Department of Mechanical and Aerospace Engineering

Techno-economic analysis of energy efficiency and renewable energy technology retrofits to a high rise social housing apartment block in Glasgow

Author: Agris Baumanis

Supervisor: Dr. Paul Tuohy

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Abstract

The energy efficiency and low carbon technology retrofits in the domestic sector will play a crucial role into achieving the ambitious CO_2 reduction targets of the Scottish government. Additionally, in order to decarbonise the heat, the current rate of uptake of the LZCGT technologies need to be accelerated.

The aim of this paper was to analyse the feasibility of retrofit measures that could lead to compliance with the strict EnerPHit standard. By using the dynamic building simulations tool IESVE, a combination of building fabric, LZCGT and air quality measures were applied to a high rise apartment block in Glasgow.

The modelled energy consumption, resulting GHG emissions and cost efficiency was compared and evaluated in order to recommend a solution that could meet the compliance of EnerPHit standard.

The key results indicated that a combination consisting of significantly improved external wall, roof and window thermal resistance, can reduce the heating demand below 25 $kWh/m^2/y$. Although, this lead to significantly increased frequency of overheating and excessive humidity. Both, of these issues can be eliminated by implementation of a MVHR system.

Furthermore, the results presented a strong case for supplying the heat by using ASHP or GSHP in order to significantly, in a cost efficient way reduce the GHG emissions as well as tackle the fuel poverty issues. Finally, due to limited available surface area, the building integrated PV system, achieved high on-site consumption.

Acknowledgements

I would like to thank my supervisor, Dr. Paul Tuohy, for his guidance in the completion of this thesis and this study course. Furthermore, I want to thank my boss, Keith Kemsley, for giving me the flexibility at work that allowed me to pursue this degree, whilst being full time employed. Lastly, I want to thank everyone who was exposed by my continuous over exaggerated stress levels regarding the submission deadlines.

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1. Introduction

Although, impressive deep retrofit designs have been developed and pilot projects executed achieving even the strict EnerPHit standards, there is no any widely used streamlined approaches or solutions that could be applied for the high rise apartment blocks retrofits in Scotland. Therefore, this paper will evaluate the possible energy efficiency retrofit solutions for a high rise residential tower block in Glasgow, Scotland with the aim to meet EnerPHit standards.

This chapter will give the relevant background of the problem, set out the aim, main objectives and research question of this paper as well as describe the methodology and approach allowing to meet this goal.

1.1. Background

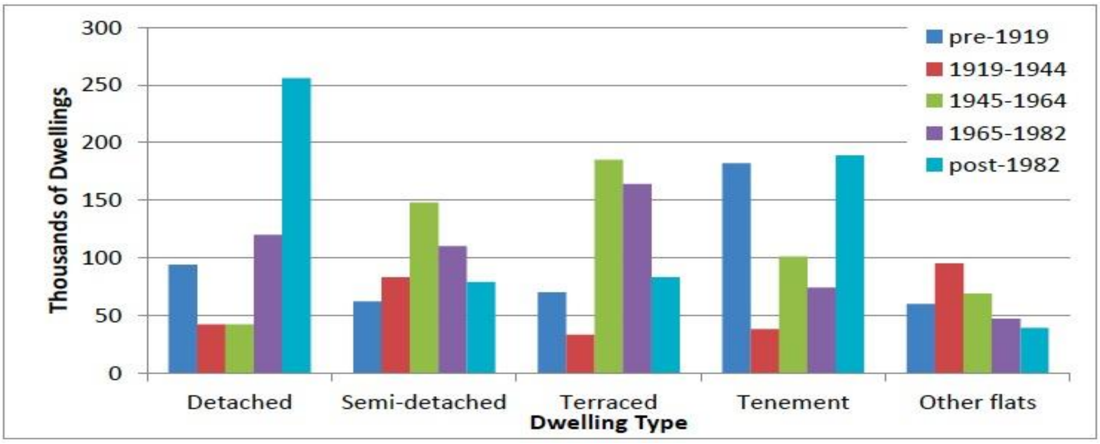
According to Paris Climate Change Agreements, the majority of the nations of the world, including UK, have committed to reduce the greenhouse gas (GHG) emissions down to 45% of 2010 levels by the end of next decade (UN Climate Change, 2019). The recent wide-spread Declaration of Climate Emergency at national and local levels furthermore aggravated the need for immediate action. In response, the Scottish Government announced ambitions plans to become net-zero energy by the end of 2045 (Scottish Government, 2019).

Residential buildings in the UK are some of the oldest in the developed world where domestic sector is responsible for almost one third of the total energy consumption. Majority of the energy (80%) is spent for space and water heating, therefore, there is a significant potential of reducing GHG emissions by improving energy efficiency and carbon intensity of UK building stock (UK Government, 2018). Majority of the residential property that will be used in year 2050 are already built, therefore, the energy efficiency retrofitting will play a significant part in tackling the emission reduction targets. This has led to the development of a number of low energy building standards.

With the current progress and speed of retrofitting across the European Union, it is highly unlikely that the EU will achieve the 2050 emission targets. Additionally, existing unsystematic and partial measures are not adopted at the scale even for the 2020 policy objectives. In UK alone, an estimated 2 million heat pumps by 2025 and 15 million by 2035 will be required to meet the net zero emission target by 2050 (Imperial College London, 2019).

Fuel poverty rates are still unduly high in Scotland, where nearly 1 in 4 of households meets the definition of fuel poor (Scottish Government, 2017). However, large-scale renewable generation does not reduce fuel poverty because residents still have to pay for their imported energy. Moreover, majority (85%) of high rise apartment blocks, usually built for social housing purposes, were built in the period from 1945 to 1982 (Figure 1).

Figure 1 Scottish Dwellings by Age and Type in 2017 (Scottish Government, 2018).



By prioritising energy efficiency retrofits for these apartment blocks, social landlords could rapidly tackle the fuel poverty issues, reduce the GHG emissions as well as future proof their assets.

1.2. Problem statement

Inefficient residential housing stock in Scotland results in excessive GHG emission and high fuel poverty rates. To tackle this, a rapid increase in scale and quality of the building retrofitting to a low energy standards is required. The lack of clear retrofitting solutions for high rise apartment blocks is slowing down the progress in reaching the Climate Change targets as well as elimination of fuel poverty.

1.3. Project aim and objectives

Aim

Despite the government`s efforts, the household quality and resulting building related GHS emission and full poverty situation is still poor in Scotland. Therefore, there is a demand from large scale landlords to look for solutions to tackle the fuel poverty, meet the ever changing standards energy efficiency and future-proof their assets. By using a high rise tower block in Glasgow, Scotland as a case study, this paper seeks to examine feasibility of multiple energy efficiency and RE technology retrofitting solutions as well as the possibility to meet EnerPHit standard. The research will be conducted by running computational simulations using IESVE in order to evaluate and compare chosen retrofits which could potentially lead to compliance of EnerPHit standards.

Objectives

The main objectives of this paper are:

1. To **research** the background of the domestic energy demand in Scotland and current situation regarding the fuel poverty as well as the policy environment.
2. To **investigate** the current industry practice as well as the state of the art solutions and technologies allowing to achieve low or net-zero energy efficiency standards such as EnerPHit.
3. To **model** a high rise tower block using IESVE building simulation software and select and **simulate** potential retrofit solutions and their performance.
4. To **calculate** the estimated costs and savings for viable solutions and **compare** and **analyse** the results.
5. To critically **evaluate** and **discuss** the findings in order to be able to **conclude** and **recommend** a solution.

1.4. Scope

The limited time, volume, software capabilities and lack of available measured consummation data lead to necessity to limit the scope of this paper.

1. The focus will be on Scotland and high rise apartment blocks.
2. Most of the input values for the simulation will be taken from relevant UK regulations and industry practice.
3. Solely the electric energy conversion technologies will be considered.
4. No conventional energy supply systems will be evaluated (no gas grid or Fuel Poor Network Extension Scheme available).
5. Focus will be only on fabric efficiency, and space and water heating demand reduction. All internal gains from lightning, occupancy and equipment will not be kept the same in all models.
6. Neither mechanical nor MVHR will be considered.
7. The practical feasibility of installation will be considered only at surface level.
8. No wiring or plumbing schematics will be designed for any of the systems.
9. For the current system, the storage heaters and off peak immersion water heater will not be modelled, instead direct electric panel heaters and direct electric immersion heater will be used.
10. Only approximate capital investment costs will be calculated. Values obtained from the online sources and from companies in the industry.
11. Only Renewable Heat Incentive subsidies will be applied. No other potential zero interest loan or funding scheme will be applied.
12. Only financial metric used to analyse potential solutions will be cost efficiency regarding the CO_2 emission reduction.
13. The IESVE *Apache* thermal calculations and simulation module instead of *ApacheHVAC* system simulation interface module was used.

1.5. Methodology

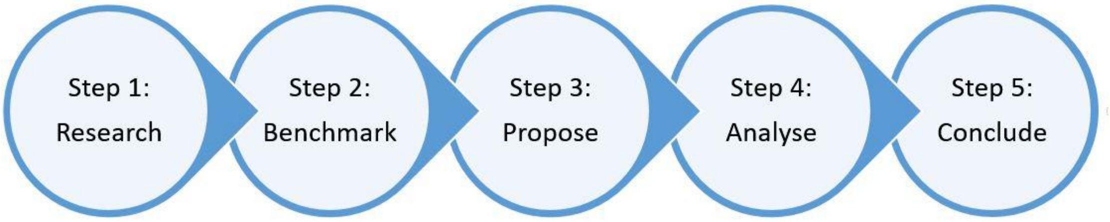
This paper used a deductive (top-down) modelling approach to investigate the techno-economic feasibility of low energy retrofit for the Scottish housing stock. The author explored the known theory and existing practice, to be able to formulate a hypothesis, and test if it applies in the used case study.

The author will use quantitative data generated by this study to confirm or reject the following hypothesis:

“EnerPHit deep retrofit of high rise residential buildings can be achieved in an economically viable way whilst significantly reducing the CO_2 footprint and running costs of the building”.

Following steps will be taken to confirm or reject this hypothesis (*Figure 2*):

Figure 2 The main steps of this paper.



Step 1:

Undertake focused and critical review of available literature to establish the theoretical background for the problem and potential solutions.

Due to rapid development in last decade in the RE industry, peer reviewed journal articles from last 5 years were prioritised. Additionally, articles and reports released by UK and Scottish government bodies and relevant international NGOs were also used for the review. For the industry best practice and case studies some grey literature and articles from commercial sites were used.

Step 2:

Create a baseline model in IESVE by using a tower block in Glasgow as a case study.

To be able to evaluate the feasibility of proposed energy efficient retrofits a representative and accurate base (benchmark) model is necessary. This will allow to estimate the energy savings, achieved level of GHG reduction as well as economic viability.

The baseline model was based on a real 8 storey residential property in Glasgow. Up to scale layout drawings, obtained from the *Turner Property Services Ltd*, are used as an input in the high-resolution building energy simulation program IESVE. *Apache* thermal analysis program was used as simulation engine. No measured consumption data was available. Therefore, building envelope thermal properties, heating and

DHW system`s set points and targets as well as the behaviour patterns were based on standardised input values from CIBSE Domestic Heating Guide and BS EN 12831-3:2017 (CIBSE, 2017), (British Standards, 2017).

The thermal conditioning system is only capable to deliver space and DHW heating. Cooling is not prevalent in the existing property as well as due the weather historically. The air conditioning systems are not prevalent in domestic properties in Scotland.

To verify the model, separate elements of the simulation results were inspected. Annual, and both extremes, coldest and warmest days were inspected and analysed to see if the outputs are rational and adequate.

To validate the model, two alternative methodologies using the exact inputs, where possible, were used to determine the energy needed for space and DHW heating. First, an Energy Performance Certificate (EPC) for each of the flat types was created by using RdSAP software. Second, an equivalent heat loss calculation was conducted using the methodology described in CIBSE Domestic Heating Guide.

Step 3:
Select, describe and apply potential retrofitting solutions to the base model.

Based on the literature review, multiple retrofitting options was proposed and applied to the base model to simulate the level of improvement on following indicators:

a) Energy demand for heating and hot water (kWh/year);
b) Specific heating demand (kWh/m²/year);
c) Relative cost of CO_2 reduction (£/kg of CO_2);
d) Overheating and excessive humidity frequency (% of annual hours) and Primary Energy Demand (kWh/m²/y) for EnerPHit compliance.

As the GHG emissions are considered to be as important as the energy consumption and running costs, the evaluation of the feasibility of a retrofit compared the cost efficiency of CO_2 reduction measures.

Step 4:
The achieved improvements on the indicators will be analysed and evaluated to provide the best solution from proposed ones.

Step 5:
Self-reflective and critical discussion of what was achieved, limitations, recommendation and suggestions for the future work are included as well as the main conclusions.

The significant amount of research available for this topic as well as the short time designated for this study makes a deductive approach more suitable. Moreover, due to the lack of primary data, computational simulation based approach better allows to generate the required data for analysis and recommend a system that can meet the requirements.

Main strengths of the chosen software based experimental approach are seen in the ease to experiment with every parameter affecting the energy demand and thermal comfort of a building in a relatively short time period. Additionally, we also recognized the ease of producing high resolution outputs for analysis.

However, the lack of real life measurement data, use of standardise input parameters, and subjective interpretation can lead to inaccuracies and oversimplifications. Moreover, the results and conclusions are vulnerable to the selection, observer, confirmation and many other biases of the author.

1.6. Structure

Chapter 1 introduces with the background of the problem, describes the aim and main objectives of this paper, and the methodology that will allow to answer the research question.

Chapter 2 presents a focused review of the relevant literature. The background of domestic heating load and resulting fuel poverty in Scotland is explored. Research of the UK policy, building standards as well as rating systems affecting energy efficiency and GHG emissions were conducted. Additionally, the research of the state of the art retrofitting practises, case studies and potential technologies were conducted. And lastly, a brief look was taken into the software used for the dynamic simulation and its verification and validation.

Chapter 3 introduces the base model used as a case study for this paper. The main assumptions and simplifications applied to the input variables as well as some limitations of the IESVE are listed. Furthermore, a detailed look was taken into the actual inputs used for the base model simulation – the weather data, dimensions and heating and hot water related parameters. The main outputs of the base model are listed and analysed, therefore, allowing to propose the potential retrofit solutions. Lastly, the simulated energy demand is validated by using CIBSE and RdSAP calculation methodology.

Chapter 4 contains the main body of results, describes and analyses the performance all retrofit solutions applied to the base model. Additionally, the capital, operational costs and Renewable Heat Incentive income is calculated. The relevant outputs are compared and recommended solution is identified. The final tweaks to the recommended model is applied upon executing the analysis of the worst performing indicators. The final results, compliance with EnerPHit standard and the hypothesis is partially confirmed and commented.

Chapter 5 presents a discussion on the key findings of this paper. Moreover, discusses the extent to which the aim and objectives of the thesis were met. Lastly, suggestion for a potential future work that should be undertaken is discussed.
Chapter 6 lists the main conclusions and key takeaways of the paper.

1.7. Summary

Chapter 1 has presented the background of the project topic, the problem statement as well as the aims and main objectives of this paper. Therefore, allowing to develop the necessary methodology that will allow to answer the research question. Furthermore, the structure of this paper is briefly presented to the readers.

2. Literature review

To achieve the first two objectives, a focused literature review was conducted to examine the topics surrounding the research question as well as potential, state of the art solutions of the problem. The rapid development of the renewable industry in last decade can make five years old article our legislation outdated and irrelevant, therefore, the emphasis was put on the latest literature and research available.

The literature review was organised in following structure:
First, the scale and significance of the domestic heating load in UK were established, setting the background of the research question. Second, the current situation and consequences resulting from the inability of meeting the domestic heating demand - fuel poverty in Scotland were investigated. Third, relevant policies, standards and rating systems affecting energy performance of buildings and resulting heat demand were reviewed, allowing to define the level of reduction that should be achieved to meet the EnerPHit standards. Fourth, the review of building retrofitting as means of reducing the energy demand and therefore tackling the fuel poverty directly was conducted. Some case studies of existing practice were investigated. Fifth, the potential technologies that could be used for retrofitting were identified.

2.1. Background

2.1.1. Domestic heating load

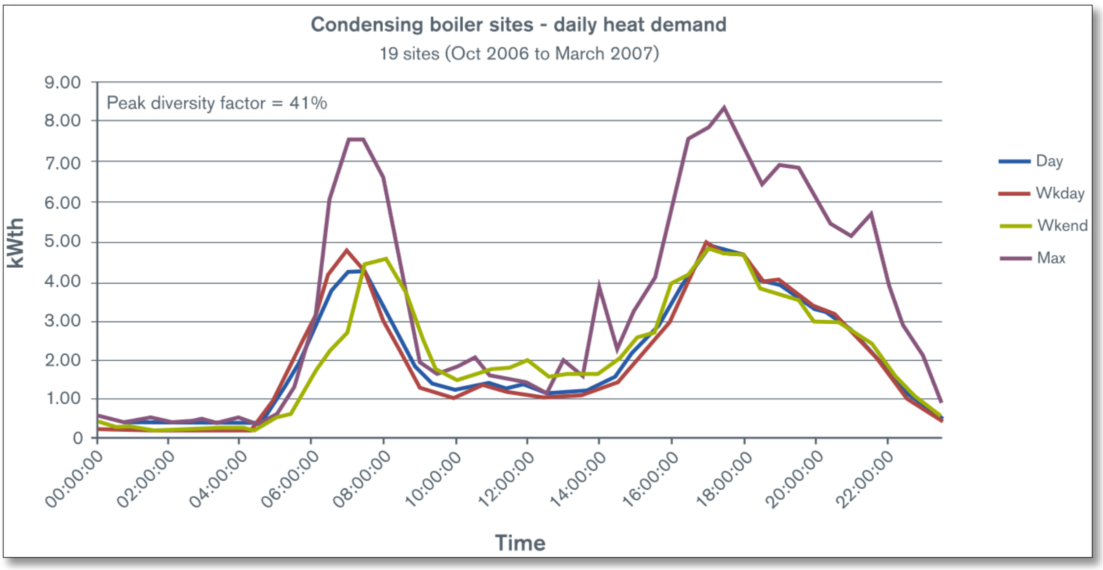
According to United Nations Environment Programme Report, over the lifespan of domestic buildings, for construction, operation and maintenance globally consumes around 40% of the total energy and is responsible for 33% of all CO_2 emissions. By using currently available knowledge and technology, this sector has the greatest potential to achieve significant reductions in GHG emissions (United Nations Environment Program, 2010).

The final energy consumption of the UK Domestic Sector in 2017 accounted for 28% of total final energy consumption in the UK. The space and water heating is accountable for 80% of this total domestic energy consumption in the country. This consumption is directly correlating with the fluctuations in temperature and weather patterns. For example, due to a milder winter in 2016, the total consumption in 2017 dropped by 3.7 % (UK Government, 2018).

The UK housing stock, being amongst the oldest in the developed world, is also one of the least energy efficient (Stafford, et al., 2011). The improvements in building fabric energy efficiency for new builds and retrofits, low and zero-carbon technology and energy efficient appliance use as well as changes in awareness and consumer behaviour have immense potential to reduce domestic energy consumption and GHG emissions. (Burford, et al., 2019).

To be able to improve on the system, the current state has to be identified. The Ofgem (2016) estimated peak heat demand in UK around 300 GW. Figure 3 illustrates the high peak diversity factor of 41%.

Figure 3 Heat demand profile for gas condensing boiler. Source: Robert Sandsom (2014)



However, a recent study shows significantly lower figures. Watson & Buswell (2019) used a measured, half-hourly gas consumption data collected in 2009 and 2010. This data was collected from over 6000 smart gas meters in Great Britain and it allowed to model half-hourly national domestic heat demand. Depending on the annual ambient temperature, resulting peak domestic heat load ranged from 159 GW to 170 GW. Existing national heat models were developed from a much smaller sample of properties as wells as shorter time period. Additionally, the new model varies accordingly with the ambient air temperature, thus, making this model more rigorous. The authors point out that the demand profile on cold days was much flatter than in previous models, therefore, the predicted peak demand is 40% lower than in previous estimations. Hence, the UK Clean Growth strategy - electrification of heat may be achieved more easily than previously assumed.

2.1.2. Fuel poverty

Due to increasing energy costs and inefficient dwellings, fuel poverty is becoming more widespread social issue. Therefore, tackling fuel poverty has become a key concern in Scotland's renewables policy (Scottish Government, 2017).

The fuel poverty threshold in Scotland is based on Brenda Boardman`s definition which is included in *The Scottish Fuel Poverty Statement*:
“A household is in fuel poverty if, in order to maintain a satisfactory heating regime, it would be required to spend more than 10% of its income on all household fuel use. If over 20% of income is required, then this is termed as being in extreme fuel poverty” (Scottish Government, 2002). This statement dictated that the fuel poverty has to be eradicated by November 2016. However, according to the *Scottish House Condition Survey*, in the 2017, still more than 600 000 or nearly 1 in 4 of households in Scotland met this definition and 174 000 or 7% met the extreme fuel poverty`s definition. Currently, this definition is under review by Scottish government to include wider assessment of vulnerability to fuel poverty and its impacts (Mould & Baker, 2017).

Morrison and Shortt (2007) in their paper present a novel method for clarification of the Scottish Fuel Poverty Indicator. The authors propose to use GIS to combine the census data with geo-referenced energy efficiency data on local housing stock. Therefore, this allowed for highlighting small areas and households that may be susceptible to fuel poverty, which previously was not included in the official numbers (Morrison & Shortt, 2008).

The *Winter Mortality in Scotland 2017/18* report indicates that there is a link between fuel poverty and increased winter mortality or excess winter deaths and that increased winter mortality is associated with low indoor temperatures. (National Records of

Scotland, 2018). To escape the fuel poverty, the occupants must be able to afford to maintain following indoor air temperatures: “For vulnerable households, 23°C in the living room and 18°C in other rooms. For other households, 21°C in the living room and 18°C in other rooms” (Scottish Government, 2017).

Current fuel poverty discourse in the UK points that the vulnerable groups are disproportionately affected by the three main distributional injustices – low incomes, high costs of energy and inefficient housing (Gillard, et al., 2017). However, state of the art literature indicates that the occupant behaviour is the fourth driver of fuel poverty. Kearns et al (2019) demonstrate that single parent households were more likely to move into fuel poverty comparing with older person households. Additionally, Kearns et al (2019) find that that the poor mental health has the effect on the movements into fuel poverty, rather than being a consequence of it. Moreover, they reveal a lack of effect of energy efficiency improvements and limited impacts from gaining employment (Kearns, et al., 2019).

In the recent paper by Sovacool et al (2019), they asses four household improvements - solar photovoltaic panels, low carbon heating, electric vehicles and energy service contracts, and point out the potential to alleviate the vulnerability to fuel poverty. However, there is potential threat in creating new injustices. For example, those unable to afford onsite electricity generators, low carbon heating system or electrical vehicles, lose out on the benefits of these innovations as well as could be penalized by measures to reduce household carbon emissions (Sovacool, et al., 2019). Energy justice scholars go one step further discussing that the energy is contributory in realisation of fulfilling life, therefore, it should be treated as human right (Sovacool, et al., 2013).

The latest review, of how the Warmer Homes Scotland Scheme has performed, suggests that existing support schemes are making a positive impact. Additionally, improvements in the energy efficiency performance are responsible for one third of the reduction in households living in fuel poverty in Scotland (Scottish Government, 2018). Moreover, Donaldson (2018) suggests that there is a correlation between urban brownfield land and social housing and investigates how deployment of renewables on brownfield land can be used to address heat poverty in social housing in Glasgow.

