12 panels (19.2m^2)	2.6
Average detached house	29.5	18 panels (28.8m^2)	4.0

(Energy Saving Trust, 2015)

Retrofit Scenario combined with Solar PV System

Using the values in Table 13, the estimated size of solar panel system required for the retrofitting 50% of the dwellings in the estate can be estimated. A range was estimated using the assumption that a 1kW system will produce between 700 and 900 kWh of electricity per year.

Table 14: Retrofit Scenario 4 – Number of Solar PV Systems Required for Dwellings in Estate

House in estate	Number of houses	Space heating demand	Power rating (kW)	Lowest possible generation	Highest possible generation	Number of Solar PV systems	Number of Solar PV systems

	in estate	(kWh/yr)		(1kW = 700kWh) (kWh/yr)	(1kW = 900kWh) (kWh/yr)	required (low generation)	required (high generation)
Detached (pre-1919)	35	111,755	4.0	2,800	3,600	40	31
Terraced (1945-1964)	70	160,650	2.2	1,540	1,980	104	81
Semi-detached (1945-1964)	60	158,700	2.6	1,820	2,340	87	68
Detached Post 1982	95	184,490	4.0	2,800	3,600	65	51

If there are more systems required than number of houses, then net zero carbon emissions for that particular type of dwelling cannot be achieved. The detached house type built before 1919 could potentially be net carbon throughout the year, most likely when there is more direct sunlight, as for 35 homes the range of systems numbered between 31 and 40. The 95 detached dwellings built after 1982 only require between 51 and 60 4kW systems to produce total space heating demand, therefore, net zero carbon can be achieved for these dwellings in the estate. Furthermore, the terraced and semi-detached homes (1945-1964) require more solar panel systems in order to produce the overall heating demand, and can therefore, not reach net zero carbon emissions. These homes will have to undergo further energy efficiency upgrades in order to reduce heating demand to an appropriate value which 2 kW solar PV systems can accommodate to, as it is not possible to increase the roof area of a dwelling.

Rate of Installation

From the literature review, it was estimated that solar panel systems must increase to a rate of 7% in order to reach 2050 targets. Therefore, after installing fabric and heating systems upgrades to 50% of the estate, which will take until 2035 approximately, it will take a further 10 years to install solar PV systems. Moreover, even though most of the dwellings could not achieve net zero carbon emissions, solar panels can still be added to dwellings in order to reduce the dwellings dependency on electricity or gas grid, and hence, reduce CO_2 emissions further.

4. Discussion of Results

In Retrofit Scenario 1, where fabric upgrades only were applied to the estate, the most effective fabric improvement installed was increasing insulation levels. When 75% of the estate was insulated to the maximum level, there was a 62% reduction in space heating demand. Since the estate represents the most common houses in Scotland, and make up 54% of the total housing stock, this equates to 41% of whole stock being retrofitted resulting in a 33% reduction in space heating demand. Increasing levels of air tightness to the dwellings was found to be most effective when implemented with insulation rather than on its own, and the same applies to upgrading windows to triple glazing; the maximum reduction in energy usage was 13% and this was assuming that all of the houses in the estate are upgraded with triple glazing. Also, glazing upgrades commonly costs more than improving insulation and air tightness, and so, it was concluded that it was not a cost effective energy efficiency measure.

An extreme fabric approach was investigated when insulation, air tightness and glazing were all improved at the same time. This approach resulted in 75% of the estate attaining fabric standards set out by ZCH, and thus achieving half of the requirements needed to reach net zero carbon status (note that Allowable Solutions was not included in this study). Furthermore by retrofitting 75% of the estate in this manner, it resulted in an 84% reduction in space heating requirements of total estate, which equates to a 45% reduction in space heating of total Scottish housing stock.

Furthermore, it was estimated that at least a 5% rate of retrofit per year should be adopted in Scotland in order to reach 2050 target of reducing overall emissions by 80%. However, current rates of retrofit in Scotland at the present time fall short of this, therefore, there must be reductions in costs of retrofit measures and improvement of energy efficiency policies and programmes in order to see an increase in this rate. Also, it is clear that extreme fabric upgrades are a vital first step in reducing carbon emissions of the Scottish housing stock, and therefore, government policies should focus on this approach in forthcoming years.

For the second retrofit scenario, these results highlighted already existing presumptions that installing heat pumps on their own to a dwelling will not be as effective without implementing upgrades to the building fabric also. Heat pumps will play an essential role in decarbonising heating supply to buildings in the future but only if the electricity grid is eventually decarbonised. It is estimated that this may be achieved after 2030. The benefits of installing heat pumps can only be fully utilised when electricity is decarbonised and fabric upgrades are applied to the dwelling as well.

Retrofit Scenario 3 explored the impact of combining fabric upgrades and heating system upgrades to the dwellings in the estate. The combination of improving the insulation and installing a heat pump reduced the space heating requirements by considerable amounts but did not have the same effect on the CO2 emissions. Therefore, it was not considered to be a viable option to achieve net zero carbon standard. Improving the insulation and air tightness levels, along with installing a heat pump to the dwellings was found to be the most effective retrofit combination as there were significant reductions achieved in both space heating demand and subsequent CO_2 emissions. When this combination was applied to 75% of the estate, there was a reduction of 75% in space heating and 72% in CO_2 emissions. This equates to 41% of the total housing stock being retrofitted in this manner and achieving a 41% in reduction of space heating and approximately 38% reduction in CO_2 emissions from whole Scottish housing stock. As a result of this, this was deemed the best combination of retrofit measures.