The results indicate that by using GSHPs on all vacant and derelict land would allow to supply up to 80% of a property's average heat demand in Glasgow, 47% of them estimated to be in fuel poverty (Donaldson & Lord, 2018).

The UK Government`s *Clean Growth Strategy* proposes that all fuel poor homes to be upgraded to Energy Performance Certificate (EPC) band C by 2030. Additionally, all properties, where practical, cost-effective and affordable, should be EPC band C by 2035 (BEIS, 2017). However, in November 2018, the Scottish Government set a higher target of EPC grade B for social housing and fuel-poor households and a lower standard of EPC C for private sector housing (Scottish Government, 2018).

The latest Energy Efficient Scotland consolations summary suggested that if the standards are not aligned with those for the owner occupied sector, there is a risk of some housing stock being removed from the private rented sector (Scottish Government, 2018).

Gupta & Gregg (2018) developed a high resolution Geographical Information System (GIS) based modelling method to operatively map and manage energy consumption and CO_2 emissions. The authors point out that by using this visual approach on a house by house level, the community groups and local authorities can address the mass domestic refurbishment challenges in towns and cities. Identifying the type and cost of carbon emission reduction measures that are most suitable for each property can help in scaling up refurbishments that could allow to eliminate fuel poverty as well as to meet the carbon reduction standards set out by the government. The results indicate that from 2008 till 2012 a reduction of 10% - 14% in average annual energy consumption per property within the six communities investigated in this study. Solid wall insulation provides the greatest energy reduction, however, the greatest CO_2 reduction can be achieved by combining improvement of building fabric, heating system and addition of PV generation (Gupta & Gregg, 2018).

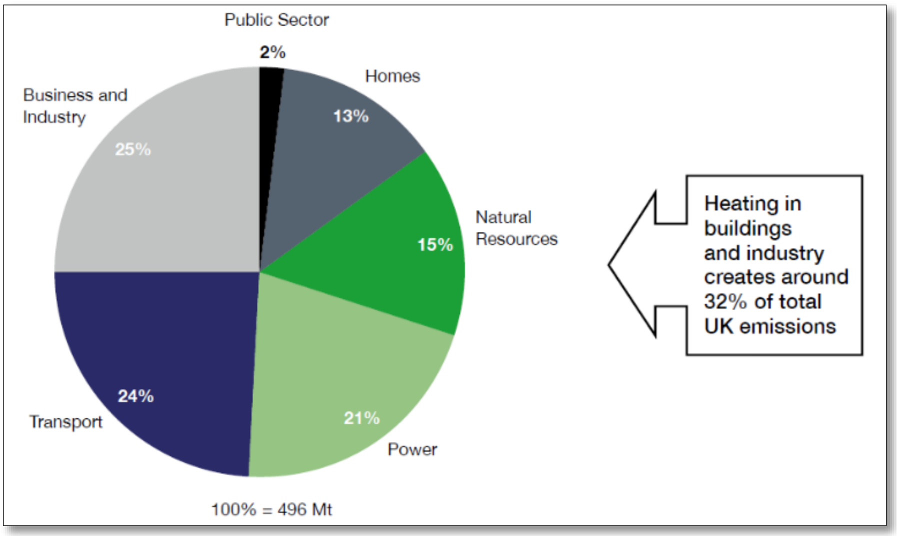
2.2. Policy, standards and rating systems

2.2.1. Decarbonising heat

Electrification of heating has a significant potential to decarbonise domestic energy use by allowing to utilise excess renewable generation and reduce constraints of power network (Armstrong, et al., 2019).

The UK *Clean Growth Strategy* sets out a set of policies and suggestions to facilitate the clean growth - increased economic growth and decreased emissions. This document points out the significance of the emissions created by heating the homes and businesses. In 2015, it accounted for 32% of UK emissions (Figure 4). The innovation and significant investment is required to drive the reduction of these emissions, however, this will facilitate jobs creation and more export opportunities (BEIS, 2017).

Figure 4 UK emissions by sector in 2015. Source: BEIS (2017)



Two main objectives are set out by UK government:

1. To meet domestic commitments at the lowest possible net cost to taxpayers, consumers and businesses.
2. To maximise the social and economic benefits from this transition.

Low carbon technologies, processes and cost efficient systems will play important role in meeting these objectives. This strategy identifies the areas where greatest technological breakthroughs and large-scale deployment is required:

- Accelerating clean growth;
- Improving business and industry efficiency – 25% of UK emissions;
- Improving the energy efficiency of our homes – 13% of UK emissions;
- Rolling out low carbon heating;
- Accelerating the shift to low carbon transport – 24% of UK emissions;
- Delivering Clean, Smart, Flexible Power – 21% of UK emissions;
- Enhancing the benefits and value of our natural resources – 15% of UK emissions;
- Leading in the public sector – 2% of UK emissions;
- Government leadership in driving clean growth – 25% of UK emissions.

Focusing on low carbon heating the emphasis is on following actions: By 2020, eliminate the installation of high carbon fossil fuel heating in properties that currently are off the gas grid; Improve standards for new boiler installs and require adaption of control devices; Incentivise the low carbon heating; Invest public funds, to develop new energy efficiency and heating technologies (BEIS, 2017).

Zimmermann & Pye (2018) argue that the numerous policies required for the decarbonisation of UK will naturally create inequality across the society. By investigating 79 impact assessments, they identified that the majority of them, either did not consider or only partially considered the impacts on vulnerable groups. This was confirmed even further after interviews with relevant actors in the industry. Furthermore, Zimmermann & Pye (2018) concludes that the current policy appraisal process does not undertake thorough distributional analysis and therefore may be insufficiently capable of assisting policy-makers in developing equitable policies. Therefore, a further research is required to improve the understanding of how distributional impacts can be successfully tackled to inform UK energy and climate policy.

Chaudry et al. (2015) identifies three essential elements on achieving CO_2 emission reduction in the heating sector:

1. Reduction of the heating demand
2. Reduction of carbon intensity of the energy carrier
3. Deployment of low carbon heat technologies

Imperial College London (2019) Report suggests that it is unlikely that it will be possible to meet Climate Change Act target for an 80% reduction just by reducing the head demand trough more efficient buildings and heating systems. In addition, it will require that the heat related emissions of CO_2 from buildings are near zero by 2050 and rapid deployment of electric vehicles. Furthermore, a net zero target could require accelerated deployment of these technologies - by 2025 up to 2 million heat pumps and 9 million EVs should be implemented. However, Eyre (2011) indicates that electrification of domestic heat in UK would be extremely difficult and more likely infeasible. He emphasises the need for further research in the role of heat pumps in the UK domestic sector and the impact on the electric grid.

In a study analysing the key uncertainties in the UK heat infrastructure development, Chaudry et al. (2015) suggest that the uncertainty about the actual ways to decarbonise the heat will be challenging to policy makers. For large scale deployment of low carbon heat technologies, a range of technical, economic and market challenges are the main causes for uncertainty. Furthermore, they point out that the use of the gas network will reduce in future, but it will be used to meet peak demands up until 2050. However, Qadrdan, M et al. (2019) argues the high pressure gas transmission network gas load duration curve will be affected only slightly, but the low pressure gas network`s load duration curve will experience quite significant changes. Additionally, although the annual volume of gas consumption will decrease in the future energy system with a significant share of RE generation and highly electrified heat supply, the peak gas supply at cold windless nights remains the same if not increase.

Armstrong et al. (2019) in their paper of pitfalls in decarbonising heat suggests that there is contradiction between the climate policy and the building standards and legislation that determine white goods. In this paper, they identify that an electric hot water tank is 14% more efficient comparing to an A rated instantaneous gas boiler. However, the European energy labelling directive forces a conversion coefficient for electric water tanks to account for assumed 40% grid losses.

Many authors in the literature point out that UK will not be able to decarbonise its energy supply via electrification of heat alone. Currently, the district heating is used to heat only 2% of the total heating demand. Therefore, more widespread incorporation of district heating is necessary (Brocklebank, et al., 2018) (Renaldi & Friedrich, 2019), (Lund, et al., 2018).

In the UK, where there is little to no 2nd and 3rd generation large scale district heating systems, implementation of 4th generation district heating is more feasible comparing to other countries. Transition from 2nd or 3rd generation involves upgrading existing distribution and heating systems as well as incorporation of RE and low grade heat sources that otherwise would not be utilised. This allows to achieve higher efficiencies in heat supply and heat distribution. Additionally, this allows to incorporate combined heat and power, flue gas condensation, heat pumps, geothermal extraction, low temperature excess heat, and heat storage systems. Moreover, there are lower distribution losses, less pipe expansion, lower scalding risks, and potential to use plastic pipes according to Averfalk & Werner (2017). More efficient buildings with lower heat demands makes it possible to utilise these lower heating medium temperatures (Averfalk & Werner, 2017).

2.2.2. Declaration of climate emergency

To avoid exceeding the 1.5°C threshold and meet the Paris Climate Change Agreement by 2030, the world needs to reduce GHG emissions down to 45% of 2010 levels (IPCC, 2018). The United Nations Climate Change Executive Secretary, Patricia Espinosa, described the current situation as a climate emergency and requested everyone to take part in tackling this issue. She points out that the current commitments by national governments are falling short on this target and that increased ambition on tackling the climate change is necessary (UN Climate Change, 2019).

In the response to this, many councils in the UK, have declared a climate emergency. At the time of writing this paper, already 171 councils in the UK have declared a climate emergency (Climate Emergency UK, 2019). Scotland have set even more ambitious, legally binding targets and agreed to achieve a net zero emissions of GHG by 2045, five years ahead of UK. However, the Scottish government, made it clear - these ambitions are contingent on the UK adopting a target for 2050 (Scottish Government, 2019).

Following commitments were made by the Scottish government (Scottish Government, 2019):

1. Accelerate deployment of fully operational carbon capture utilisation and storage facilities.
2. Accelerate action to decarbonise the gas grid, and consider the balance of taxes across different heating fuels to enable affordable low-carbon heating in homes and businesses across Scotland.
3. Re-design vehicle and tax incentives to support industry and business investment in zero emission and sustainable transport choices.
4. Commit to adhering to future EU emission standards regardless of our position in relation to the EU.
5. Reduce VAT on energy efficiency improvements in homes.
6. Ensure continued support for the renewables industry.

2.2.3. Building standards Scotland

The main purpose of the standards is to ensure that, by outlining the essential requirements that must be met during construction of new buildings or refurbishing existing housing stock, all buildings in Scotland are built to be energy efficient, safe and sustainable. The Technical Handbook – Domestic provides guidance on achieving the standards (Scottish Government, 2017).

Study done by Burford et al. (2019) identified that properties, in the sample of 403 new build residential buildings, complied with the Scottish building regulation`s emissions reduction target. However, only a small proportion achieved this reduction by uptake of LZCGT. The authors, Burford et al., point out the significant correlation between heat and electrical demand, size of the property and occupation which statistically misrepresent the emissions counting. Therefore, this implies that the Scottish building standards are facilitating the local CO_2 emission reduction, instead the Section 3F policies.

2.2.4. Section 6 (energy)

Section 6 (energy) is focusing on ensuring that sufficient fuel and energy conservation measures are incorporated into dwellings. Additionally, the designer of a new building should holistically consider limiting the energy demand, by assessing the performance of the building envelope and building services. This section facilitates greater consideration of building integrated low-carbon technologies (e.g. PV, solar water heating, and HP). The focus is primarily on reducing the CO_2 emissions, however, the energy demand reduction measures and resulting energy costs, both, will be minimised (Scottish Government, 2011).

Burford et al. (2019) argue that by approaching 2020, the compliance with Technical Standards is becoming increasingly more difficult. Additionally, the Section 6 promotes the incorporation of renewable energy, however, it does not impose the use of LZCGT. Nevertheless, the LZCGTs are the first tool of choice for developers to fulfil the required CO_2 emission reduction. This leads to a situation where additional energy generation with LZCGT is favoured over energy conservation measures. Many of the commonly incorporated LZCGTs still emit considerable amounts of CO_2. Therefore, fabric energy efficiency and passive design measures might have better long term effect on GHG emission reduction.

2.2.5. Section 7 (sustainability)

Section 7 addresses aspects related with the delivery of sustainable buildings. The emphasis is on resource use for space and water heating, GHG emissions and water use. Additionally, focus on adoptability during the lifetime of the dwelling by defining a designated area for working from home and space for mobility vehicles. Moreover, factors like enhanced noise insulation, increased natural light usage and improved security are looked at. A compliance with the standard would allow to use the Sustainability Label that can serve as demonstration of development`s environmental commitment. (Scottish Government, 2011).

Burford et al. (2019) argue that sustainability was introduced to the Scottish Technical Standards to stimulate and award developments that surpass the minimum standards.

Specific requirements are described to comply with one of the three Sustainability Levels: Bronze/Bronze Active, Silver/Silver Active or Gold. However, the Bronze and Silver level can be met without the use of LZCGT. Moreover, currently all new buildings automatically meet the Bronze Level. The added label “Active” was introduced to indicate that LZCGT was incorporated. This helps the Local Authorities in meeting their responsibilities under Section 3F of the Town and Country Planning (Scotland) Act 1997. For this purpose, following LZCGTs are included: heat pumps, solar thermal panels, photovoltaic panels, water turbines, wind turbines, low carbon CHPs, fuel cells, biomass and biogas (Burford, et al., 2019).

2.2.6. Decent homes standard

The Decent Homes Standard introduce by the UK Government in 2000 aimed to provide a minimum standard of housing conditions for all public sector dwellings. The following standards have to be met (UK Government, 2006):

- the property must meet the current statutory minimum standard for housing;
- the property must be in a reasonable state of repair;
- the property must have reasonably modern facilities and services;
- the property must provide a reasonable degree of thermal comfort.

Figure 5 shows the declining number of non-decent homes in England since 2001.

Figure 5 Number of non-decent council owned dwellings: England (2001-2018) (The Ministry of Housing, Communities and Local Government, 2019)

2.2.7. Standard Assessment Procedure (SAP)

The energy performance requirements of UK buildings are quantified by fabric energy efficiency and CO_2 emission rates. The minimum requirements are set out in Building Regulations. The developers have to describe design parameters using the Standard Assessment Procedure. This allows to determine the target fabric energy efficiency and CO_2 emission rate for new residential buildings, and a target CO_2 emission rate for all new building types (Ling-Chin, et al., 2019).

SAP methodology is also used by the UK Government to determine and compare dwellings regarding their environmental footprint. A precise and dependable assessment of building energy performance is required to support initiatives of energy and environmental policies. SAP is based on standardised assumptions for occupancy and behaviour, allowing for like for like comparison of two properties. (UK Government, 2013).

Burford et al. (2019) indicate that the SAP calculations are applied only to “regulated energy" in Building Standards which excludes significant electrical energy required for additional water heating on white goods and other appliances that tend to have a cold supply in the UK.

The latest official version is SAP 2012. However, an updated version - SAP 10.0, which is a result of public consultations of necessary changes, has been published. This allows the industry to familiarise and adapt to changes (BEIS, 2018).

CO_2 emission factors and fuel prices have been updated using the latest data available. Table 1 shows the significant reduction of CO_2 emission factor of the UK electricity grid, due to reduction of coal power plants and increase of RE generation. These changes in addition of potential gas boiler ban for new builds from 2025 will furthermore facilitate the decarbonisation of heat via HP (Ofgem, 2016); (The Times, 2019).

Table 1 SAP 10.0 Fuel prices and CO_2 factors (BEIS, 2018)

Fuel	SAP 2012 Cost (p/kWh)	SAP 10 Cost (p/kWh)	SAP 2012 CO_2 ($kgCO_2/kWh$)	SAP 10 CO_2 ($kgCO_2/kWh$)
Main Gas	3.48	3.94	0.216	0.210
Bulk LPG	7.6	6.47	0.241	0.241
Oil	5.44	3.76	0.298	0.298
Wood Logs	4.23	4.65	0.019	0.028
Electricity	**13.19**	**16.55**	**0.519**	**0.233**

Moreover, calculation methods and default values has been changed assessment of PV, domestic hot water demand, overheating risk, thermal bridging, mechanical ventilation, lighting energy and unit efficiencies (BEIS, 2018).

2.2.8. Energy Performance Certificate (EPC)

The development of EPC schemes in the EU provide a powerful and comprehensive information tool to quantitatively predict annual energy demand from the building stock, creating a demand-driven market for energy-effective buildings (Li, et al., 2019). Properties with improved energy rating have reduced energy bills resulting in a positive impact on property investments and rental return. The EPC scheme, which was designed to be an important driver to promote building energy performance improvements, plays a crucial role in this process according to Li et al (2019). However, there are some existing problems that prevent it from serving as a reliable and trustworthy information tool to motivate large scale building renovation (Li, et al., 2019).

In 2017, EPC band C or higher was achieved by 42% dwelling in Scotland, up from 39% in 2016 and from 35% in 2014. Moreover, since 2010, the amount of properties in lowest EPC bands (E - G) reduced from 27%to 13% (Scottish Government, 2017).

Hardy & Glew (2019) study quantified the problem, stating that at least 27% of all EPCs lodged between 2008 and 2016 are inaccurate. Many errors were identified via comparison of two EPCs for the same property. If only one EPC is available for the property, it is more challenging to identify any errors as per their study. Correcting for this suggests that the true error percentage for the EPC record is in the range 36–62%. This has direct implication on the UK budget as the domestic RHI is paid for the deemed energy consumption values stated on the EPC (Hardy & Glew, 2019).

The next generation EPC should rely on building information management (BIM) technology, benefit from big data techniques and use building smart-readiness indicators to create a more reliable, affordable, comprehensive and customer-tailored instrument, which could better represent energy efficiency, together with occupants' perceived comfort and air quality (Li & Sun, 2019).

2.2.9. Renewable Heat Incentive (RHI)

The Renewable Heat Incentive is a UK Government`s financial incentive to facilitate renewable heat generation and use in residential and commercial buildings and processes, therefore helping to reduce carbon emissions and meet renewable energy targets. Owners of eligible installations receive quarterly payments for seven years (domestic) or twenty years (non-domestic) for each renewable kWh of heat it produces (Ofgem, 2019).

Table 2 shows the current domestic RHI tariffs and heat demand limits. For domestic properties, all but solar thermal RHI payments are based on the deemed heating and hot water demand stated in the EPC. For heat pump installations, the electric input into the unit is deducted from eligible use (Ofgem, 2019).

Table 2 RHI tariffs on 01/07/2019 and heat demand limits (Ofgem, 2019).

	Biomass boilers and stoves	Air source heat pumps	Ground source heat pumps	Solar thermal
p/kWh	6.88	10.71	20.89	21.09
kWh/y	25 000	20 000	30 000	No limit

The main motivation for the Department of Energy and Climate Change to implement the RHI scheme is (DECC 2011, p. 1):
"The objective of the Renewable Heat Incentive (RHI) is to drive a step change in the uptake of renewable heat technologies in order to help deliver an increase in renewable heat from the current 1.5% of total heat demand to a level of 12% by 2020."
However, the House of Commons Committee of Public Accounts latest report points out the failure of the scheme to achieve its objectives or provide value for money for the £23 billion expected total cost to taxpayers. In the first four years, only 60,000 renewable domestic installations were done under the scheme, 78% less than the initially intended and compared to 6.2 million gas boilers in the same time period (House of Commons Committee of Public Accounts, 2018).

The RHI is not an option for households and businesses who are unable to afford the high upfront investment required for low-carbon heating system. Additionally, due to the cost of installing gas and oil boilers, they remain popular in the UK (House of Commons Committee of Public Accounts, 2018).

Over 28 000 biomass boilers have been funded by the scheme. Air pollution is a serious public health issue; however, DECC and Ofgem does not fully comprehend the impact on air quality from these installations. Although, the Ofgem require biomass boilers to have an emissions certificate, no actual monitoring of emissions from boilers in use is done, even when non-compliance is identified (House of Commons Committee of Public Accounts, 2018).

Donaldson & Lord (2014) argue that although the RHI is transparent at policy level, to fully support implementation, a significant improvement in how the RHI is managed and supported at a construction phase is needed.

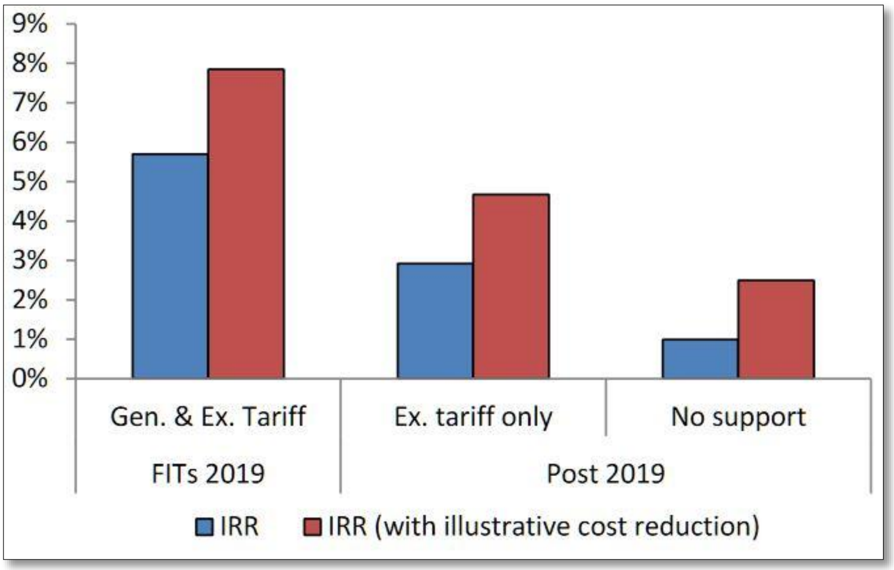
2.2.10.Feed in tariff (FiT) and Smart Export Guarantee (SEG)

The FiT scheme was established in 2010 and incentivised the small scale renewable electricity generators. At the time the programme was introduced, it was estimated to add £440 million per year to energy bills in 2020, however, the latest estimate is £1.6 billion (Shrestha, 2018). Nevertheless, over 700 000 small-scale solar PV systems have been installed and registered under the FiT scheme since the launch of the scheme in 2010. This allowed the industry and expertise to grow and mature as well as cost of RE generator, PV in particular, to drop significantly. Therefore, since 01/04/2019, this renewable electricity generation incentive has been discontinued (Ofgem , 2019).

The closure of the FiT scheme faces a lot of criticism from the industry. Not just because this decision is contradicting with the overall Government`s commitments regarding the GHG emission reduction targets, as well as negatively affect jobs in the industry, air quality and create a situation where the owners of the systems will not be compensated for the overproduction of renewable electricity that is fed back to the grid (BEIS, 2018).

FiT schemes closures impact assessment report done by Department for Business, Energy and Industrial Strategy (2018) investigated the Internal Rate of Return (IRR) for 3 different scenario. This illustrates the attractiveness of the investment with and without the FiT support. Figure 6 shows the economics for a representative 3 kWp PV generator in all three scenarios – existing generation and export tariffs continue, only export tariffs continue, no tariffs continue. It is clear that expected and therefore deployment will decreases with option 2 and 3.

Figure 6 IRRs for 3 kWp solar generator (BEIS, 2018).



The blue bars in Figure 7 illustrate the combined installed solar capacity under the FiT scheme until the end of 2017. The several dotted grey lines show the forecasted deployment scenarios from external publications - National Grid's Future Energy Scenarios 11; Bloomberg New Energy Finance. Brown, orange and yellow lines represent deployment scenarios used for solar PV in this impact assessment. The counterfactual scenario estimates an annual growth of 4%; the "unsupported-high" and "unsupported-low" scenarios assume growth rates of 2% and 1% respectively (BEIS, 2018).

Figure 7 SUB 5MW solar deployment (BEIS, 2018).

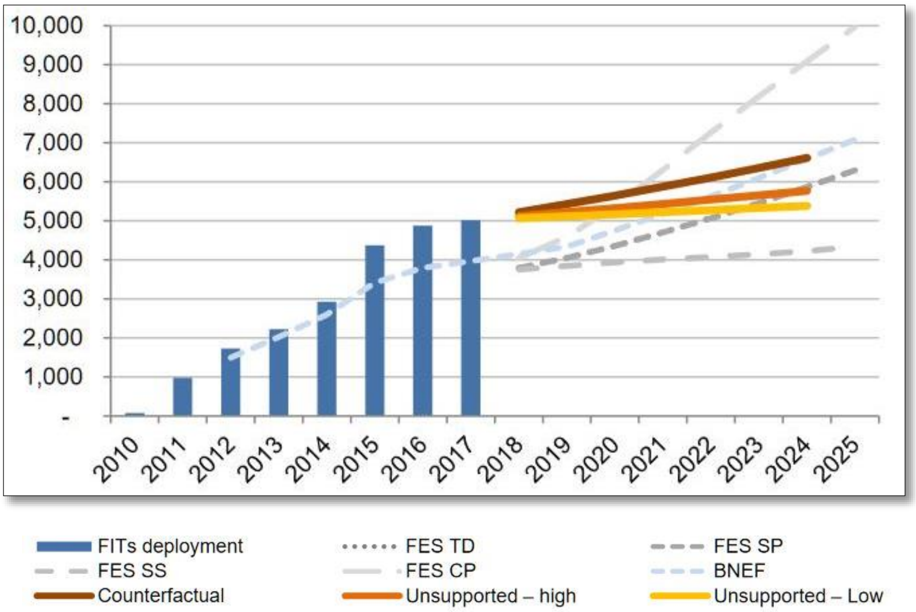


Table 3 shows the annual capacity growth used in this BEIS assessments deployment scenarios. The medium and central scenarios are assumed to be a half and quarter of this deployment respectively.

Table 3 Annual capacity growth assumptions

	Counterfactual	"unsupported-high"	"unsupported-low"
Solar	4%	2%	1%
Wind	9%	5%	2%
Hydro	7%	3%	2%
AD	6%	3%	2%
mCHP	0.7%	0.3%	0.2%

To compensate the new owners of renewable electricity Microgeneration technologies after the closure of FiT scheme, the government plans to implement a Smart Export Guarantee (SEG), which will compensate the exports of following technologies: anaerobic digestion, hydro, micro-combined heat and power (50kW or less), onshore wind, and PV exporters with up to 5MW capacity (Department for Business, Energy & Industrial Strategy, 2019). The scheme plans to mandate the licensed suppliers with 150,000 or more domestic customers to provide compensation for the exported energy. However, there will not be any set minimum tariff rate. The only requirement is that the rate has to be greater than zero. As the exported power has to be metered, this will enhance the use of small-meters. Moreover, the flexibility of the scheme allows purchasing the power from small scale storage and other forms of generation (Department for Business, Energy & Industrial Strategy, 2019).

2.2.11. Electric vehicles incentives

In addition with the plans for all new cars and vans to be zero emission by 2040, the Department for Transport public consultation is proposing that, to ensure all new buildings are ready for future, it is mandatory for all new built homes to have an electric car charger installed (Department for Transport, 2019).

Moreover, to promote the uptake of electric vehicles, UK Government launched Electric Vehicle Home charge scheme which gives a £500 grant towards the cost of installation of an EV charge point. Furthermore, additional £300 funding is available from Energy Saving Trust. Combined funding allows to cover up to 80% of the total cost of the charge point (Office for Low Emission Vehicles, 2019), (Energy Saving Trust, 2019).

2.2.12. Individual Council level

In the UK, councils are able to choose the means of achieving the emission targets. For example, the Glasgow City council is setting more strict building standards for new builds. From September 2018, all new planning applications for domestic properties will be required to demonstrate Gold Level (Glasgow City Council, 2017). Moreover, at least 20% of reductions should be achieved via the use of renewable technologies (Glasgow City Council, 2017). However, there is some flexibility in means of achieving this (Table 4). Meeting the Gold Aspect 1 standard is equal to CO_2 reduction of 27% against the Target Emissions Rate required by the 2015 Building Regulations, a 42.8% improvement against 2010 standards and a 60% improvement on 2007 standards.

Table 4 Alternative Gold Level Options: Domestic (Glasgow City Council, 2017)

Option 1 Gold Hybrid	Option 2 Nearly Zero Emissions	Option 3 Net-Zero Carbon
Achieve Gold Aspect 1, along with Silver Active Level Aspects 2-8 inclusive	Achieve Passivhaus energy performance requirements with Gold Level Aspect 1 and Silver Active Level Aspects 4-8	Achieve Platinum Level Aspect 1 and Silver Active Level aspects 2-8 inclusive
PLUS: All will be required to include a minimum 20% carbon dioxide emission abatement through the use of low and zero carbon generating technologies, except certified Passivhaus developments which are exempt.		

2.2.13. Effectiveness of Government policies

As described above, there are many standards and incentive set by the UK and local governments, however, industrial stakeholders have some concerns over the performance of these policies (Ling-Chin, et al., 2019).

In their study Ling-Chin et al. (2019) communicated with more than 600 experienced engineers, consultants, managers and directors working in the UK. The stakeholder perspectives on challenges, barriers and thermal performances were investigated. Three main topics and conclusions of discussion is described in Table 5.

Table 5 Key points of the industrial stakeholder discussion (Ling-Chin, et al., 2019).

Topics	**Key points**
The gap in performance between estimated and actual energy performance of buildings	Although buildings often underperform, building operators should understand both predicted and actual building energy use.
	Energy performance gap is caused by management factors such as - degradation over time, faulty installation and hand over. Additionally, lack of knowledge of what was built and how design strategies and components will perform in real life. Moreover, communication issues between designers,

	constructors and operators. Furthermore, lack consequences for responsible stakeholders when actual energy consumption exceeds estimations.
New approaches to energy efficient retrofitting	Support for investment should be based on evidence instead of intuition.
	A new approach could emerge in near future that would include - flexible eligibility; support to vulnerable household services; directing funds into high quality activities; raised awareness and uptake for private landlords.
No insulation without ventilation	As good air-tightness will be achieved when retrofitting existing dwellings, ventilation becomes critical in avoiding condensation and mould as well as ensure air quality.
	Ventilation options - intermittent extract fans, heat recovery room ventilators and MVHR must be specified based on demand control.

Although, some stakeholders believe that upgrading existing buildings with RE systems and heat pumps could be the means of meeting emission reduction target, others, due to challenges associated with the incorporation of energy efficiency improvement, were unsure about it. Furthermore, it was pointed out that effective design, control, monitoring and constructability focused design will improve thermal performances of buildings (Ling-Chin, et al., 2019).

Hooper et al. (2018) argue that increasing use of scenarios in the UK policy has been driven by the Climate Change Act (2008), as well as the need to discover the best solutions for meeting legally-binding carbon budgets. These scenarios are not designed to produce accurate estimates of the future, however, they have a tendency to isolate the energy sector issues from the broader policy and drivers. Moreover, the land, which differs considerably for different energy options, often is beyond the scope of energy scenarios (Hooper, et al., 2018).

Successful outcomes of energy scenario could be facilitated by either inclusion of broader sectors and policies or by examination of the consequences in terms of their feasibility within the broader policy landscape. Otherwise, there is a risk of suggesting practically unachievable energy pathways that are not compatible with the full range of sustainable development policy drivers (Hooper, et al., 2018).

2.2.14.Passivhaus and EnerPHit

Passive House is energy efficient, comfortable and affordable building standard. Over 65 thousand properties designed, built and certified to this standard worldwide, making the Passivhaus the leading low energy building standard (Passivehaus Trust, 2019). Passive Houses allow for space heating and cooling related energy savings of up to 90% compared with typical building stock and over 75% compared to average new builds. However, most energy savings can be achieved in warm climates where active cooling is present in most properties (Passive House Institute, 2015).

The main difference between Passivhaus and net-zero energy or energy plus approaches is that there is no requirement for renewable energy generation. The main goal is to reduce the heating demand of a building by focusing on the quality of the thermal resistance and airtightness of the building envelope, the use of mechanical ventilation with heat recovery (MVHR) system as well as maximising solar gains. However, designing buildings to maximise solar gains in order to reduce heating loads during winter, leads to increased risk of overheating (The Zero Carbon Hub, 2015).

The Passive House Standard often cannot be achieved in older buildings in an economically viable way. **EnerPHit** is the equivalent standard for refurbishment of existing buildings. It assures the same advantages of the Passive House Standard and leads to significantly better thermal comfort, structural integrity, costs and energy requirements; however, the energy demand limits are higher. For the UK climate, max heating demand is 25 kWh/m^2a comparing with 15 kWh/m^2a for the Passive House Standard. EnerPHit follows the same five principles as Passivhaus:

1. Building Envelope: should consist of a continuous layer surrounding the building. Specific minimum levels of performance are required for each element.

2. Airtightness: The airtight layer reduces heat losses from draughts and protects the building fabric from condensation. To ensure performance, an airtightness test is mandatory after completion.
3. Solar Gain: Windows need to be designed to provide sufficient heat in the winter whilst reducing overheating in the summer.
4. Thermal Bridges: A careful construction detailing is required to eliminate thermal bridges.
5. Ventilation: Provision of optimal indoor air must be guaranteed as well as uncomfortable draughts and associated heat losses must be eliminated. This only can be achieved with a MVHR system, which extracts air from bathrooms and kitchens and supplies fresh preheated air to living rooms and bedrooms (Passive House Institute, 2016).

In 2015, the requirements for the Primary Energy Renewable (PER) demand and generation of renewable energy was introduced. It replaces the previous requirement for non-renewable primary energy demand of 120 kWh/m²/y. This allows to achieve one of three EnerPHit classes - Classic, Plus or Premium. The main difference between them is the use of renewable energy sources. The *Classic* EnerPHit certification can be obtained without any renewable energy generation; however, for *Plus* and *Premium* – 60 and 120 kWh/m²a respectively of renewable generation is required. However, the previous Passive House Classic Standard requirement for the non-renewable primary energy demand, still can be used in the transition period. Additionally, general minimum criteria for thermal comfort, moisture protection, occupant satisfaction, frequency of excessive humidity and overheating applies to all standards (Passive House Institute, 2016).

The risk of overheating during the summertime is a common topic in the literature. Increased indoor temperatures can be life threatening, for example, due to the heat wave in 2003, it`s estimated that additional 2091 deaths occurred in the UK, mostly amongst vulnerable groups (Johnson, et al., 2005). The evidence indicates that the difference in overheating in similar flats is caused by occupant behaviour (Sameni, et al., 2015). Moreover, Fletcher et al. (2017) in their empirical study of an assisted living Passivhaus building in the UK observed significant overheating even during the heating season and night time. Fletcher et al. suggest that if operated incorrectly, the

Passivhaus might not suitable for vulnerable occupants. Moreover, McLeod et al. (2013) point out that internal gains in the UK social housing context could be higher than Passive House Planning Package default values. Additionally, they suggest that within the next 30–40 years, active cooling may become a requirement in urban Passivhaus building in the UK.

However, Fosas et al. (2018) argue that increased insulation only accounts for up to 5% of overall overheating. Pointing out that unless the overheating was present prior the added insulation due through poor design, the increased insulation actually reduces overheating in low energy buildings. The results of their study identified that, if overheating levels are within acceptable levels (below 3.7%), the use of improved insulation is sensible and improves indoor thermal environment.

2.2.15.BREEAM and LEED

Certified green buildings are known to demonstrate high environmental performance. Two leading and most widely used standards are Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED).

BREEAM was first published by Building Research Establishment in 1988, based in Watford, England, UK. It is the oldest sustainability assessment method for master planning projects, infrastructure and buildings. It recognises the value in assets from new builds, in-use and refurbishment. BREEAM determines sustainability value in categories ranging from energy to ecology and addresses factors like - low impact design and CO_2 emissions reduction, design resilience, adaption to climate change and biodiversity protection (Building Research Establishment, 2019).

LEED developed in 2000 by the United States Green Building Council. It is green building rating system available for all building types and building phases. It promotes creation of healthy, efficient and cost-saving green buildings. LEED certification level is based on points earned across multiple categories - Location & Transportation, Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials

& Resources, Indoor Environmental Quality, and Innovation (U.S. Green Building Council, 2019).

Due to many similarities, projects worldwide are starting to pursue dual certification. Achieving this would display a high level of social responsibility as well as serve the marketing purposes. Therefore, Suzer (2019) investigated the compliance and correlation between green building rating systems. Due to majority (83%) of the environmental concerns are addressed in both systems, high level of compliance was identified. However, LEED scores are significantly higher than BREEAM scores. Nevertheless, for dual certified projects, the estimated award level differs only one level if at all.

MacKay (2009) argues that CO_2 emission reduction could be achieved if Section 3F policies would better define the criteria for the correlation between new build developments and regional energy requirements. Moreover, the Section 3F policies facilitate more design oriented ways to reduce GHG emissions. The building design industry agrees that the overall energy consumption reduction via improved fabric efficiency is the most cost effective and long-term measure to reduce CO_2 emissions. In other words - site specific passive design should be first priority before considering the application of LZCGT (MacKay, 2009).

2.3. Retrofitting

It is highly unlikely that the grid scale renewable generation alone will be able to achieve Scottish Government’s emission targets. Demand reduction will be essential in reaching these goals. Improved insulation and better quality buildings offer the highest potential of tackling problems such as fuel poverty. Even low-tech measures as maintenance can have an effect (6-27%) on improving energy efficiency (Kelly, 2006).

Social housing retrofit involves large scale interventions managed by one landlord, therefore, is has potential to accelerate the reduction in fuel poverty rates and CO_2 emissions (Streicher, et al., 2017). Additionally, due to similar building stock, successful retrofitting solutions can be applied to other landlords. Furthermore, large social housing landlords can utilise the economies of scale to obtain better offers from the suppliers and installers for solutions tackling the fuel poverty according to Swan & Brown, 2013. Additionally, they have the power to directly influence the policy at higher levels (Swan & Brown, 2013).

Many of the authors in the literature, mention the potential of reduced running costs, enhanced comfort and living conditions or environmental aspect as the main motivation for the RE integration in social housing. However, some authors mention the benefit for the end users stemming from higher control of their energy system as well as the increased architectural value as the main driving force (McCabe, et al., 2018).

Financial risks, the novelty and technological complexity as well as the lack of institutional support and incentives are the main barriers for uptake of RE technologies in the social housing sector (McCabe, et al., 2018).

The importance of the end user engagement and understanding of the installed technology dominated the literature (Abi-Ghanem & Haggett, 2011), (Moore, et al., 2015), (McCabe, et al., 2018). Abi-Ghanem & Hagget (2011) argue that positive outcome of the Microgeneration technologies depends on the design and the awareness of the technology. Both, the awareness of reduced consumption and costs as well as the behavioural change, are necessary to achieve this. Additionally, McCabe et al. (2018) suggest that the end user perceived benefits and acceptance of the technology stands out as the main factor for a successful RE retrofit. Furthermore, Moore et al. (2015) demonstrate the importance of user centred design for low carbon heat social housing retrofits to improve the efficiency of the installation. The key user requirement identified by their study - improved information must be delivered to end users of the system. Therefore, allowing to directly affect the behavioural aspect of the energy efficiency.

Study done by Teli et al. (2016) argues that not always the CO_2 reduction targets may be achieved through retrofitting, however, the level of social impact might be underestimated. Additionally, they point out that due to differences between standard models and social housing properties, it is required to use historic data in building energy modelling.

A net zero refurbishment method developed by **Energiesprong** consists of fully integrated refurbishment packages which can be scaled up to any size of refurbishment. The deep retrofit is achieved by adding offsite manufactured, bespoke external wall, window and roof “jacket” to significantly improve the thermal properties of the building. Additionally, roof integrated PV system is included to allow the building to achieve Net Zero energy use on annual basis. The solution is non-intrusive and can be completed within a week without the needs to temporary relocate the residents (energie sprong uk, 2019).

A traditional way of retrofitting would not have a performance guarantee. The quality of retrofits where monitoring is mandatory has improved significantly. The builder and resident benefit from the direct feedback on behaviour and technical performance of the retrofit. Therefore, these zero energy houses get high tenant satisfaction (energie sprong uk, 2019).

2.3.1. Case studies

High-density, high rise towers built in the 1960's is a prominent feature of UK`s city landscape. In Portsmouth one of such buildings, Wilmcote House, has been retrofitted up to EnerPHit standard, making it one of the biggest retrofits of this kind. Initially, ECD Architects who did the design of the refurbishment, proposed three potential solutions:

1. Instillation of a communal heating system with insulation of the envelope up to current UK building regulations.
2. Insulate the envelope to EnerPHit standard, therefore eliminating the need for new heating system as the MHVR and reduced heating demand would be sufficient.
3. Demolishing and building new tower from scratch.

Demolition and rebuild was significantly more expensive; moreover, that would involve the biggest disruptions for the residents. The option number 2 suggested to extend the existing building allowing to simplify the thermal envelope and reduce thermal bridges. Additionally, super-insulated roof and extended the insulation below ground.

The building was modelled in Revit for coordination and detailed design as well as visual material for consultation with tenants. Additionally, Passive House Planning Package was used to determine the thermal performance of the building and refurbishment design options.

The targeted heating demand reduction by 90% and a minimum 30 year extension to the lifetime of the property, with the entire project carried out as residents remained in the their homes was achieved. This shows that deep retrofit to the EnerPHit standard delivering significant improvements in thermal comfort, energy and carbon savings and can be cost effective in long term (ECD Architects LTD, 2018).

A similar deep retrofit meeting EnerPHit standard of two social housing blocks in Manchester, consisting 32 maisonettes, was designed by R-Gen Developments with the help of 2e Architects. Again, the possibility of demolishing and rebuilding was looked into and decided against. Mainly, because this approach would mean displacing residents and also it would not be possible to rebuild the same amount of units on the site (Green Building Store, 2016).

Due to concerns about structural safety, after stripping off the outer leaf of brickwork and concrete tiles, the main elevation had to be re-built with timber panels, pre-fitted with mineral wool insulation and airtightness tapes (Green Building Store, 2016). Moreover, the unheated stairwells were insulated in the same manner. However, the decision to remove the existing boilers meant that the residents had to move out temporarily. Table 6 shows the level of improvements achieved with the retrofit.

Table 6 Results of EnerPHit retrofit in Manchester (Antonelli, 2015).

	Space heating demand	Heat load	Primary energy demand	Airtightness (at 50 Pascal)
Before	300+ kWh/m²/y	123 W/m²	Not known	10 Ach (assumed)
After	23 kWh/m²/y	12 W/m²	120 kWh/m²/y	0.8 Ach

Another large-scale, deep retrofit project in Glasgow designed by Collective Architecture is planning to upgrade 3 residential tower blocks, originally built in the 1960’s, to the EnerPHit standard (Collective Architecture Ltd, 2016). The project targets to reduce space heating demand by up to 80% for the 314 homes. Proposals also include new communal entrances as well as new lifts. Additionally, external balconies will be enclosed to enable residents to use them all year round. One of the architects, Rupert Daly pointed out that aiming for EnerPHit level of retrofit was not much more difficult than the standard refurbishment; however, the thermal bridges from the balconies caused some problems. (Collective Architecture Ltd, 2016).

2.4. Technologies

2.4.1. Envelope

An innovative financing model is suggested, allowing the landlord to use the running cost and maintenance savings to pay for the investment (Jacobs, et al., 2015). The owner would increase the rent accordingly and provide the energy as a service. The residents get a warranty of a minimum heating and hot water supply whilst paying the same or slightly less than previously. Additionally, the residents are protected against the future energy price increase. Furthermore, monitoring equipment is installed to provide a real time feedback to tenants and allow to identify if the retrofit is achieving its Net zero energy target (Jacobs, et al., 2015).

For case studies in Netherlands, the improved insulation and MVHR system is responsible for ±70% reduction of thermal energy demand and ±15% reduction of electricity is achieved from lighting and appliances (Jacobs, et al., 2015).

2.4.2. Heat pumps

Air source heat pumps (ASHP)

Heat pumps are important part of integrating the electricity in the heating sector. UK electricity grid today emits only 57% of the CO_2 emissions comparing to the year 2009, therefore, the HP outperforms the gas boiler even more regarding the CO_2 emissions (UK Government, 2019).

Qadrdan et al. (2019) questions the capability and efficiency of heat supply system to meet peak demand during cold winters if ASHPs are supplying large share of overall heat demand. They argue that a backup supplementing heating technology would be necessary. However, majority of the literature is reporting significant savings over conventional systems or direct electric heating systems even in colder climate countries like Scotland.

Marczinkowski & Østergaard (2019) analysed the energy systems incorporating RE generation, HP and storage. Their results indicated that a combination of these technologies should be implemented to improve overall viability of the energy system. However, it is important to operate the HP only during hours of RE overproduction, which require an integration of smart control system (Marczinkowski & Østergaard, 2019). Furthermore, Armstrong et al. (2019) argue that the thermal inertia of dwellings with direct electric heating systems our heat pumps could act as a storage service for the electricity network. Peak RE overproduction in UK could be absorbed if only few percent of hot water tank heaters would be controlled in more intelligent way (Armstrong, et al., 2019).

Asaee et al. (2017) used a high resolution building performance simulation software, ESP-r, to evaluate ASHP retrofit for in Canadian housing stock as well as potential energy savings and GHS reduction and their results show 36% reduction of energy consumption and 23% of GHG emissions if all eligible houses undertake the retrofit. However, the authors point out that the feasibility of ASHP systems is influenced by the carbon intensity of the replaced system, existing legislation and incentives as well awareness and understanding of the homeowners.

Kelly & Cockroft (2011) in combination of simulation and field data study analysed energy performance of an ASHP, electric heating and an equivalent condensing gas boiler retrofit. The results reported 12% CO_2 emission reduction comparing to gas boiler system and 55% savings comparison to all-electric system. Although, the gas boiler running costs were 10% lower than ASHP system, the RHI payments will make ASHP cheaper to run (Kelly & Cockroft, 2011).

Touchie & Pressnail (2014) evaluated a novel energy retrofit measure for high rise residential buildings. Proposed solution incorporates an ASHP operating in enclosed balcony spaces of each individual flat. The enclosed balcony space serves as a thermal buffer zone with the potential to improve the COP of the HP due to utilisation of solar gain capture. The results of the modelling indicated the whole building energy consumption can be reduced by 39%. However, the cost if the retrofit cannot be covered by the energy savings alone. Additionally, the outdoor unit would take up usable floor space on the balcony, which could lead to resistance from the tenants (Touchie & Pressnail, 2014).

For historical buildings, the HVAC systems like MVHR and HP as well as the controls are often the only way for energy efficiency improvements (Schibuola, et al., 2018). Demand (DCV) or CO_2 controlled ventilation is promising technology allowing reducing energy consumption arising from the air treatment and distribution, particularly in the properties with highly variable occupancy (Schibuola, et al., 2018). However, the experimental assessment shows the demand controlled ventilation (DCV) system`s unreliability when it comes to maintaining indoor relative humidity within adequate levels when ventilation flow rates fluctuate widely (Scarpa, et al., 2018). Moreover, there are significant discrepancies between predicted and measured heat losses when MVHR or HP systems are being used (Scarpa, et al., 2018). The main causes are - limited control, lack of understanding on the day/night and seasonal operation, as well as occupant behaviour. This might become a serious problem, when the “as-built” performance will be included in future Building Regulations (Scarpa, et al., 2018). Additionally, low precision models, not matching with the measured consumptions could compromise the national CO_2 targets (Gupta, et al., 2018).