Finally, in Retrofit Scenario 4, the feasibility of retrofitted homes in the estate reaching net zero carbon emissions was assessed. The combination of measures chosen to undergo solar PV installation was insulation, air tightness and heat pump retrofits applied to 50% of the estate. It was observed that the larger dwellings which had more available roof space to install a solar PV system with higher power rating (4kW) can reach net zero carbon emissions, as the number of systems required to meet all the detached houses heating demand was less than the number of detached type dwellings. However, dwelling types such as terraced or semi-detached required more solar PV systems than the number of available dwellings to install these systems on. Essentially, more solar panels were required in order to balance supply of electricity to dwelling demand. Therefore, these dwellings will need to undergo more retrofitting measures in order to reduce their heating demand. Detached dwellings make up 25% of the estate, which equates to roughly 14% of the total Scottish housing stock, therefore, 14% of housing stock could potentially be net zero by 2050.

Furthermore, it is clear that the whole Scottish housing stock will not reach net zero carbon standards by 2050 after the implementation of both fabric upgrades and LZC technologies such as heat pumps and solar PV systems. However, the Climate Change Plan aims to have buildings near zero carbon by 2050, and from the results shown, this could be achieved using one or more of the strategies outlined in this project. Moreover, the Climate Change Plan also aims to specifically reduce domestic heat demand by 23% by 2032, and this would most definitely be achieved even by implementing an extreme fabric upgrade approach alone.

5. Future Work and Recommendations

It has been highlighted in the previous sections that enhancements to the building fabric, in particular, the insulation, air tightness and glazing types, can reduce space heating demand of a dwelling based on its ‘as built’ energy performance. However, it has not been evaluated whether or not the application of these retrofit measures achieve the optimum thermal comfort within the dwellings. Therefore, further work could include applying these retrofit scenarios to models in ESP-r and assessing the thermal comfort and indoor air quality of the houses. ESP-r will allow user to analyse the performance of the dwellings throughout the seasons of the year, and check whether the dwellings are likely to overheat in the summer or not.

Another recommendation would be to add Mechanical Ventilation with Heat Recovery (MVHR) to analyse the impact on the energy usage and CO2 emissions of the dwellings, and whether or not, with the installation of this system, net zero carbon emissions could be achieved once solar PV systems are added. Finally, it is recommended that when applying retrofit measures to a housing stock, that a building simulation tool always be used first in order to analyse the effects of the installations before installing them in a home.

6. Conclusions

To conclude this project, a suitable approach for retrofitting the current Scottish housing stock to net zero carbon by 2050 was achieved, however, only a small percentage of the housing stock was able to accomplish net zero carbon emissions. By exploring different retrofitting scenarios applied to the estate under study, the most optimum combination of energy efficiency measures were determined to reduce space heating requirements and associated CO_2 emissions. A broad literature review was carried out which evaluated the state of the current Scottish housing stock, the criteria required for achieving net zero carbon emissions in homes including approaches, and past and present retrofit measures carried out in Scotland and the government policies and programmes related to them. The rate at which retrofits are carried out was also investigated.

An estate model consisting of the most common house types found in Scotland was comprised and the HUE tool was utilised to examine alternative approaches to retrofitting the estate in terms of energy usage and emissions reduction. The baseline estate outlined the energy performance of the dwellings as built, and as expected, it was found that the majority of buildings were inefficient as they were built before energy efficiency measures were introduced to dwellings. This was mainly due to having poorly insulated and leaky facades which encourages heat loss through the building fabric and low to medium efficiency gas boilers installed to heat the homes.

Therefore, to improve the performance of the houses in the estate, enhancements were made to the estate model and simulations were run. It was found that changing the building fabric, in particular improving the insulation levels caused the greatest reduction in space heating requirements, followed by improvements to air tightness and then installing triple glazing windows, which did not contribute any significant energy savings to the estate. Installing heat pumps to dwellings in the estate only proved to be efficient when combined with building fabric upgrades, the most optimum and cost effective result being insulation and air tightness upgrades combined with heat pump. Triple glazing costs the most out of the three fabric improvements explored in this project, and since it only reduced the space heating requirements slightly, it is not a worthwhile investment to the Scottish housing stock as a whole.

Once an optimal combination of measures was defined and applied to a percentage of the estate, solar PV systems were installed on each type of dwelling in order to assess whether net zero carbon emissions could be achieved. It was found that only the detached dwellings achieved this target, therefore, the other dwellings will have to undergo further energy efficiency measures, such as MVHR in order to reduce energy demand to a level that a typical PV system can generate enough energy for.

Furthermore, the rate at which all these retrofits are applied to the Scottish housing stock must be increased to at least 5% of stock per year in order to reach 2050 climate change targets. Although net zero carbon emissions was the aim of this study, the Climate Change Plan set outs that buildings should be as close to net zero carbon, wherever feasible by 2050. Therefore, as can be seen from the significant reductions in space heating demand and corresponding CO2 emissions, the strategies outlined in this project is more than capable of achieving this less ambitious aim. Overall, if further reductions are made to the stock which cannot achieve net zero emissions through the strategies outlined in this project, and the electricity grid is completely decarbonised after 2030 when heat pumps are proposed to be installed in higher numbers, the Scottish housing stock will likely to attain net zero carbon emissions by 2050.

7. References

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