Solar assisted heat pumps (SAHP)

SAHP operates on the similar principle as regular ASHP. The main difference is that the liquid refrigerant with low temperature and pressure is delivered into a solar collector-evaporator directly vaporised from incident solar radiation and/or ambient air. Then a compressor increases the pressure and temperature to usable levels before entering the condenser (Shi, et al., 2019).

To reduce electricity consumption, a solar heat pipe collector and a SAHP water heater can be combined. This type of system operates as a conventional heat pump when the solar radiation is low, however, when the solar radiation is high, it operates in the heat-pipe mode. When operation in the heat-pipe mode, refrigerant absorbs thermal energy and enters the condenser directly without using the compressor. The combination of these two modes, allows achieving the COP of 3.32 (Huang, et al., 2005).

Ji et al. (2008) propose a photovoltaic solar assisted heat pump (PV-SAHP). The results of an experimental study indicates that this type of system can reach significantly higher COP values (on average 5.4) comparing to conventional HP systems. Additionally, due to cooling effect, increase the PV panel generation efficiency (Ji, et al., 2008). Combined maximum system efficiency reached COP of 16.1. (Ji, et al., 2008). Although these values are achieved on a short experimental study, other authors in more up to date studies also achieve improved SCOP values comparing to convectional ASHP. For example, Li & Sun (2019) state that considerable social-economic benefits can be achieved by the use of PV-SAHP. The annual net electricity consumption could be reduced by 79%. Moreover, the life cycle cost can be reduced by 57%. Considering both economic and environmental aspects, these systems are better suited in the cold climate area than the traditional ASHP.

Nevertheless, currently the market share in the UK is very small, MCS product search shows that only two companies and 9 units have been certified by the scheme (The Microgeneration Certification Scheme, 2019). However, the SAHP technology is gaining more attention in various industries.

Ground source heat pumps (GSHP)

Liu et al. (2014) state that by incorporating the GSHP, up to 71% of the households reported reduction in energy costs. However, only a small proportion (5%) of household saved more than 50% on their energy costs. Variation in energy savings depends on occupancy, system performance, and energy saving strategies as well as user behaviour. Therefore, it is important to educate the end users to avoid the misuse of the HP and radiator controls and use of additional heaters. Direct correlation can be observed between the energy savings and end users awareness of clean energy solutions and environmental issues (Liu, et al., 2014).

2.4.3. Solar

Development of the grid scale renewable generation does not tackle the fuel poverty directly as the occupants still are paying for their energy. However, solar systems in residential buildings directly reduce the amount of energy imported form the gird (Andreadis, et al., 2013).

Photovoltaic

The output energy of the solar PV system can be expressed as follows (Eteiba, et al., 2018):

$$E = A \times \eta_{m} \times Pf \times \eta_{PC} \times I$$

Equation 1 Energy generated by a PV panel in kWh

Where:
A = the total area of the photovoltaic generator (m^2)
ηm = the module efficiency
Pf = the packing factor
ηPC = the power conditioning efficiency
I = the hourly irradiance (kWh/m^2)

The module efficiency (ηm) are dependent on the temperature of the panel Therefore, rated efficiency of the module is based on standard test conditions (STC); an air mass of 1.5; cell temperature of 25°C and annual irradiance of 1000 W/m^2 (Peng, et al., 2017)

Solar Thermal

Petrichenko et al. 2019 identified that there is a significant potential to achieve net zero-energy building level via energy efficiency measures and building integrated solar energy supply. However, potential for coverage all load is lower in high rise buildings. Additionally, in colder climate countries like UK it is impossible to achieve net-zero energy levels with solar technologies alone, therefore auxiliary systems like HP should be also implemented (Petrichenko, et al., 2019).

Andreadis et al. (2013), based on Dundee as case study, showed that solar potential exists, capable of significantly reducing the fuel poverty if sufficient government funding is available. Moreover, they presented that by using bespoke solar thermal collectors, for instance a trapezoid shaped one, would give additional 8% of roof area for solar energy capture in Dundee. The optimally sized solar collectors could provide 83–97% and 30–62% of the hot water demands in summer and winter, respectively (Andreadis, et al., 2013).

Bornatico et al. (2012) by using particle swarm optimization algorithm for midsized family house achieved significantly lower solar fractions of 21.8%. However, this solar fraction was achieved by using a relatively large (14.5m²) collector together with a 500l water tank. The optimal size of the solar water heating system cylinder is 230 L, with suggested tank height of 1m and optimal mass flow rate of 40kg/h (Andreadis, et al., 2013).

2.4.4. Storage

The issues of the mismatch in time and magnitude of the available solar thermal energy and required heating load has led to intensive research into possible solutions. Seasonal solar thermal energy storage (SSTES) allows storing the excess energy generated in summer to be later used in winter months (Ma, et al., 2018). In this study, the critical collector size and storage capacity to meet 100% solar fraction, by using different storage technologies, was successfully estimated.

All different technologies have different drawbacks, where sensible heat storage has been demonstrated only in large scale district heating plants whilst the chemical and latent heat storage concepts are in laboratory study stages (Xu, et al., 2014).

Abualqumboz & Rodley (2018) mathematical modelling of Borehole TES in sandstone formations in Dundee. The system was set up to use the generated electricity to meet first electrical demand, second the heat pump, then, the excess energy is injected to the BTES (Abualqumboz & Rodley, 2018). The modelled charge period of BTES from May till September stores enough energy for a three month discharge period in following months. The presence of BTES increased the solar fraction (SF) significantly, however, the critical solar PV area that achieves 100% SF was not recommended as this would make it reduce the economic viability of the system (Abualqumboz & Rodley, 2018).

Latent storage

Latent storages devices are using phase change materials to store thermal energy. They offer a higher energy density and nearly constant temperature level in comparison to sensible storage (water cylinder) systems (Sunamp Ltd, 2019). There are only few consumer level produces utilising this technology. UK Company Sunamp Ltd is one of them; they are producing salt hydrate based latent storage units with a fin-tube heat exchanger (Waser, et al., 2018). However, current units requires flow temperature of 58°C, which forbids the use of low temperature heat pumps, which can reach only 55°C of flow temperature (Sunamp Ltd, 2019).

Da Chuna & Eames (2018) numerical model evaluated the replacement of gas fired boilers with heat pumps coupled with a latent thermal store. The reduced use of the HP at the time of peak electricity rates resulted in 58% lower CO_2 emissions. Moreover, these savings would improve even further in line with UK's electrical carbon intensity reduction. (da Cunha & Eames, 2018). Pointner & Steinmann (2016) argue that, when discharging, the heat flux for even state-of-the-art latent heat storage systems is decreasing significantly. Pointner & Steinmann (2016) illustrate that by mechanical separation of the storage material and heat exchanger allows to eliminate this problem.

A study done by Kelly et al. (2014) investigated the potential of a HP load shifting using a phase change material enhanced thermal storage. The results indicated that a relatively large conventional water cylinder of 1000 l would be required for HP load shifting for a typical UK detached house. The storage volume could be cut in half (500l) if PCM would be used. However, due to reduced COP of the HP when operating with thermal buffering as well as standing heat losses, there was a significant (60%) increase in energy consumption (Kelly, et al., 2014). Consequently, increasing the CO_2 emissions, however, this is partly due f the time-varying CO_2 intensity of the UK grid at the time of the study (Kelly, et al., 2014).

Cabrol & Rowley (2012) investigated the PCM use as thermal storage within the concrete floor slab in combination with under floor heating (UFH) and ASHP. Multiple PCM, building performance standards and climate setups were simulated. The results showed improved temperature stability during the heating season and reduced overheating during the summer months. Moreover, all cases achieved lower running costs as well as CO_2 emissions compared to a condensing gas boiler system. However, when utilising a floor-embedded PCM material, it was found that the thermal properties of the PCM material must be carefully matched with case-specific building fabric thermal performance parameters in order to ensure effective internal environmental control (Cabrol & Rowley, 2012).

Marczinkowski & Østergaard (2019), suggest that storage technologies such as BESS and TES should only be considered if the energy resources are well integrated. The analysis done in the EnergyPLAN shows that the BESS tends to only address the issues in the electricity sector, however, the TES solves some electricity sector`s problems as well as improving the heating sector (Marczinkowski & Østergaard, 2019). Moreover, freeing biomass resources which allow for some improvements in the transport sector. Both storage types increase the CAPEX, however, the total systems costs are lower with TES, and the BESS tends to increase the overall costs (Marczinkowski & Østergaard, 2019).

For all storage categories, costs tend to increase as a function of the retrofit level, as energy systems cannot be significantly downsized, and the energy cost savings are outweighed by the investments in retrofit (Marczinkowski & Østergaard, 2019).

2.5. Modelling, verification and validation.

The dynamic thermal modelling software is widely used for building and retrofit design. It allows to simulate and evaluate multiple what-if scenarios which can lead to an optimized design and retrofit solutions for buildings. There are number of energy simulation software available - ESP-r, EnergyPlus, eQuest, DOE-2, TRNSYS and IES-VE.

Building energy simulation models, are classified as prognostic law-driven models. They are used to estimate the outcome of a complex system given a set of well-defined laws, for example, heat transfer, mass balance, energy balance and conductivity (Coakley, et al., 2014).

PV*SOL is a dynamic simulation program of photovoltaic systems with 3D visualization and detailed shading analysis. It is used worldwide for the simulation and planning domestic and commercial scale PV systems (Valentin Software GmbH, 2019). PV*SOL is validated in the US National Renewable Energy Laboratory with measured annual performance gap of a less than ±8 % (Freeman, et al., 2014).

The Integrated Environment Solutions Virtual Environment (IESVE) is a dynamic building physics simulation tool. The IESVE allows to analyse the dynamic response of a building based on the hourly inputs and generate high resolution outputs. It is widely used tool in the industry, current users average 75 000 IESVE projects per year. The IESVE meet the following approved international standards (IES Ltd, 2019):

- CIBSE TM33 and CIBSE Guide A/ISO 7730 Calculation procedure
- EU EN13791: July 2000
- IES tools can undertake the following methodologies:
- UK National Calculation Methodology (NCM)

However, an increasing number of studies demonstrate the performance gap - the differences between the predicted and measured performance of the building (Yingchun, et al., 2019). It is a difficult task to represent building physics, all models are using assumptions. Often stochastic, non-linear values are replaced with fixed ones. For example, the infiltration rate, will be set as a fixed value, however, it is dependent on many factors, such as wind condition, temperature difference between indoor and outdoor space as well, not just the air tightness of the building (Yingchun, et al., 2019). Additionally, the occupancy behaviour is hard to predict with high certainty. However, these discrepancies can help to produce guidelines to educate the occupants how to use their buildings more efficiently or control device profiles (Judkoff, et al., 2008).

All of these tools have been validated by series of experiments, inter-program comparison exact analytical solution. The empirical validation is based on the comparison with real measurement data, this comparison provides the most reliable results. However, this approach is expensive and time consuming (Nageler, et al., 2018). Moreover, the empirical validation studies usually have been conducted for primitive situations under well controlled and monitored environments (Ahn, et al., 2016).

The difference between the analytical solution and the results from the simulation indicate an error in the algorithm of the code. The major test types are - temperature decay, steady-state conductivity, infiltration, glazing conductivity and transmissivity and mass charging by radiation (Judkoff, et al., 2008).

The performance gap is minimally affecting the results when comparing of relative difference between two designs (Judkoff, et al., 2008).

2.6. Summary

This chapter investigated the literature surrounding the research topic. The key points will be used in the following chapters.

This review established the scale and significance of domestic heating`s effect on the GHG emissions targets set out at global, individual country and even council level.

The recent Declaration of Climate emergency, ambitious Climate Change targets as well as multiple UK Government and local council policies and standards are pushing reduction of energy use and resulting CO_2 emissions through improved fabric efficiencies and incorporation of LZCGT.

However, many of the policies and targets are effective only on paper. UK Government has failed to eliminate the fuel poverty which mainly is caused by energy inefficient building stock. Additionally, the uptake rate of LZCGT technologies as a part of RHI scheme are below the original estimation. Therefore, this indicates that the carbon emission reduction practices in the residential sector need to be accelerated.

Furthermore, there are some contradiction actions taken by the UK government - the FiT scheme has been discontinued in the midst of Declaration of Climate Emergency, which is expected to significantly slow down the uptake of PV and other Microgeneration technologies in the residential sector. Furthermore, the ban on the future gas boiler installations in new builds is discussed at the same time when Fuel Poor Network Extension Scheme is set out to tackle fuel poverty. These actions cause a lot of uncertainties within the industry.

This chapter also introduced the deep retrofit standard EnerPHit and showed multiple case studies where it has been successfully incorporated into a retrofit projects. Although, there is a lot of attention given towards the passive house standards and overheating during the summer months, it is argued that with a proper, holistic design approach as well education of the end user, these issues can be eliminated.

More detailed look into the potential retrofitting approaches and technologies identified, that *fabric first* method is most rational approach for reducing energy demand, running costs and CO_2 emissions. Innovative net-zero deep retrofit concept developed by Energiesprong has achieved great results and high resident satisfaction rates. Additionally, relatively matured and still subsidies technologies like air and ground source heat pumps are in line with the decarbonising of the heat strategy as well as furthermore reducing CO_2 emissions. Heat pump technology suitability to meet the targets are even more amplified by the significant reducing in the last decade of carbon intensity of the UK grid. For the new SAP 10.0 an up to date value of 0.233 kg/kWh will be incorporated, allowing to compete with the Gas emissions.

There is strong consensus in the literature regarding the importance of the end user`s awareness and understanding of the technologies to achieve a successful implementation of LZCGT.

This chapter also briefly introduced the dynamic building physics and PV generation and shading simulation software IESVE and PV*SOL which was used in this research. Although, a performance gap between modelled and measured consumption exists in all modelling tools, it is minimally affecting the accuracy of decisions made by comparing relative difference between two or more designs.

The main takeaway is that the demand reduction should be prioritised and that electrification of heat via heat pumps will play a significant role in decarbonisation of the UK domestic sector.

3. Base model

The information about the current consumption is a crucial part of any improvement based analysis. This chapter will describe the case study used for this research and the input parameters and assumptions used to construct the base motel for the energy demand simulation in IESVE as well the PV generation simulation in PV*SOL.

3.1. Model description

A high rise residential building at 30 Invergyle Drive, Glasgow will be used as a case study for this paper. The building is rotated 15° east of true North and is the only high rise property in near proximity; therefore it is relatively exposed to the sun and dominant winds (Figure 8).

Figure 8 Surrounding area of the apartment block (Google LLC, 2019).

It was originally built in 1960s, however, an extensive improvement to the building fabric (external wall and loft insulation as well as window replacement) was done approximately ten years ago. Figure 9 shows that the existing external wall cladding and pitched roof have been added in the time period from January 2007- May 2009.

Figure 9 Satellite image from 01/01/2007 (left) and 31/05/2009 (right) (Google LLC, 2019).

Currently, the owner of the property, Southside Housing Association is undertaking another massive improvement to the building. The existing storage heaters and off peak immersion hot water cylinder are being replaced with an ASHP (placed on individual balconies) with wet radiator system and 170l hot water cylinder, (Dunn, 2019). Although the performance of this setup will be analysed, the benchmark model will be based on the existing system.

The building has 8 stories and it holds 30 flats - 16 two bedroom and 14 single bedrooms. South elevation has only two windows per floor; therefore, there is space for a building integrated solar PV panels (Figure 10).

Figure 10 Base model elevations (Holmes Miller Architects, 2019)

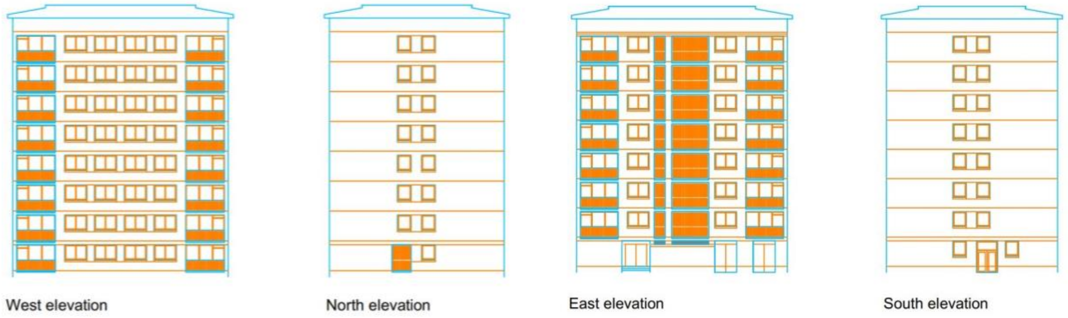
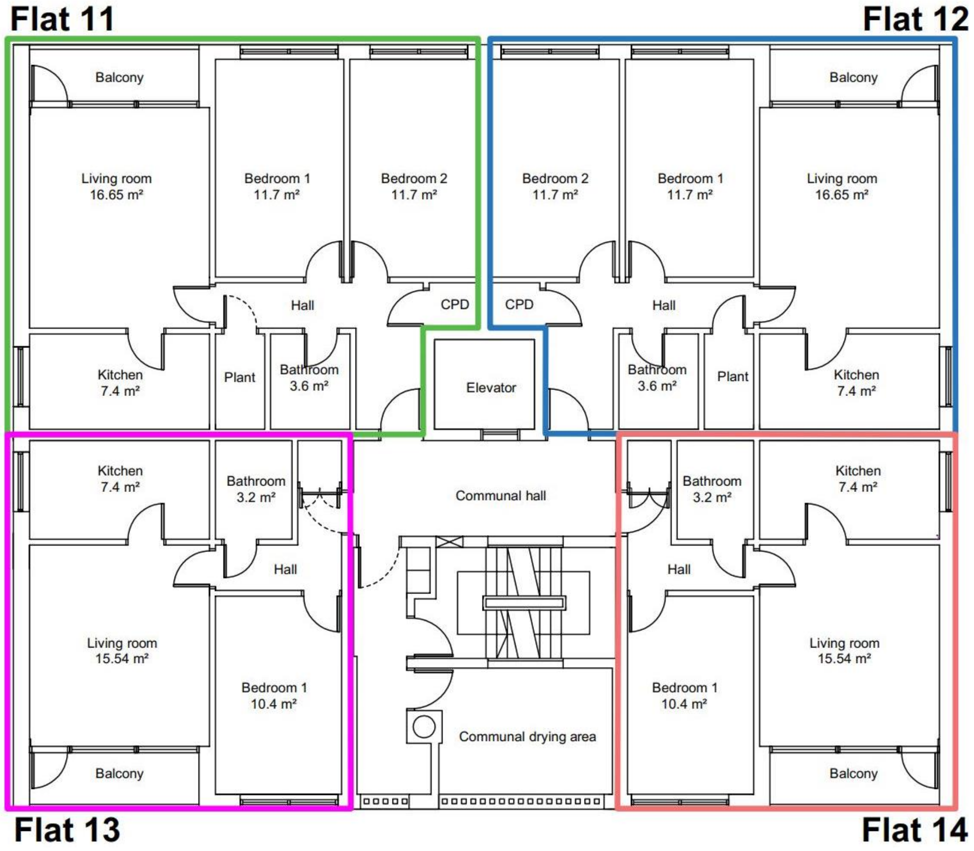


Figure 11 shows the layout of the floor 1 to floor 7. There are only two 2 bedroom flats, the remaining half is occupied by unheated communal areas. These exact dimensions and layout will be used to replicate the property in the IESVE. Total combined threated area is 1553 m². All communal areas will be unheated, however, the lighting and equipment loads of these areas will be included in the primary energy demand of building.

Figure 11 Base model layout 1^{st}-7^{th} floors (Holmes Miller Architects, 2019).



3.2. Assumptions and simplifications

Following assumptions and simplifications were used in this paper:

- Existing electric panel heater heating systems efficiency = 1
- DHW delivering efficiency = 0.95
- DHW supply temperature = 42 °C
- DHW storage temperature = 60 °C
- Every flat is occupied by typical working family; therefore, most of the energy consumption occurs outside the office hours.
- Outside CO_2 concentration = 400 ppm
- UK grid carbon intensity = 0.2556 kg/kWh (UK Government, 2019)
- Existing PVC double glassing windows are relatively new, therefore, any window replacement will reduce the infiltration only by 10%
- External wall insulation (EWI) upgrade will reduce the infiltration rate by 30%
- EWI and window replacement will reduce the infiltration rate by 40%
- Annual energy consumption of communal areas = 18768 kWh

- Elevator = 3000 kWh;
- Lights = 0.1 kW x 8 floors x 8760h = 7008 kWh
- Mechanical ventilation (extract only) = 0.5kW x 8760h = 4380 kWh
- Other loads = 0.5 x 8760 = 4380 kWh

3.3. Model input parameters

3.3.1. The weather input data

Climate plays a key role in the thermal performance of any building. The weather file for the simulation is based with climate data from Glasgow airport (55.87°N, 4.43°W). It contains following variables: dry bulb & wet bulb temperature, wind speed & direction, solar altitude & azimuth, solar radiation, cloud cover, atmospheric pressure, external moisture content for each hour of the year (Table 7).

Table 7 Glasgow airport weather data - Min, Max and Mean values.

Var. Name	**Unit**	**Min. Val.**	**Min. Time**	**Max. Val.**	**Max. Time**	**Mean**
Dry-bulb temperature	(°C)	-10.9	09:00,15/Feb	26.5	16:00,15/Aug	8.91
Wet-bulb temperature	(°C)	-10.9	09:00,15/Feb	21.1	16:00,15/Aug	7.41
External dew-point temp.	(°C)	-10.9	09:00,15/Feb	19.04	19:00,15/Aug	5.94
Wind speed	(m/s)	0	04:00,03/Jan	20.8	14:00,05/Dec	4.57
Global radiation	(W/m^2)	0	01:00,01/Jan	913.72	15:00,07/Jul	100.63
Solar altitude	(deg.)	0	01:00,01/Jan	56.7	13:00,21/Jun	11.6
External moisture content	(kg/kg)	0.0015	09:00,15/Feb	0.0138	19:00,15/Aug	0.0061
External relative humidity	(%)	29.5	15:00,16/May	100	01:00,17/Jan	82.7
Atmospheric pressure	(Pa)	96330	00:00,13/Feb	104160	09:00,06/Jan	101500
Cloud cover	(oktas)	0	00:00,03/Jan	8	01:00,01/Jan	5.87

The Table 8 shows the insignificant amount of hours when outdoor air temperature is above the design room temperature, therefore, the cooling demand will not be high enough to justify a cooling system.

Table 8 Hours per year when external dry-bulb temperature is above 22°C

Dry-bulb temperature above 22 °C					
°C	> 22.00	> 23.00	> 24.00	> 25.00	> 26.00
Hours in range	50	22	17	9	3

However, the outdoor air temperature below the base temperature of 15.5° C, which is industry practice (Day, 2006), occurs 7810 h or 89% of the year, therefore, indicating significant heating demand. The standard design outdoor temperature (DOT) for Glasgow is -4° C, this is used to determine the peak heat load in kW (for 99.6% of the year) and size the boiler accordingly (CIBSE, 2017). The climate date used in this simulation contains 65 (0.7%) hours of the year when the air temperature drops below -4°C, peaking at -10.9°C (Table 9).

Table 9 Hours per year when external dry-bulb temperature is below -4°C.

Dry-bulb temperature below -4 °C							
°C	< -10.00	< -9.00	< -8.00	< -7.00	< -6.00	< -5.00	< -4.00
Hours in range	1	5	9	15	28	42	65

3.3.2. Dimensions

Tables 10 and 11 shows the dimensional inputs that were used to model the 16 two bedroom and 14 single bedroom flats.

Table 10 Dimensions of the two-bedroom flats.

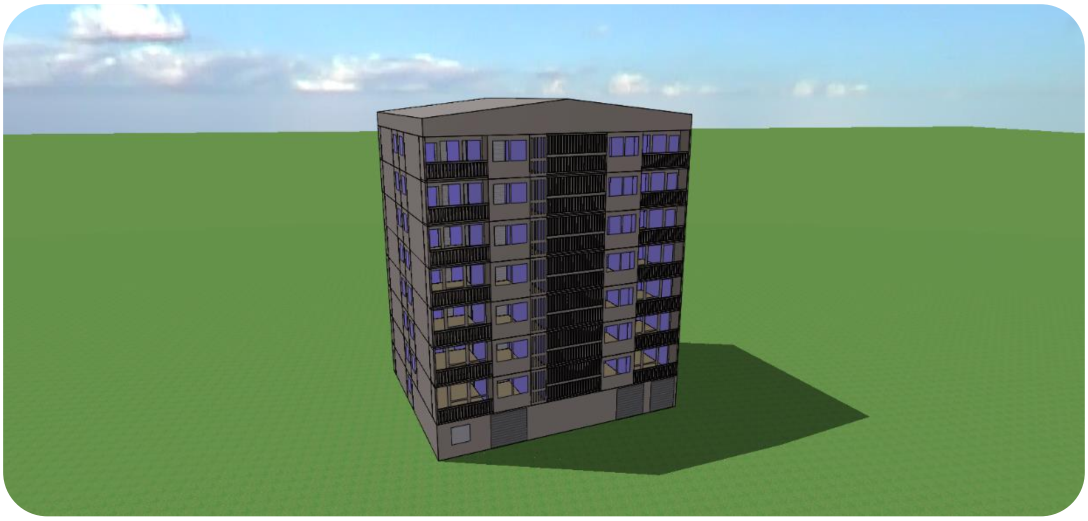
Room name	Room temp (°C)	Floor Area (m²)	Wall Height (m)	External Wall Length (m)	Glazing Area (m²)
Living room	21	16.65	2.50	8.20	5.95
Kitchen	18	7.40	2.50	2.00	1.18
Bedroom 1	18	11.70	2.50	3.60	2.37
Bedroom 2	18	11.70	2.50	2.60	2.37
Bathroom	22	3.60	2.50	-	-
Hall	18	6.40	2.50	-	-
CPD	16	1.20	2.50	-	-
Plant	16	2.00	2.50	-	-

Table 11 Dimensions of the single-bedroom flats.

Room name	Room temp (°C)	Floor Area (m²)	Wall Height (m)	External Wall Length (m)	Glazing Area (m²)
Living room	21	15.54	2.5	7.9	5.95
Kitchen	18	7.4	2.5	2	1.18
Bedroom 1	18	10.4	2.5	3.6	2.37
Bathroom	22	3.2	2.5	-	-
Hall	18	3.9	2.5	-	-
CBD	16	1.2	2.5	-	-

Figure 12 shows the 3D rendering of the benchmark property modelled in IESVE. This is the core model that will be used in all simulations.

Figure 12 Base model`s E elevation in IESVE.



3.3.3. Heating and DHW demand input variables

Due to the limited scope and time for this research as well as lack of real life consumption data, some simplifications and assumptions from will be used (Chapter 3.2) to simulate the energy demand of the base model. Moreover, the aim of this paper is not to develop model that will exactly match with the actual consumption of the property at 30 Invergyle drive. The goal is to quantify and compare the benefits and costs of suggested improvements for this type of building. Therefore, standardised energy and occupancy related variables from relevant UK regulations and industry practice was used (CIBSE, 2017), (British Standards, 2017). Table 12 shows heating, DHW, internal gain and air change parameters and profiles that were used for each room type.

Table 12 Thermal profiles for each room type.

Variable	Living rooms	Bedrooms	Kitchens	Bathrooms	Halls	Stores
Available heating capacity	1.6 kW	0.8 kW	0.8 kW	0.5 kW	0.5 kW	0 kW
Heating setpoint/setback	21°/18°	18°/18°	18°/18°	22°/18°	18°/18°	n/a
Heating profile	7-23; 23-7	7-23; 23-7	7-23; 23-7	7-23; 23-7	7-23; 23-7	7-23; 23-7
DHW consumption	n/a	n/a	n/a	40 l/pers/day	n/a	n/a
DHW profile	n/a	n/a	n/a	7-10 - 17-23	n/a	n/a
Lighting and equipment gains	100 W	30 W	100 W	30 W	25 W	10 W
Lighting diversity factor	0.5	0.5	0.5	0.5	0.5	0.5
Internal gain profiles	7-23; 0-24	7-23; 0-24	7-23; 0-24	7-23; 0-24	7-23; 0-24	0-24
People gains	90W per person (two bedroom flats - 3 pers.; single bedroom flats - 2 pers.)					
Infiltration rate	0.5 Ac/h	0.5 Ac/h	0.5 Ac/h	0.5 Ac/h	0.5 Ac/h	0.5 Ac/h
Natural ventilation rate winter	0.25 Ac/h	0.25 Ac/h	1.25 Ac/h	1.25 Ac/h	0.25 Ac/h	n/a
Natural ventilation rate summer	2 Ac/h	1 Ac/h	2 Ac/h	2 Ac/h	0.5 Ac/h	n/a
Natural ventilation profile	7-23	7-23	7-23	7-23	7-23	n/a

Details of the existing fabric properties were acquired from the Southside Housing Association, EPCs and site survey. Maximum heating capacity was limited to simulate more realising responsiveness of the heating system when trying to reach the set point temperature, however, the capacity is sufficient to offset the peak heat loss. The IESVE incorporates linear and thermal bridge losses in the U-value of each construction type (IESVE, 2019). Table 12 shows the combined U-values used for the benchmark model.

Table 13 Thermal properties of existing construction types.

Construction type	Insulation thickness	Insulation conductivity	Total thickness	U-value
Ground floor	50 mm	0.05 W/mK	370 mm	0.61 W/m²K
External walls	100 mm	0.05 W/mK	330 mm	0.39 W/m²K
Ceiling/floor	-	-	280 mm	1.01 W/m²K
Windows	-	-	18 mm	2.58 W/m²K
Doors	-	-	37 mm	2.16 W/m²K
Roof	200 mm	0.039 W/mK	390 mm	0.18 W/m²K
Party walls	-	-	102 mm	1.87 W/m²K

3.4. Base model simulation outputs

This paper will investigate only the change in energy used for thermal conditioning of indoor climate and DHW heating. Lighting, occupancy, equipment gains will be fixed for all models.

Table 14 shows that annually 153.24 MWh of electric energy is required to maintain the indoor air temperature at set levels and provide DHW for the tenants. Heating system capacity peaks at 73 kW or ~2.4 kW per flat. Additionally, the Predicted Percentage of dissatisfied (PDD) is kept within acceptable levels (British Standards, 2005), however, the mean CO_2 concentration is above the acceptable levels (Department for Education, 2016). This is because the night time occupancy, when the ventilation rates are the lowest, is placed into the bedroom and day time into the living room. Exhaled, CO_2 is the only source of this pollution in the model. To tackle this, ventilation rates would need to be increased beyond rational levels even during the heating season.

Table 14 Main energy and thermal comfort outputs of the base model.

Variable	**Building**	**Living rooms**	**Kitchens**	**Bedrooms**	**Bathrooms**	**Halls**
Heating (kWp)	72.77	1.33	0.36	0.34	0.38	0.29
Air Temperature (°C)	18 - 27.2	18 - 27.2	18 - 25.7	18 - 27.1	18 - 24.1	18 - 23.3
Mean CO_2 (ppm)	847	1335	400	1698	400	400
Overheating, T > 25°C	-	0.56%	0.09%	1.9%	0%	0%
Mean PDD (%)	9	7	11	10	8	11
Heating (MWh/y)	**108.86**	-	-	-	-	-
DHW (MWh/y)	**44.38**	-	-	-	-	-

Figure 13 show the significant fluctuation of the space heating demand throughout the year and steady DHW demand. Resulting specific heating demand is 70 kWh/m²/y, which is significantly higher than EnerPHit requirements of 25 kWh/m²/y.

Figure 13 Monthly heating and DHW demand (MWh)

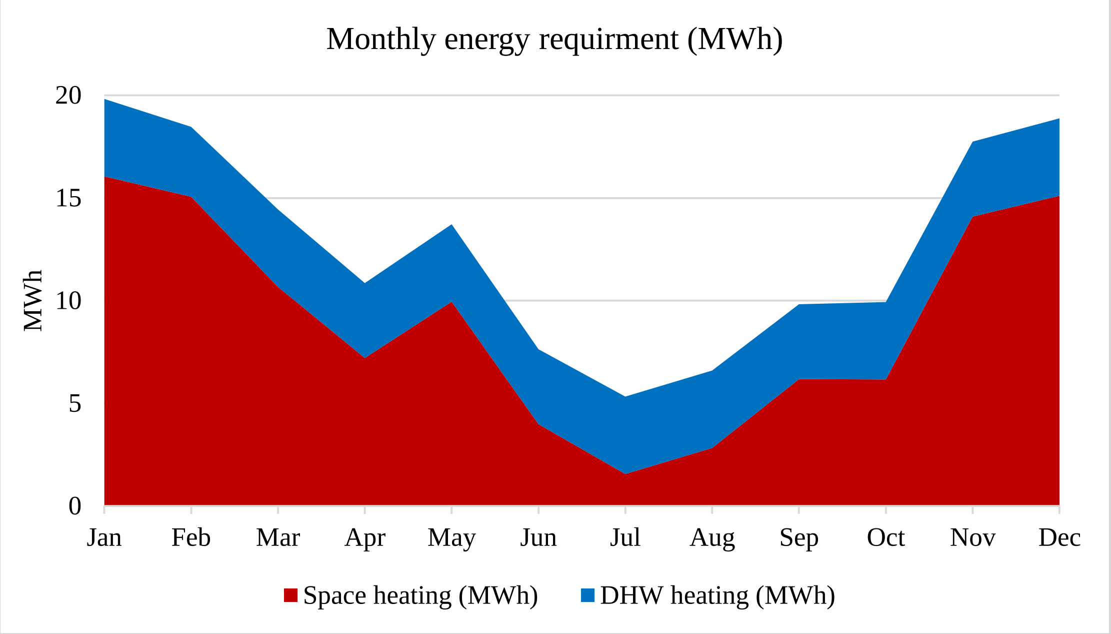
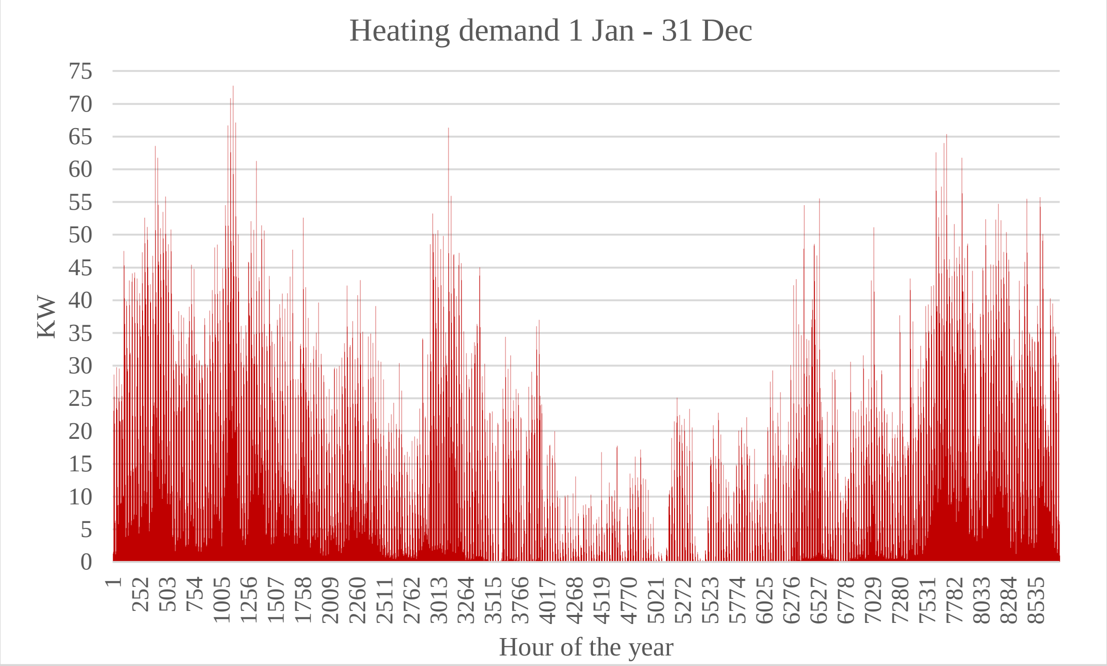


Figure 14 shows the hourly peak space heating load for the building throughout the year. The resulting specific heat load for the building is 47 W/m².

Figure 14 Hourly heating demand base model (1 Jan - 31 Dec).



3.5. Base model verification and validation

To illustrate the computational logics behind the IESVE dynamic simulation and gain some confidence in the model, verification by demonstration will be used as the primary verification method of the outputs of the base model.

The temperature difference is the main driver of the heat transfer, Figure 15 shows the expected direct correlation between the heating degree days (Glasgow Airport, base temperature of 15.5°C) and heating demand throughout the year (BizEE Software Limited, 2019). The sharp discrepancies during May and November is caused by the seasonal natural ventilation rates applied to the model where summer period is from the beginning of the May till end of October. Additionally, the time period of degree day data available online for free comparing to averaged outdoor temperature data in the default IESVE weather file for Glasgow Airport is causing some minor discrepancies.

Figure 15 Correlation between HDD and space heating demand.

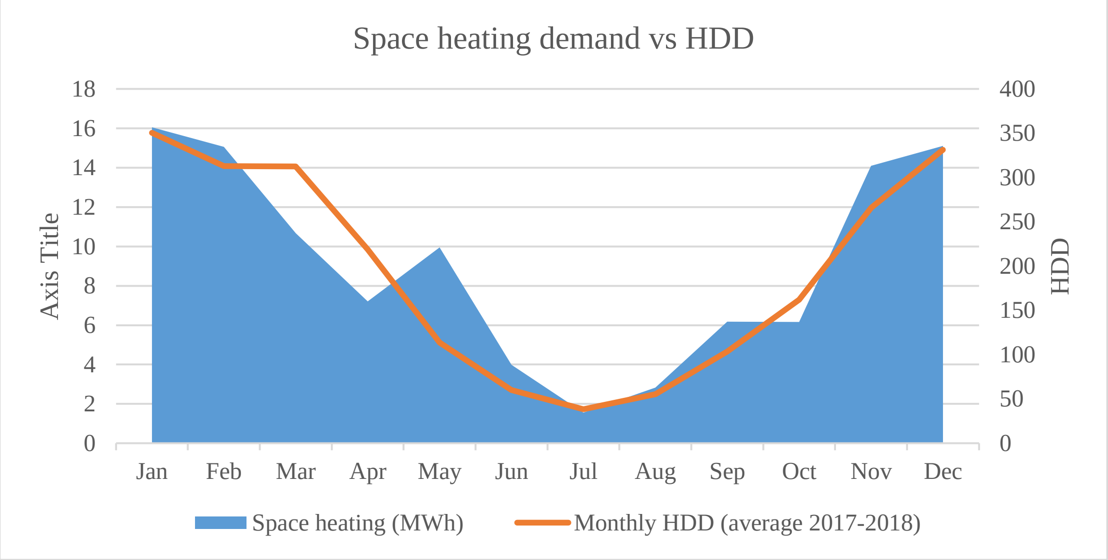


Figure 16 shows that the heating system is capable to meet the target temperature of the living room at the coldest day of the year. Although, the night set-back temperature period ends at 7:00, the heating load increases rapidly already at 6:00. This is to allow the target temperature of 22°C to be met exactly at 7:00. Although, the heating load starts to decrease at 8:00 and the outdoor air temperature increase at 10:00, it is clearly visible that the heating demand is inversely proportional to the outdoor temperature. The heating power draw decrease two hours prior is because target temperature was already met an hour before.

Figure 16 Living room temperature and heat load (15 Feb).

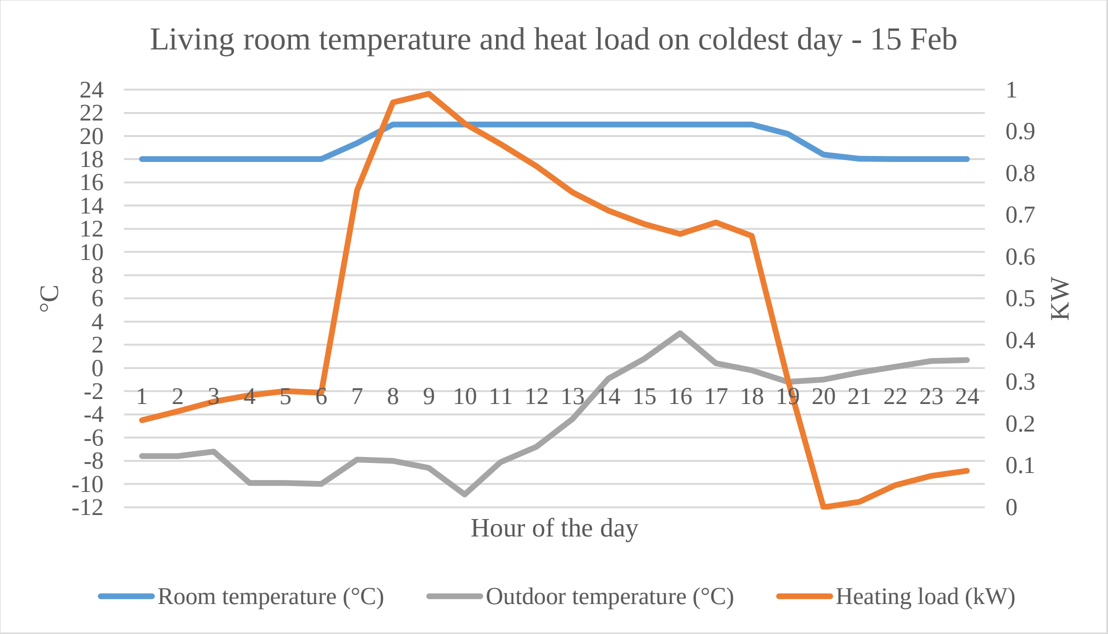


Figure 17 illustrates that the heating system is not being used, additionally, the natural ventilation alone is not sufficient mean of keeping the room temperature bellow 25°C in summer. As the outdoor temperature increases, the negative internal gain (cooling) of the indoor room decreases, until the freshly brought outdoor air starts to contribute to the heat gains and overheating during the hottest days of summer.

Figure 17 Living room temperature and heat load (15 Aug).

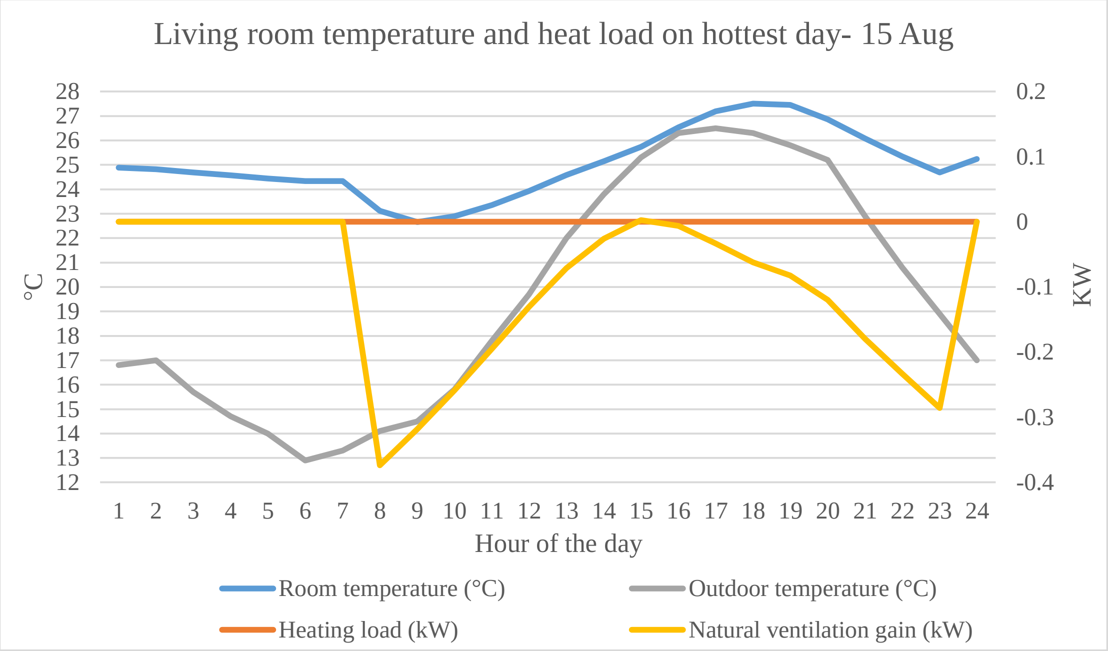
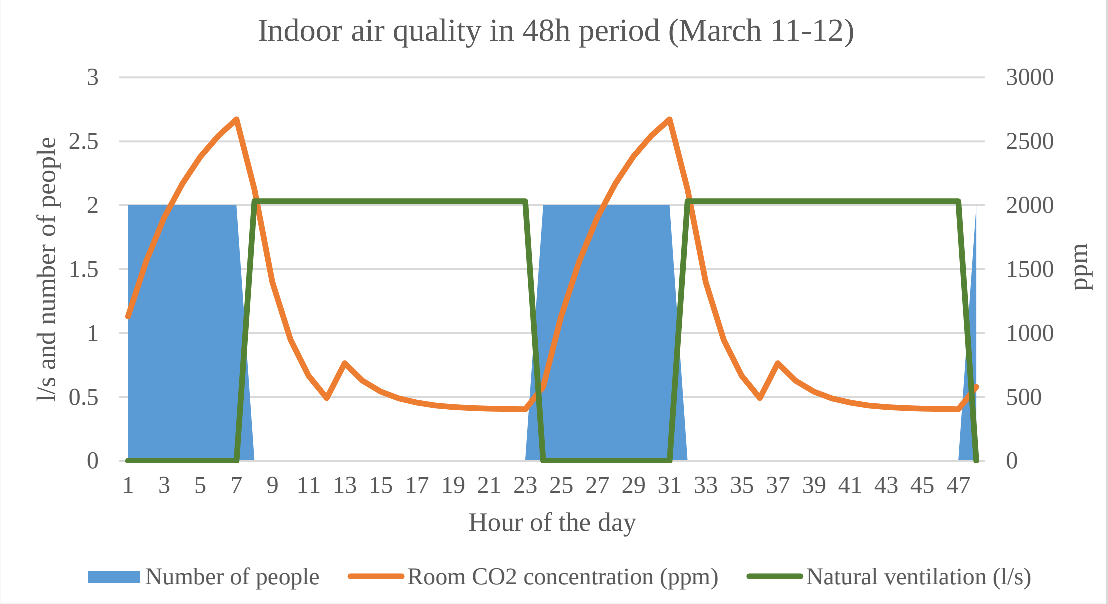


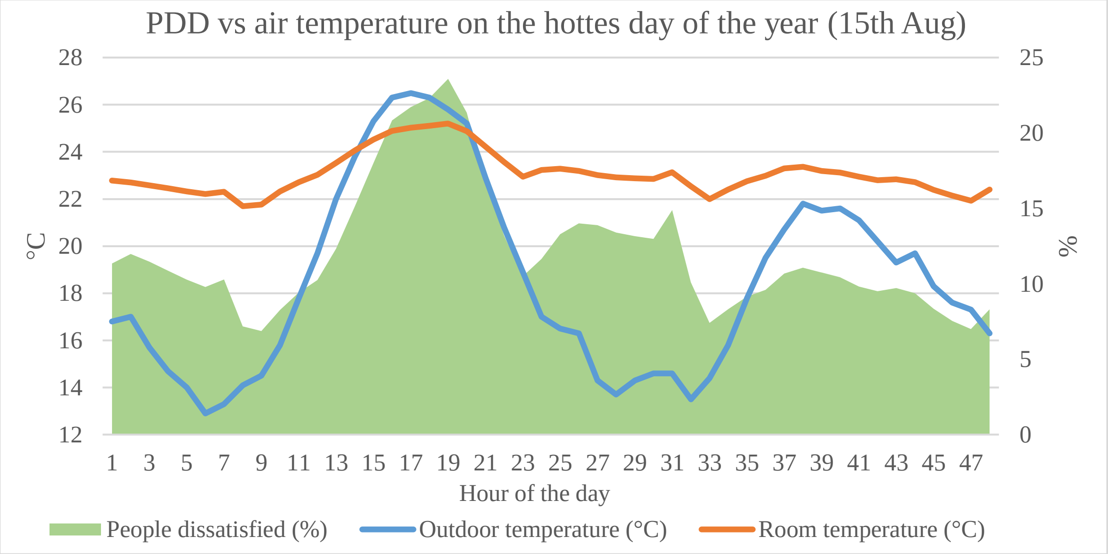
Figure 18 shows the direct correlation between the occupancy, ventilation rates and CO_2 emissions. Double bedroom at night is occupied by two people, therefore, significantly increasing the CO_2 levels above the recommended levels of 1000 ppm (Department for Education, 2016). At 7:00 o'clock, the natural ventilation (opening of a window) pattern starts, this rapidly reduces the CO_2 concentration down to background levels of 400 ppm.

Figure 18 CO_2 concentration in the bedroom (11-12 March).



Although, the absolute temperature is not the only factor affecting Predicted Percentage of Dissatisfied (thereafter, PDD) (British Standards, 2005), the Figure 19 shows that the rapid outdoor air temperature increase, during the morning of the hottest day of the year, causes the indoor air temperature to increase above 22°C and, therefore, the PPD to increase from close almost minimum of 5% up till 24%.

Figure 19 PDD and air temperatures on 15-16th Aug.



Validation is a crucial step in building physics modelling. Unfortunately, real life consumption data of this property is not available, therefore, other methods were used to determine the degree to which the model is an accurate representation of the real world.

First, the outputs of the base model was compared with the key results generated by using the CIBSE *Domestic Heating Design Guide*, which is based on British Standards (BS EN 12831-1:2017). Second, it was compared with outputs form a Reduced Data SAP (RdSAP) calculations.

Table 15 shows the comparison of main output between the base model and both, CIBSE and RdSAP method. Annual heating demand estimate using CIBSE method is 18% higher; however, DHW demand is 7% lower than the base model. Increased heating demand could be caused by the constant air change rate used in CIBSE method, versus winter and summer rates applied for the base model. RdSAP results are as follows – the heating demand estimation is 17% lower and DHW demand is 24% higher. This difference in heating demand might be caused due to the fact that air change rates cannot be manually inputted in RdSAP software. Regarding the hot water demand, the occupancy and daily water per person values cannot be matched with the CIBSE or base model.

Table 15 IESVE base model`s outputs comparison with CIBSE and RdSAP.

	Base model	CIBSE	% of base model	RdSAP	% of base model
Heating @ -9.4°C (kWp)	**72.77**	82.09	113%	-	-
Heating (MWh/y)	**108.86**	128.04	118%	79.5	73%
DHW (MWh/y)	**44.38**	41.27	93%	54.91	124%
Total CO_2 emissions (kg/y)	**42907**	47407	110%	37625	88%
Living rooms @ -9.4°C (kWp)	**1.33**	1.23	92%	-	-
Kitchens @ -9.4°C (kWp)	**0.36**	0.39	108%	-	-
Bedrooms @ -9.4°C (kWp)	**0.34**	0.38	112%	-	-
Bathrooms @ -9.4°C (kWp)	**0.38**	0.19	50%	-	-
Halls @ -9.4°C (kWp)	**0.29**	0.37	128%	-	-

Interestingly, the CIBSE method`s calculated heating demand is 61% higher comparing to RdSAP software. This shows that both methods would need some amendments. Nevertheless, knowing how many stochastic and non-linear parameters are involved in a dynamic building simulation, the combined space and hot water demand differences of +10% and -12% for CIBSE and RdSAP respectively, gives enough confidence in the accuracy of the base model.

In this chapter, the base model was described, analysed and validated. The simulated heating demand of 70 kWh/m²/y now can be used as benchmark for the applied retrofit solutions in the following chapter.

4. Potential retrofit solutions

This chapter will describe and analyse the proposed retrofit solution for energy demand reduction and as supply options. The aim is to identify the general feasibility of a retrofit solution as well as the potential of achieving EnerPHit standards. EnerPHit *alternative* method`s main requirement is to keep the annual space heating demand below 25 kWh/m². Additionally, annual frequency of overheating (indoor temperature above 25°C) below 10% and excessive humidity (absolute indoor humidity above 12 g/kg) below 20% *(Passive House Institute, 2016)*. Therefore, following indicators were used to analyse and propose recommended retrofit:

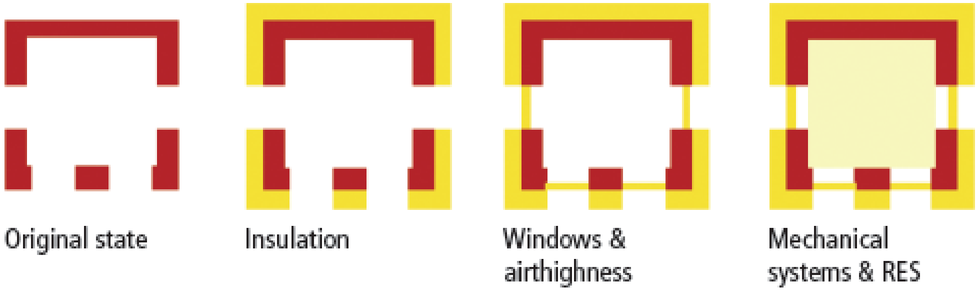
1. Annual energy demand for space and DHW heating (kWh).
2. Annual CO_2 emissions for space heating and DHW water (kg).
3. Primary energy (PE) demand (kWh/m²/y).
4. Percentage of overheating hours (%).
5. Percentage of excessive humidity hours (%).
6. Relative CO_2 emission reduction (£/kg of CO_2).

The chapter consists of description of executed simulations, finance data used, key result analysis, recommendation of the final solution and a brief summary.

4.1. Executed simulations

The main takeaway from the literature review was that the *fabric-first* principle is most rational approach when planning energy efficiency retrofit for a building. Potential solutions will be applied and analysed following component by component approach (Figure 20).

Figure 20 Component by component retrofit approach (source: www.europhit.eu).



To investigate the potential of reducing the specific heating demand to meet EnerPHit requirements of 25 kWh/m² per year, following *Insulation* related retrofit activities were simulated using IESVE:

1. **Additional 100 mm of external wall insulation (EWI).**

PermaRock Mineral Fibre; λ = 0.036 W/mK; New U-value = 0.177 W/m²K.
Following the Grenfell tragedy, the use of combustible materials in high rise buildings are banned *(CIBSE, 2018)*. Chosen product is fire tested in accordance with BS 8414 - compliant with BR 135, additionally, it can be used on buildings over 18m. The installation of any additional EWI will require scaffolding that fully surrounds the building. Therefore, the cost of the insulation material itself is relatively small share (11%) of the total cost of the improvement.

2. **Additional 200 mm of external wall insulation.**
3. **Additional 100 mm roof insulation.**

ROCKWOOL mineral wool; λ = 0.044 W/mK; New U-value = 0.138 W/m²K.
The existing flat part of the roof is easily accessible and additional insulation can easily be added on top of existing 200mm insulation.

4. **Additional 200 mm roof insulation.**
5. **Additional 100 mm external wall insulation and 100 mm of roof insulation.**
6. **Additional 100 mm external wall insulation and 200 mm of roof insulation.**
7. **Additional 200 mm external wall insulation and 200 mm of roof insulation.**

Following *Window & airtightness* related retrofit activities were simulated:

1. **Existing window replacement with double glassed windows.**

Planitherm Total+; U-value = 1.42 W/m²K; g-value = 0.71.
Depending on which way the glazing bars are fitted, it might be possible to replace the windows from inside. For this solution, no scaffolding cost will be included.

2. **Existing window replacement with triple glassed windows.**

Planitherm Total+; U-value = 0.80 W/m²K; g-value = 0.61.
For this solution, no scaffolding cost will be included.

The next step, after energy demand reduction measures are applied, is to investigate, the indoor air quality and the effect of and MVHR system. Afterwards, the low or zero carbon generation technology adaptation will be considered. Initially, the LZCGT will be applied to base model, thereafter, they will be applied to the chosen energy demand reduction solution. Finally, the MVHR will be applied to the base model as well as the final recommended system.

Following *Mechanical & RE systems* related retrofit activities were simulated:

1. **MVHR system installation.**

Nuaire WM1 MVHR unit; Specific fan power = 0.73 W/l/s; HR_{η} = 91% Max airflow rate = 180 m^3/h.
This unit is capable to provide an average of 3.6 Ac/h (extract) for the kitchens and bathrooms, and 1.8 Ac/h (supply) for Living rooms and bedrooms in two bedroom flats and 2.8 Ac/h in single bedroom flats.

2. **Individual ASHP installation for space and DHW heating.**

Mitsubishi Ecodan (5kW) ASHP + 150 l DHW cylinder + wet radiator distribution system for each flat.
This system would replicate the on-going retrofit in the building used for the case study. Each of the flats has a balcony which can accommodate an ASHP. Although, the peak heat load is smaller than 5 kW, this is the smallest, widespread available domestic ASHP size. Additionally, it provides faster hot water tank recharging times. All Mitsubishi Ecodan units an inverter driven, therefore, it can modulate the output to match demand. Weather compensation is included by default.

3. **Communal ASHP installation for space and DHW heating.**

Mitsubishi CAHV (45 kW) ASHP + 1000 l thermal buffer + HIUs + wet radiators.
The main benefit of a communal system is that due to the diversity factor for space and DHW heating, the system can be sized smaller than the peak load (72.7 kW). For the base model, only 228h or 2.6% of the year, the space heating load is above 45 kW. Additionally, the thermal mass of the building and combined water volume in all radiators and pipework serves as a thermal store. Added 1000 l buffer cooled from 55°C down to 45°C can provide 23 kW load for 30 minutes, which can be recharged

in 15 minutes. Additionally, at least 360 litres are required for defrost cycle *(Mitsubishi Electric Corporation, 2012)*.

This solution might not be suitable for those landlords who do not want to administrate the individual heat meter measurements and deal with payment collection for the individual tenants. Therefore, an individual ASHP on each balcony might be more preferable option, as the cost of heating and DHW is added to the electricity bill.

4. Communal GSHP installation for space and DHW heating.

3 x NIBE F1355-28 (84 kW) GSHP + 500 l thermal store + HIUs + wet radiator distribution system.

For this system the benefits of utilising the Tier 1 RHI tariff makes that it is more economically beneficial to go for the oversized system rather than sized for 100% of the load or less due to diversity factor and thermal store.

Table 16 shows that three F1345-40 (46kW) units will give the highest RHI income in 20 years.

Table 16 Non-Domestic RHI for different GSHP sizes.

Units	Model	Max Output	% of Peak	FLEQ run hours	Cost	Total RHI	Benefit in 20 years	SCOP at 55°C
1	1345-40	46 kW	63%	3331	£11,933	£204,660	£0	3.56
2	1345-40	92 kW	126%	1666	£23,865	£303,205	£86,612	3.56
1	1345-60	67 kW	92%	2287	£13,979	£249,648	£42,942	3.42
2	1355-28	56 kW	77%	2736	£16,688	£226,083	£16,668	3.77
3	1355-28	84 kW	115%	1824	£25,032	£286,067	£68,308	3.77

However, a system consisting of 3 x 1355-28 inverter driven heat pumps has higher seasonal efficiency, lower annual running hours, start/stop cycles and higher robustness due to higher redundancy. Therefore, selected system will consist of three 28 kW units. Although, no thermal store is needed for peak shaving as the units are inverter driven and can modulate in line with the demand and the total capacity for two units are exceeding the peak heat load, it will be added to reduce the start/stop cycles.

To supply the base model, an 1800 m combined depth of vertical ground collector is required (Appendix 1). Estimate is based on MCS installation standard: MIS 3005 and values from MCS 022 lookup tables *(DECC, 2013)*, *(DECC, 2011)*. For the case study tower block, there is sufficient land available in close proximity to accommodate 10 x 180m boreholes spaced 10m apart from each other (*Figure 21*).

Figure 21 Borehole layout at 30 Invergyle Drive 30 (Image from: Google LLC).

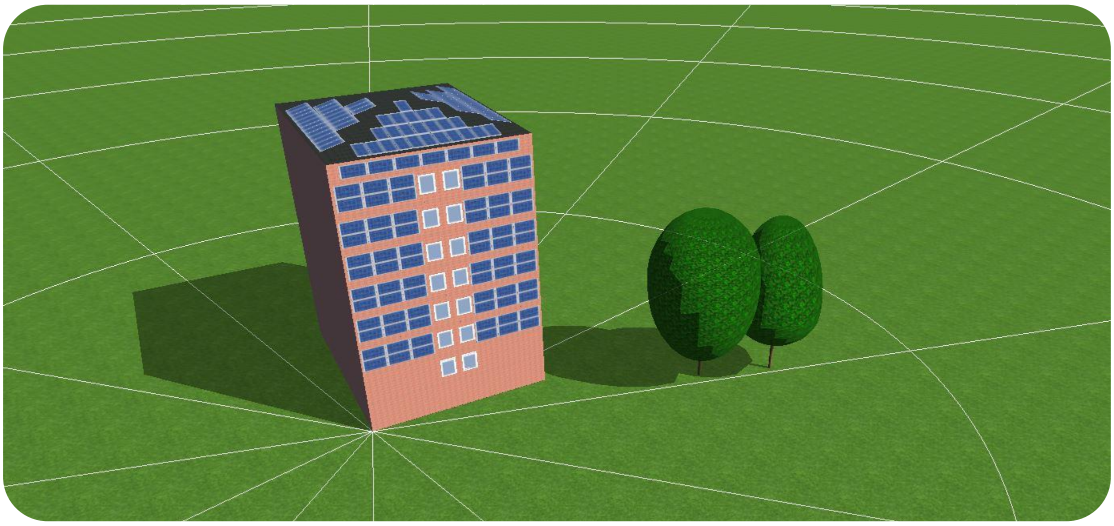
Total length depends on the actual ground conductivity and drilling conditions. In addition, not every high rise will have a suitable land nearby for a ground collector.

5. Building integrated PV installation.

A 46.5 kWp PV system integrated in the South facing façade and on East, South and West roof tops. It will consist of 150 x 310 Wp Trina Solar Mono PERC modules and 30 x Solis 1500 mini 4G inverters. This would utilise all available exposed surface of the building (*Figure 22*). The system will be split in 30 equal parts – 5 panels or 1.55 kWp for each flat. This approach will double the cost of inverters comparing to 2 x 20 kW or 1 x 40 kW equivalent, additionally, the installation cost and conversion losses will be higher. However, this will allow to utilise the single phase supplies and existing load in each flat and, therefore, avoid the potential issues and costs related with the District Network Operator (DNO) approval. Moreover, the alternative single inverter system, connected to the communal loads, would export most of the generated electricity.

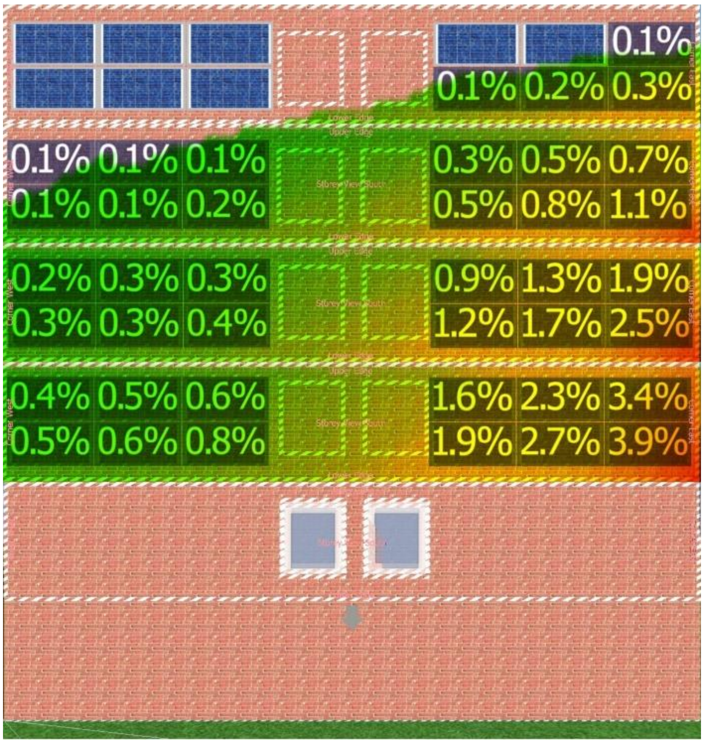
This PV system will be implemented only if the scaffolding for EWI will be erected. The estimated generation was simulated using the PV*SOL software, which will do the hourly demand and supply matching and shading loss calculation. The first two floors are obstructed, therefore, the panels are added only starting from the 3rd floor (*Figure 22*).

*Figure 22 BiPV model in PV*SOL.*



Two adjacent trees were added as shading object. Although, in early winter morning, the lower rows will be shaded, on annual basis the loss of generation is insignificant (Figure 23).

*Figure 23 Annual generation loss due to shading (2nd-5th floors) PV*SOL.*



Some considerations is needed for the practical integration of the panels within the façade, due to original 100mm and planed additional 100-200mm EWI.

4.2. Finances

Running costs and RHI income:

- The running costs of current and heat pump systems, and PV generation savings are based on 0.15 £/kWh for electricity (UK Government, 2019).
- The seasonal coefficient of performance (SCOP) for the individual 5 kW Mitsubishi ASHPs – for heating at 45°C = 3.56; for DHW at 55°C = 3.21. Communal 45 kW ASHP – for heating and DHW at 55°C = 3.11.
  Communal 46 kW GSHP – for heating and DHW at 55° = 3.56 (MCS, 2019).
- Legionella protection costs – once per week, 150l tank heated from 55°C to 60° with electric immersion heater.
- Domestic RHI tariff for ASHP – £0.1071 for every renewable kWh generated. Non-Domestic RHI tariff for ASHP – £0.0275 for every kWh generated. Non-Domestic RHI tariff for GSHP – Tier 1 = £0.0956; Tier 2 = £0.0285 for every kWh generated (Ofgem, 2019), (Ofgem, 2019). Tariffs adjusted in line with the Consumer Prices Index (CPI) – 2%.

Capital investment costs:

The cost for MHVR is based on following (BPC Ventilation LTD, 2019):

- £550 per flat for the unit;
- £300 per flat for ducting and £200 per flat for other materials;
- 300 £/day of a two man team and one 2 man day per flat;
- 30% mark-up added by main contractor.

The cost for EWI is based on 1365 m² wall area and following (Greenage, 2016):

- 12 £/m² for insulation, 10 £/m² for additional materials;
- 300 £/day of a two man team and one 2 man day per floor per façade;
- 25 £/m² for scaffolding;
- 30% mark-up added by main contractor.

The cost for roof insulation is based on 265 m² roof area and following (Insulation shop Ltd, 2019):

- 7.77 £/m² for insulation, 3 £/m² for additional materials;
- 300 £/day of a two-man team and five 2 man days for the job;
- No costs for access as it is a flat roof insulation job;
- 30% mark-up added by main contractor.

The cost for window replacement is based on following (Windows Guide, 2019):

- 30 large, 46 medium, 30 small windows at £1200, £500 and £400 respectively;
- +30% increased costs for triple glazed windows;
- 400 £/day of a two-man team and two 2 man days per flat;
- £100 per flat for additional materials;
- 30% mark-up added by main contractor.

The cost for individual ASHP system are based on following (:

- £3300 for the heat pump, £1200 for pre-plumbed water tank per flat;
- £150 for radiators +TRVs;
- 5 radiators for single bedroom flats and 6 for double bedroom flats;
- £200 per flat for additional materials;
- 400 £/day of a two-man team and two 2 man days per flat for installation;
- £250 for wiring and £125 for commissioning per flat;
- 30% mark-up added by main contractor.

The cost for communal ASHP system is based on following (Dunn, personal communication, 7th August):

- £17300 for the unit, £1500 thermal store, £1500 for plant room materials;
- £150 for radiators +TRVs, £1500 for HIU with heat meter;
- 5 radiators for single bedroom flats and 6 for double bedroom flats;
- £200 per flat for additional materials;
- 400 £/day of a two-man team and two 2 man days per flat for installation;
- 400 £/day of a two-man team and five 2 man day in the plant room;
- £250 for wiring and £125 for commissioning per flat;
- 30% mark-up added by main contractor.

The cost for communal GSHP system is based on following (Dunn, 2019):

- £25032 for 3 x GSHPs, £1500 thermal store, £1500 for plantroom materials;
- £150 for radiators +TRVs, £1500 for HIU with heat meter;

- 5 radiators for single bedroom flats and 6 for double bedroom flats;
- £200 per flat for additional materials;
- 400 £/day of a two man team and two 2 man days per flat for installation;
- 400 £/day of a two man team and five 2 man day in the plant room;
- £250 for wiring and £125 for commissioning per flat;
- 60 £/m for the borehole materials and labour;
- 30% mark-up added by main contractor.

The cost for solar PV system are based on following (CCL Components Ltd, 2019):

- 150 panels at £90 per panel and £30 per panel for mounting kit;
- 30 inverters at £185 per inverter;
- £75 per inverter for cables, DC and AC isolators, generation meters;
- 400 £/day of a two man team and one 2 man days per floor/roof;
- £125 per inverter for wiring and commissioning,
- 30% mark-up added by main contractor.

4.3. Simulation key results and analysis

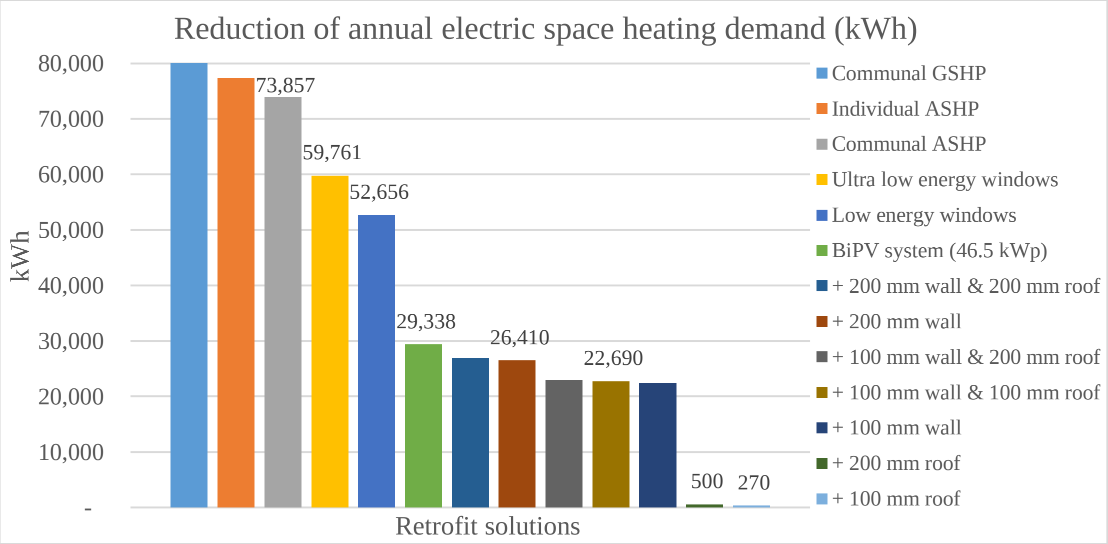
Table 17 lists all conducted simulations and their performance comparing to existing building – base model. None of the modelled solutions meet the EnerPHit space heating (> 25 kWh/m²/y), however, the MVHR solution meets the frequency of excessive humidity standard (>20%) at the cost of increased energy demand.

Table 17 Key outputs for all improvements.

Model	Capital costs	Heating and DHW el. (kWh/y)	Heating demand (kWh/m²y	Heating load (kWp)	CO_2 emissions (kg/y)	Running cost	Available subsidies	Cost of CO_2 reduction (£/kg)	Annual overheating hours	Annual excessive humidity
Existing	**£0**	**153,240**	**70**	**72.8**	**42907**	**£22,986**	**£0**	**0**	**0.6%**	**25.9%**
+ 100 mm wall	£139,562	130,840	56	64.3	36635	£19,626	£0	22.25	0.7%	35.1%
+ 200 mm wall	£160,856	126,830	53	62.8	35512	£19,025	£0	21.75	0.7%	35.6%
+ 100 mm roof	£5,614	152,970	70	72.7	42832	£22,946	£0	74.25	0.6%	25.9%
+ 200 mm roof	£8,597	152,740	70	72.7	42767	£22,911	£0	61.40	0.6%	25.9%
+ 100 mm wall & 100 mm roof	£145,175	130,550	55	64.3	36554	£19,583	£0	22.85	0.7%	35.1%
+ 100 mm wall & 200 mm roof	£148,158	130,300	55	64.2	36484	£19,545	£0	23.07	0.7%	35.1%
+ 200 mm wall & 200 mm roof	£169,452	126,271	53	62.7	35356	£18,941	£0	22.44	0.7%	35.6%
Low energy windows	£133,380	105,303	39	60.2	29485	£15,795	£0	9.94	10.0%	32.6%
Ultra low energy windows	£162,864	93,479	32	51.8	26174	£14,022	£0	9.73	12.5%	33.5%
MVHR	£66,300	161,351	73	70.2	45178	£24,203	£0	-29.19	0.6%	16.0%
Individual ASHP	£222,495	44,404	-	-	12433	£6,661	£86,656	4.46	-	-
Communal ASHP	£173,485	49,273	-	-	13797	£7,391	£102,392	2.44	-	-
Communal GSHP	£323,937	40,647	-	-	11381	£6,097	£286,067	1.20	-	-
BiPV system (46.5 kWp)	£47,125	153,240	-	-	8215	£18,585	£0	2.54	-	-

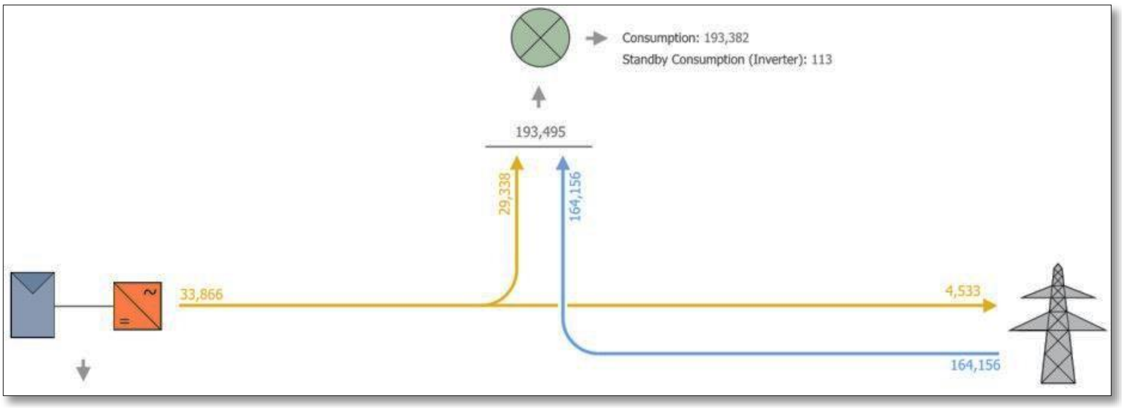
Figure 24 shows that the absolute reduction in space heating demand achieved by the additional roof insulation is insignificant (<1%). It is due to the relatively small exposed area and the fact the existing insulation levels were not terrible. Additional wall insulation combinations achieve around 20-24% reduction and window replacement retrofits 48% and 55% reduction for double and triple glassed option respectively. It is clear that all three heating supply options achieved the highest reduction in heating demand. However, this is a reduction of electric import from the grid, which will affect only the running costs and GHG emissions, the energy efficiency of the building remains the same. Therefore, a combination of both – the window replacement and improved insulation, will be required to be able to achieve EnerPHit standards.

Figure 24 Reduction of annual space heating demand for all simulations.



Due to existing heating and DHW system type (direct electric) and relatively low available space for renewable electricity generation (46.5 kWp), the modelled onsite consumption is 86.6%. Therefore, the heating and DHW energy demand for the building is reduced by 29 338 kWh/y (*Figure 25*). The solar fraction of the proposed PV system is 15.2% and 4533 kWh/y are exported to the grid.

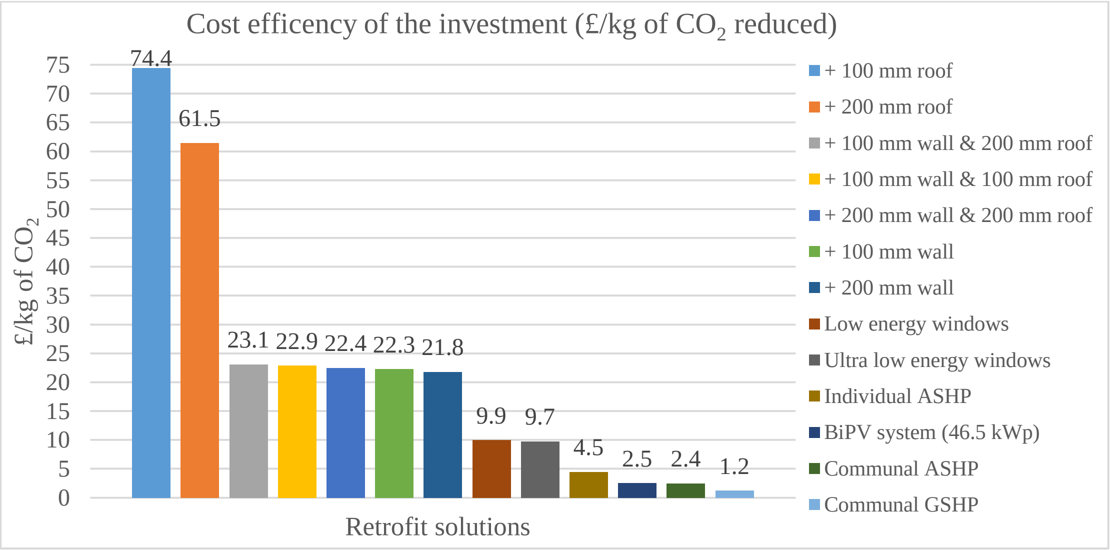
*Figure 25 Energy flow graph of a 46.5 kWp PV system (output from PV*SOL).*



Both window replacement simulations halved the heating demand of the building. However, a drastic increase of the overheating frequency from 0.7% up to 10% and 12.5% for double and triple glassed windows respectively, was observed. This is caused by the reduced air infiltration levels as well as the g-value of the new windows.

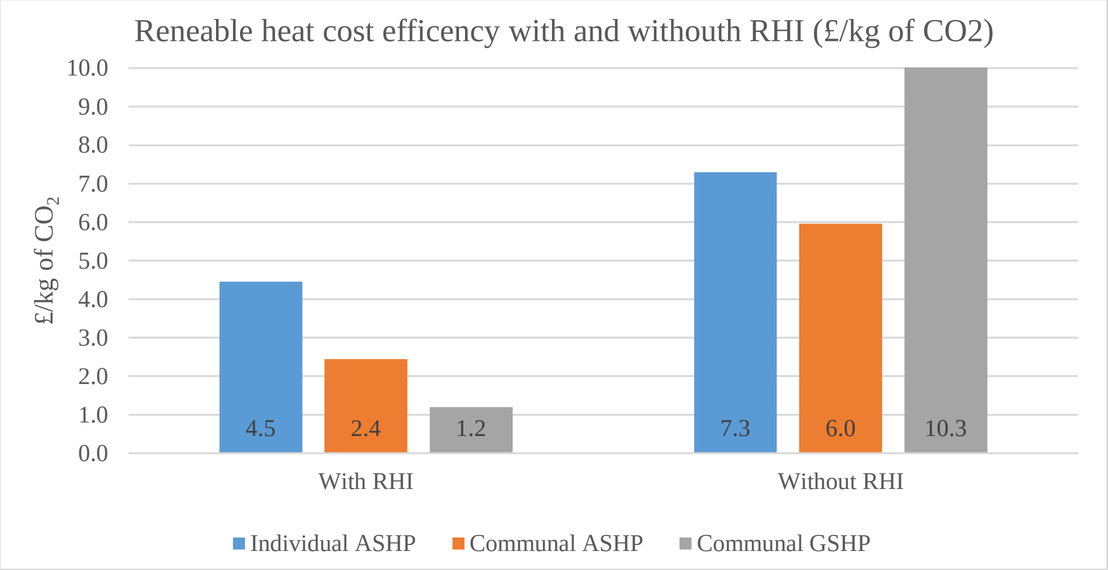
Figure 26 shows the comparison of cost efficiency for each solution expressed as the cost in pounds (£) per kilogram of CO_2 reduced. Although, due to simplicity of the install, the absolute cost of added roof insulation is relatively low (£5,614 and £8,597), the cost per kilogram of CO_2 reduction is extremely high. All retrofits solutions involving wall insulation will achieve around 22 £/kg of CO_2 reduction. Both window replacements are equally cost efficient achieving around 10 £/kg of CO_2 reduction. The renewable heat supply solutions all achieved the highest cost efficiency. This is due to the fact that around 70% of the energy delivered by heat pumps have no CO_2 emissions. Due to increase in emissions, the MVHR system is excluded.

Figure 26 Cost efficiency of the investment (£/kg of CO_2)



Although, the total RHI income (for 7 or 20 years) are included in calculation of the cost efficiency, all three heat pump solutions still rank high without the income from the Government subsidies (Figure 27).

Figure 27 Heat pump cost efficiency with and without RHI income.



4.4. Recommended solution

As the base model have had significant fabric improvement retrofit done in previous years, the suggested improvement of fabric thermal resistance, are not as competitive as the energy supply solutions.

With a limited budget, the most significant impact to electric energy demand, GHG emissions and running costs for the end user can be achieved by installing a communal GSHP system. The total cost of installation is £0.32m. However, it may be relatively easy to acquire a loan based on the guaranteed RHI income. In this case, over the 20 payback period, it is £0.28m. In other words, the quarterly RHI payments would cover most of the loan.

If there is no available space for the ground collector, then both ASHP solutions would be the second best option. The CAPEX and potentially OPEX of the communal system is cheaper as well as the RHI income is higher, however, as mentioned before, this solution involves the administration and payment collection for the heat consumed by each individual flat.

The aim of this paper was to investigate the feasibility reaching the EnerPHit standards. Therefore, a final recommended retrofit solution, consisting of a combination of best performing models analysed previously in terms of energy demand reduction as well as cost efficiency, was modelled.

As for most of the solutions the cost of labour and access remains almost fixed, there is no rationale in adding 100mm instead of 200mm of EWI if the scaffolding is erected. The same applies with the window replacement and roof insulation. Therefore, following fabric and RE supply solutions will be applied to the final model:

- +200mm of wall insulation, final U-value = 0.12 W/m^{2}K
- +200mm roof insulation, final U-value = 0.10 W/m^2 K
- Triple glassed windows, U-value = 0.82 W/m^{2}K, g-value = 0.61

To supply the new lowered peak heating demand of 33.2 kW, only a single NIBE F1355-28 unit would be sufficient. However, again, more cost efficient in terms of RHI income, is to oversize the heating system. Therefore, two units with combined power of 56 kW will be used.

At the cost of £0.65m, the recommended system`s performance indicators (1.) and reduction comparing to the base model (2.) are as follows:

Table 18 Recommended system`s performance indicators.

	Heating and DHW el. (MWh/y)	Heating demand (kWh/m^{2}y)	Heating load (kWp)	CO$_2$ emissions (t/y)	Running cost	Available subsidies	Cost of CO$_2$ reduction per kg	Overheating hours	Excessive humidity hours
1.	18.9	**17.4**	33.2	5.3	£2,842	£174,187	14.1	**30.1%**	**50.5%**
2.	88%	75%	54%	88%	88%	-	-	-29.6%	-24.6%

Table 18 shows that the thermal efficiency as well as running costs are significantly (by 88%) improved - the peak load has been reduced by 54%. Additionally, the achieved specific annual heating demand of 17.4 kWh/m^2/y, which based on *energy demand method* is the main EnerPHit requirement, is below the limit of 25 kWh/m^2/year (Passive House Institute, 2016).

However, reduced infiltration rates and improved fabric thermal resistance comes at a cost - the thermal comfort and air quality indicators have deteriorated significantly - the frequency of overheating and excess humidity has increased by almost 30% and 25% respectively. Both of these indicators need to be significantly improved to be able to meet EnerPHit requirements of >10% and >20%.

The MVHR system is mandatory for the compliance of the EnerPHit standard. However, before modelling the recommended solution with added MVHR system, the author wanted to investigate the potential of improving the thermal comfort and air quality indicators by other means.

Initially, a lower g-values for the windows were modelled. This approach does not allow to accommodate for seasonal differences. The reduction of the solar gain transfer through the glass had a positive effect on the overheating frequency in summer. However, the consequential increase of the heating demand during winter would lead to above 25 kWh/m²/y heating demand. Additionally, this solution does not address the issues with excessive humidity frequency. Therefore, it was decided to keep the current windows.

To investigate other options, the worse performing room in the building (living room 3) was analysed. Figure 28 shows the hours of overheating are irrationally high during the March, April and November, when the outdoor air temperature as well as solar gains are lower than during the summer month. The summer ventilation set point is applied for the time period from May until November. Additionally, the April stands out as the most irrational month regards to overheating hours, and therefore, it was investigated closer.

Figure 28 Solar gains and overheating hours in the living room (3).

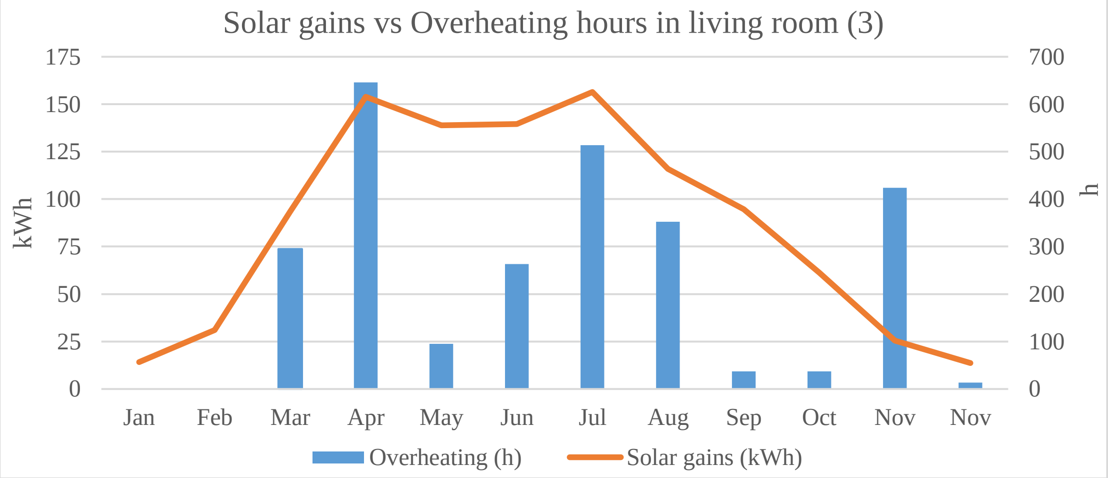


Figure 29 illustrates clearly that the inadequate overheating in April is caused by insufficient natural (winter) ventilation rates (2.89 l/s or 0.25 Ac/h). Although, the daily mean outdoor temperature is initially decreasing from 7°C to 4°C degrees and never exceeds 8°C, from 1st till 30th of April, the temperature of the building is steadily climbing. Even during the nights, not being able to cool down enough. Therefore, from average daily temperature of 24°C the building slowly overheats up till 32°C. On 1st of May, as soon as the summer ventilation rates applies, the room temperature is kept within acceptable levels. It takes 4 days with the summer ventilation (widely open widows – 34.9 l/s or 3 Ac/h) rates applied to cool down the building below 25°C.

Figure 29 Ventilation rates and overheating in the living room (3) 1 Apr - 16 May.

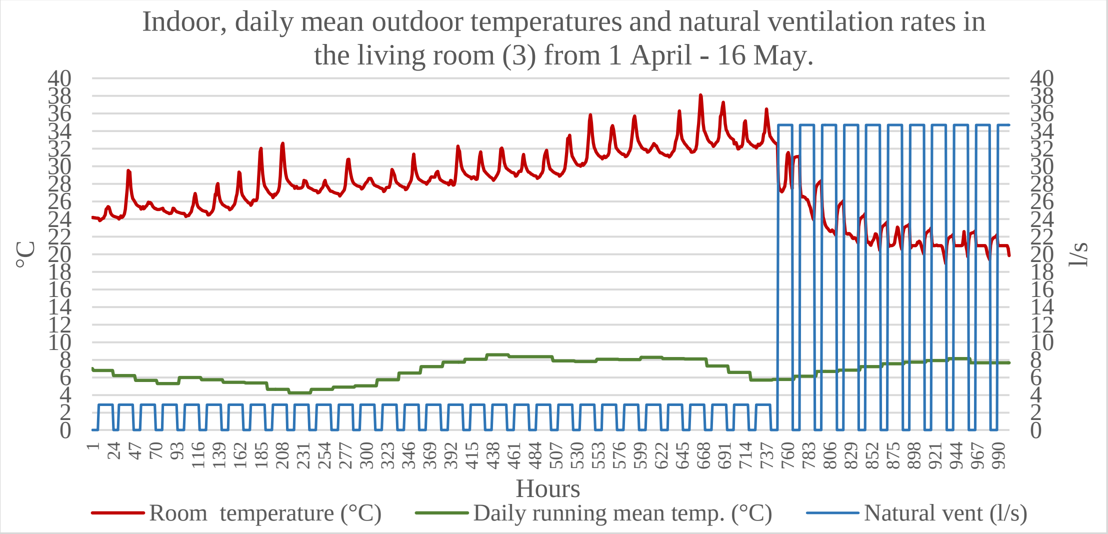


Figure 30 illustrates the relationship between the available cooling load from infiltration and natural ventilation by outdoor air, opposing solar gains and resulting indoor air temperature and PPD values in the living room during one of those 4 days.

During the night time, when only the cooling by infiltration (65W) is offsetting 155W of internal gains, the room temperature (33°C) and PPD (93%) is not decreasing. However, as soon as the natural ventilation rates are applied at 7:00, the cooling by natural ventilation peaks up to 1 kW and brings the room temperature and PPD levels down to 27° and 45% respectively. During the day, the outdoor temperature starts to increase and, therefore, it reduces the cooling power of the natural ventilation down to 0.6 kW. Additionally, during the evening the solar gains increase, peaking at 17:28 when the sun is perpendicular to the living rooms window, furthermore worsening the cooling and heating balance and leading to increased room temperature and PPD values (Figure 31).

Figure 30 Living room 3 air temperature, thermal gains and PPD for 2nd May.

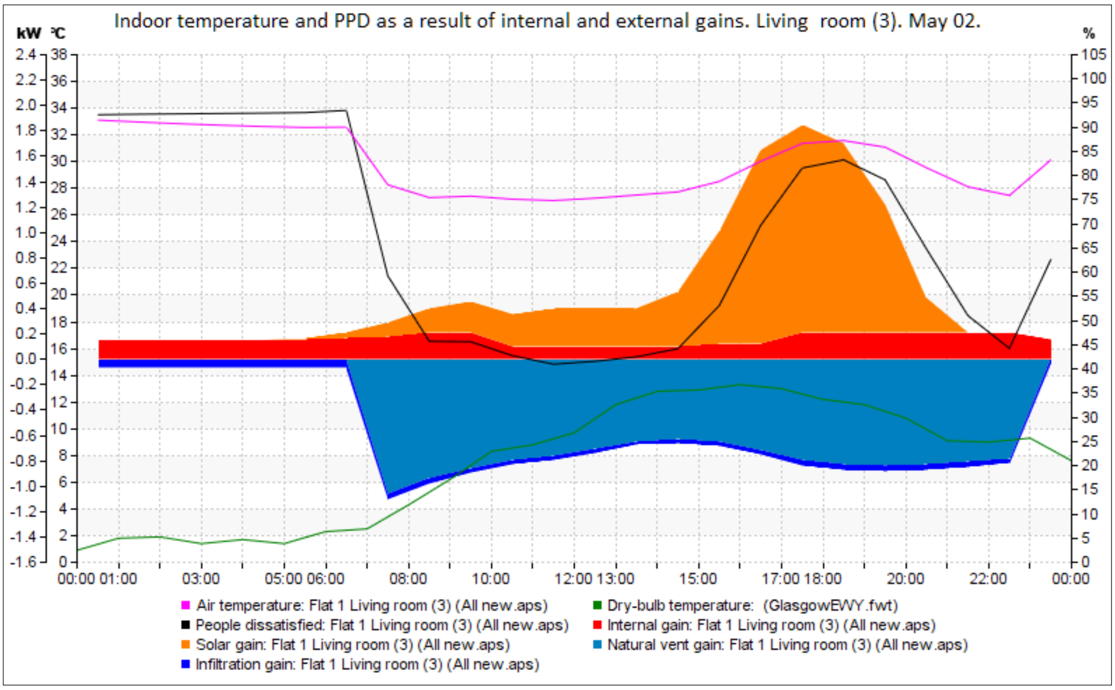
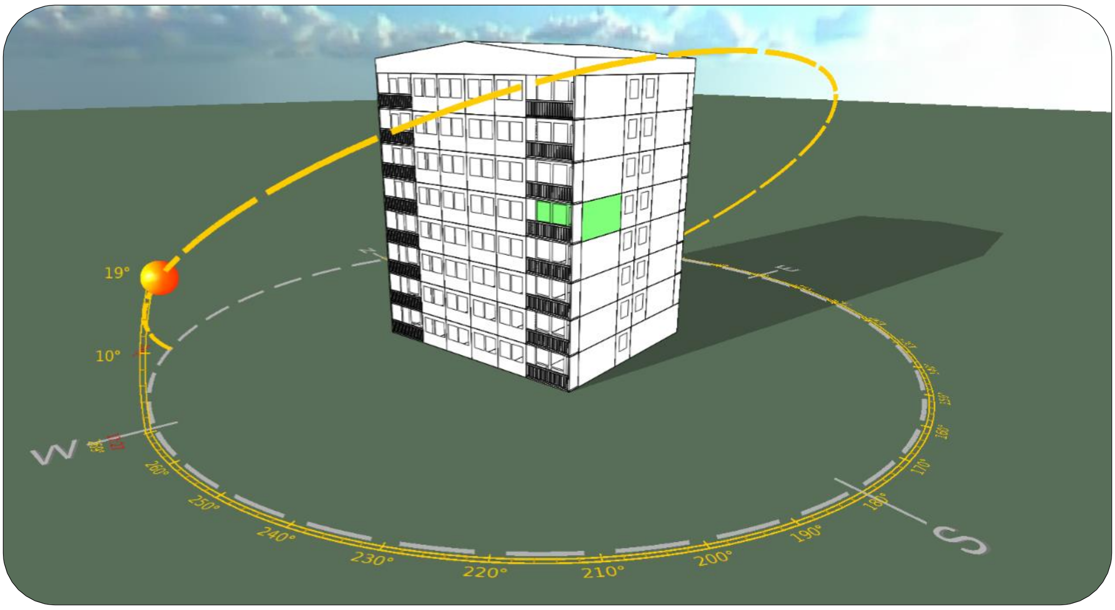


Figure 31 Maximum solar gain in living room (3), West facade, evening sun (2nd May).



It is evident that the overheating during the problematic months and, therefore, the annual frequency of overheating could be addressed buy increased ventilation rates. However, as the outdoor temperature is still quite low during March, April and November, these rates cannot be applied on a conscious basis. First of all – it would be unrealistic for an occupant to open the windows when it is 7°C outside. Second, it would have detrimental effect on the heating demand.

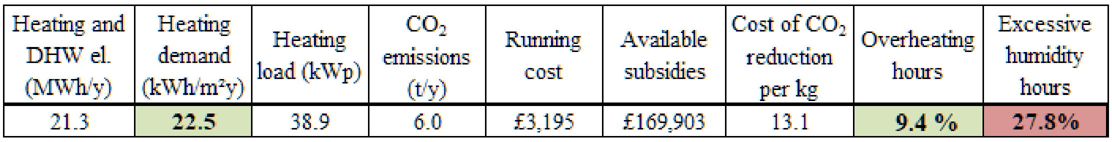
To address this, following changes to the natural ventilation profile were implemented:

1. For the most outlying days, 15 March – 1 May; 1 – 30 October, the natural ventilation rates increased by 1 Ac/h from 1pm-8pm and by 0.3 Ac/h from 8pm-1pm.
2. A night time (11pm-7am) trickle ventilation added for the summer months (May- September) - 10% of designed day time natural ventilation rates.

This simulates an increased ventilation trough more widely opened windows during the peak overheating period. Additionally, a trickle ventilation during the reaming hours of the day as well as the night time hours in summer months.

Table 19 shows that this profile improved the thermal comfort levels of the building, at the cost of increased (12%) energy demand, however, the indoor air quality remains at below acceptable levels.

Table 19 Amended ventilation profiles performance indicators.

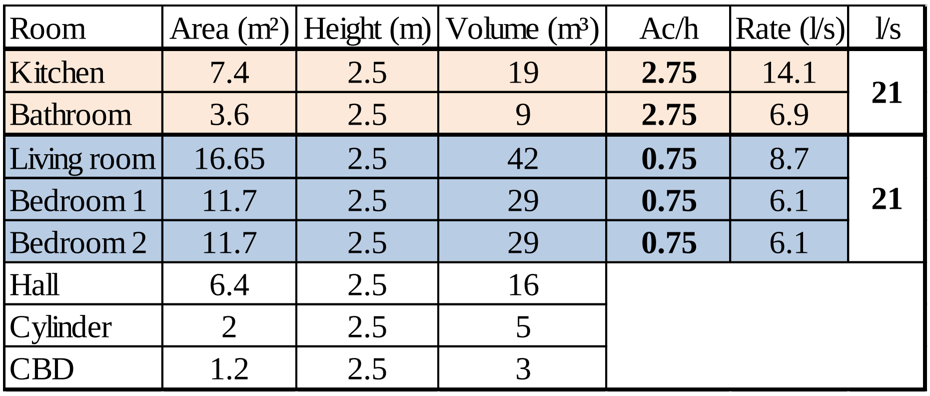


Heating and DHW el. (MWh/y)	Heating demand (kWh/m²y)	Heating load (kWp)	CO_2 emissions (t/y)	Running cost	Available subsidies	Cost of CO_2 reduction per kg	Overheating hours	Excessive humidity hours
21.3	**22.5**	38.9	6.0	£3,195	£169,903	13.1	**9.4 %**	**27.8%**

This clearly illustrates that deep retrofits without an MVHR system will not be able keep the thermal comfort, air quality and energy demand at the levels required by EnerPHit standard as well as are safe for the occupants.

The recommended combination of retrofit measures will include the MVRH system. Table 20 shows the trickle ventilation rates used in the final solution which results in 0.5 Ac/h for the whole flat.

Table 20 The trickle air change rates of the MVHR.



Room	Area (m²)	Height (m)	Volume (m³)	Ac/h	Rate (l/s)	l/s
Kitchen	7.4	2.5	19	**2.75**	14.1	**21**
Bathroom	3.6	2.5	9	**2.75**	6.9	
Living room	16.65	2.5	42	**0.75**	8.7	**21**
Bedroom 1	11.7	2.5	29	**0.75**	6.1	
Bedroom 2	11.7	2.5	29	**0.75**	6.1	
Hall	6.4	2.5	16			
Cylinder	2	2.5	5			
CBD	1.2	2.5	3			

The achieved absolute (1.) and relative to the base model (2.) performance indicators are as follows:

Table 21 Recommended system`s absolute and relative performance indicators.

	Heating and DHW el. (MWh/y)	Heating demand (kWh/m^{2}y)	Heating load (kWp)	CO$_2$ emissions (t/y)	Running cost	Available subsidies	Cost of CO$_2$ reduction per kg	Overheating hours	Excessive humidity hours
1.	20.8	**21.8**	36.9	5.8	£3,115	£169,903	16.2	**8.4%**	**18.3%**
2.	86%	69%	49%	86%	86%	-	-	-7.8%	7.6%

The primary energy compliance was tested by looking at the Primary non-renewable Energy demand (PE). The limit is calculated by following formula (Passive House Institute, 2016):

Equation 2 Primary energy demand limit for EnerPHit compliance.

$$Q_P \leq 120 + ((Q_H - 15) \times 1.2)$$

Where:

Q_P = primary energy demand (kWh/m^2/y)

Q_H = heating demand (kWh/m^2/y)

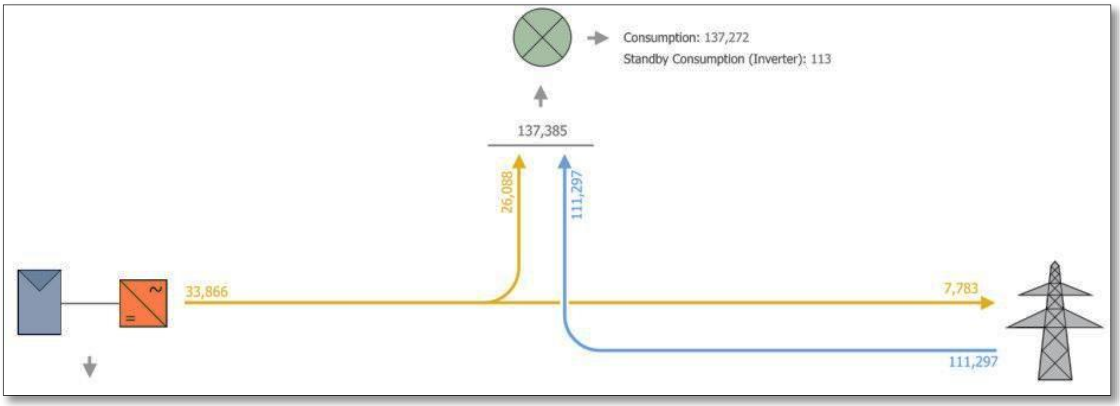
Therefore, the PE demand limit for this building is 128.16 kWh/m^2/y. The resulting PE demand for the applied retrofit is 88.3 kWh/m^2/y, meaning that the PE demand requirement is met.

Regarding the other EnerPHit targets – the *Max. heating demand*, *Frequency of Overheating and Frequency of excessive humidity* are met (Table 21).

Although, the Predicted Percentage of Dissatisfied peaks at 79% in the hottest day of the year (15th August), only for 13.9% of the year it exceeded 15% and 3.8% of the year exceeded 30%. This is a significant improvement, comparing to 45% of the year (above 15%), prior the final addition of the MVHR system.

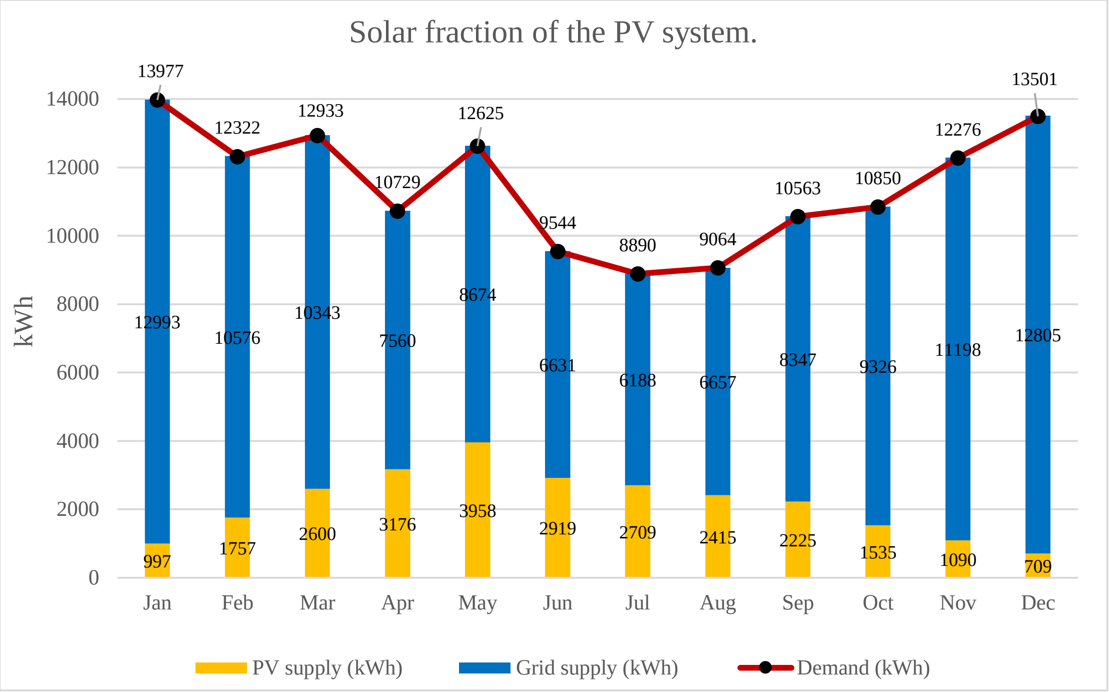
Total amount of renewable generation achieved with the proposed 46.5 kW PV system is 33 866 kWh/y, 26 088 kWh will be used on the site and remaining 7 783 kWh will be exported to the grid. Therefore, reducing the grid import down to 111 297 kWh/y (Figure 32).

Figure 32 Energy flow of the 46.5 kWp PV system.



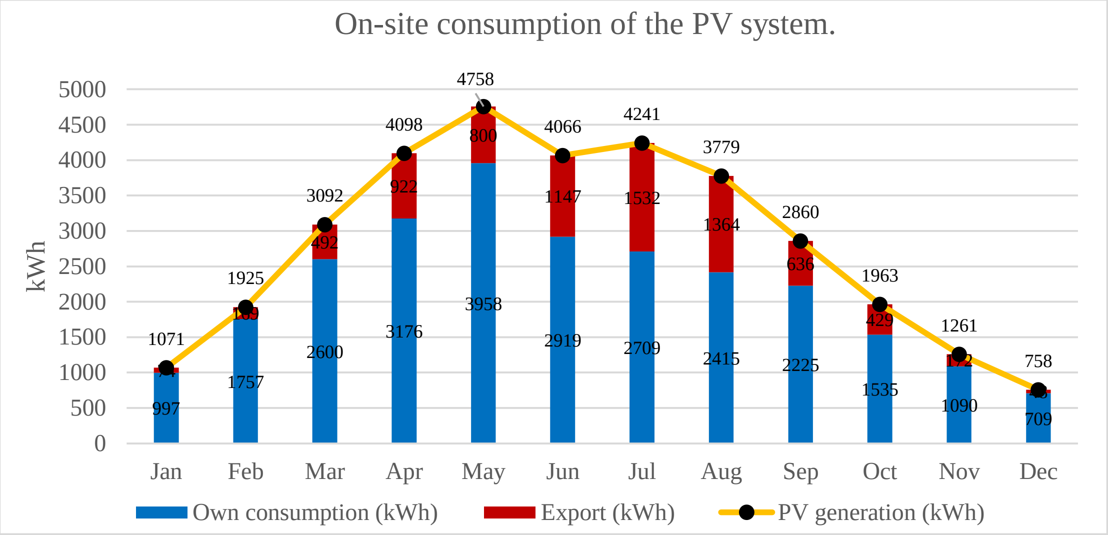
Due to reduced overall demand, the achieved solar fraction has increased from 15% to 19%, peaking at 31 % during the month of May (Figure 33).

Figure 33 Solar fraction of the 46.5 kWp PV system.



However, due to lower demand, the own consumption has decreased from 87% to 77%, peaking at 94% during the month of December (Figure 34).

Figure 34 On-site consumption of the 46.5 kWp PV system.



The total RE generation results in 21.8 kWh/m²/y, therefore, not meeting the EnerPHit *Plus* nor *Premium* requirements, which require 60 and 120 kWh/m²/y RE generation respectively.

4.5. Summary

In this chapter all proposed and modelled retrofit solutions were described, and their key energy and finance related results demonstrated and analysed. Additionally, the recommended combination of solutions was put forward for further analysis.

Final retrofit solution consists of additional 200 mm wall and roof insulation, and new triple glassed windows. The required energy was supplied by communal GSHP and a building integrated PV system. Resulting building model achieved significant energy demand and CO_2 emission reduction. Moreover, a full compliance with the EnerPHit *Classic* standard was achieved.

5. Discussion

This chapter will discuss what was achieved with this paper and critically evaluate the key findings of this research. Additionally, the author will suggest the future work required for this research.

The aim of this study was to examine the feasibility of multiple energy efficiency and RE technology retrofitting measures as well as the possibility to meet the EnerPHit standard. The research was conducted by using dynamic simulations software - IESVE in order to evaluate and compare chosen retrofits which could potentially lead to compliance with EnerPHit standard.

Literature

It is clear that to tackle the current and upcoming issues regarding the climate change, the domestic energy sector`s energy demand will have to be reduced significantly, at large scale and rapidly. As the majority of the energy consumed in domestic properties is for space and water heating, the emphasis should be on reducing demand, supplying the energy via low carbon sources as well as incorporating on site RE generation. The regulation for new build properties are incorporating the changes needed to avoid catastrophic climate outcomes by the end of this century. However, the existing building stock, often built decades ago, is lagging behind, therefore, it has to be significantly improved.

Although, the Government and its policies should be the main driving force facilitating these improvements, the effectiveness of these policies are often questioned. Moreover, the main executers of these activities will be the actual owners of the properties as well as the industry. Therefore, to facilitate the required rapid change, there is a need for a clear approach with predictable outcomes regarding the achieved savings as well as finances.

As these improvements involve significant construction works, there is a strong rationale to aim for *beyond the current building standards*. The existing deep level retrofit case studies show that the Passive house level of retrofits can be achieved even for 50+ year old high rise properties.

Base model

In order to analyse the effectiveness of the retrofit solutions, a reliable benchmark is required. In the situation where the existing consumption data is not available, the use of multiple fixed, assumption-based values causes a lot of uncertainty of the accuracy of the outputs. In this paper, the differences between the key dynamic simulation outputs and results from CIBSE and RdSAP calculations were within reasonable limits (±10%). However, the difference (61%) between the min and max values of all three methods, confirmed the widespread consensus in the literature regarding the performance gap of the measured and designed performance. Additionally, the unreliability of the EPCs data for decision making, as it is based on the RdSAP methodology.

Nevertheless, for analysis of the difference between the applied solutions, this performance gap is less of an issue, because most of the uncertainty is within the stochastic parameters that were kept fixed for all solutions. Moreover, the EnerPHit compliance, at first, is achieved on paper, therefore, the potential performance gap between estimated and measured consumption will not affect the answer of the research question.

The existing property does not achieve the specific heating demand nor the primary energy demand requirements of the EnerPHit standard.

Analysed solutions

The applied retrofits are analysed form the point of view of the large landlord such as housing associations or council being the main stakeholder. They are not directly benefiting from reduced running costs, therefore, they will not “get their money back”. Basing it on assumption that stakeholder’s main incentive is to comply with government’s regulation and improve the attractiveness and user satisfaction of their assets by spending the least amount of money. Hence, apart from the compliance with the EnerPHit standard, the main indicator chosen to represent the financial feasibility was the cost of reducing 1kg of annual CO_2 emissions. As for all electric based systems, the GHG emission reduction will be directly correlating with the grid import reduction, therefore, these measures also will tackle the fuel poverty issues.

Building envelope

The *fabric first* approach prioritised the EWI, roof insulation and window replacement. Due to relatively small affected area ($262m^2$) as well as adequate existing roof insulation (200mm), the effect on the energy demand by increased roof insulation was insignificant, however, the ease of access and installation, and resulting labour costs as well as the material costs of these improvements are relatively low. This justified the inclusion of this measure in the final recommended solution.

The EWI retrofit achieves 20-25% reduction of energy demand, although, it involves a full scaffolding solution, resulting in the highest cost of £61-£74 per kg of CO_2 reduced. However, without, improved EWI, the EnerPHit standard are not achievable, therefore, it was included in the final recommended solution. Moreover, this will ease the installation of new windows and allows to consider other improvements (BiPV) that would not be viable if the scaffolding cost would need to be incorporated.

The new double and triple glassed window (U-value = 1.4 and 0.8 W/m^2K) replacement achieved the highest reduction of all fabric related improvements. Resulting in 45-55% reduced heating demand at the cost of ~£10 per kg of CO_2 reduced.

All fabric related improvements increased the excessive humidity frequency proportionally to achieved energy demand reduction. In addition to that, the window replacement also negatively affected the frequency of overheating, going beyond the limits of EnerPHit standard.

The current ongoing heating system replacement in the case study`s property is a great example of the consequences of short-term thinking. After the external wall and roof insulation as well as the window replacement retrofit in 2008, the running cost and tenant satisfaction levels stayed low, forcing to undergo another major upgrade of the property – replacement of the storage heaters with an individual ASHP. This approach was simulated as one of the potential retrofit solutions.

Heating system

The considered HP based heating systems all achieved the lowest costs per kg of CO_2 reduced, £1.20, £2.44 and £4.46£ for *Communal GSHP*, *Communal ASPH* and *Individual ASPH* systems respectively. This was based on the SCOP values obtained for the MCS database. It is highly unlikely that these optimistic values may be achieved in real life. Additionally, the communal solutions involve higher distribution loses which were not estimated in this study. However, for the exercise of comparing the systems, this approach is acceptable.

Both communal HP solutions, if installed by a MCS accredited installer, would be eligible under the non-domestic RHI scheme, which would give the full return of the investment over 20 instead of a 7 year period. Moreover, the payment would be based on metered heat consumption, which due to potential performance gap, hold higher uncertainty, therefore, it might be a consideration if these improvements are funded by a lender who is using the RHI income as a risk reducing factor. For the *Individual ASHP,* the total RHI income over the 7 year period is highly predictable, as it is based on the EPC estimate. However, this might result in situation where the RHI income is lower comparing to one if heat meters would be installed.

Moreover, it was established that the current tier based non-domestic RHI payment calculation method for GSHP is incentivising to opt for an oversized heat pump. This creates a situation where it is not financially viable to go for a system sized for less than 100% of the peak load and utilise the diversity factors of multiple property based communal heating systems. The goal of the RHI scheme is to reduce the GHG emissions of the UK, therefore, the incentive to create demand for higher than necessary production of heat pumps is contradicting with this goal.

It is clear that not all solutions can be considered in all locations. For example, for individual balcony ASHP approach, an actual balcony able to accommodate an ASHP is required. Additionally, the actual ground conditions determine the maximum depth as well as heat extraction rates, therefore, the available land required for boreholes might not be available. Moreover, the building analysed in this paper has a relatively low floor count. For higher buildings the total ground collector lengths and, therefore, borehole count will increase, making this approach technically unfeasible.

If the funds are limited, and the EnerPHit compliance is not a target, replacing the existing electric panel heaters, with a heating system based on air source or ground source heat pump system, would be most effective in reducing energy costs and related GHG emissions. However, the change of the heating system does not reduce the heating demand of the building. To reach the objective of this paper, this solution will be recommended in addition with best performing building envelope improvements.

Solar PV

The maximum amount of unobstructed PV panels that the building can relatively easy accommodate resulted in a 46.5 kWp system.

Dividing this capacity equally for each flat allows to utilise the single phase supplies and existing load in each flat and, therefore, keeping the size of each individual system below the 3.68 kW per phase limit and avoid the potential issues and costs related with the DNO approval.

The resulting 5 x 0.31 kWp panel system per flat achieved high (86.6%) on-site consumption indication that there is no need to consider battery storage. However, an electric immersion could be added to the potential DWH tank to divert the excess PV generation for water heating, allowing to reach 100% on-site consumption. The solar fraction of 15.2 % indicated that there is no need to reduce the size of the system. Although, the achieved relative renewable generation of 21.8 kWh/m²/y does not meet the EnerPHit Plus nor Premium standard, this system will be included in the recommended solution.

Recommended solution

The viability of many of analysed solution are highly dependent on the cost of labour and access. Additionally, the energy demand reduction via building improvement, as well as the HP and PV systems complement each other.

The initially achieved specific heating demand was 17.4 kWh/m²/y. However, the key outputs for the recommended system indicated significant issues regarding the thermal comfort, resulting from increased thermal resistance of the building envelope as well as reduced infiltration rate.

It is clear that it may be problematic to apply a single generic solution to all properties. A holistic approach is required to tackle the resulting overheating as well as excessive humidity frequencies.

Although, the use of a MVHR system is mandatory for the EnerPHit compliance, initially other means of achieving thermal comfort and air quality indicators were analysed. By adjusting the natural ventilation rates, which were applied after identifying unacceptable thermal comfort levels during the summer, the excessive overheating during the summer months were kept within the EnerPHit standard. This increased the specific hating demand to 22 kWh/m²/y, still within the target levels. However, the excessive humidity frequency could not be kept below the 20%.

As the excise humidity (above 12g/kg) occurs during the wither moths, when the ventilation rates, due to low outdoor air temperatures, are low. To tackle this issue, a higher ventilation rates in winter need to be achieved. This however, will lead to increased heating demand. Without the MVHR it was not possible to keep the heating demand below 25 kWh/m²/y and excessive humidity below 20%.

The practical difficulties of installing a MVHR system in an existing building that was not designed for it was not addressed.

The final recommended system including the MVHR system met all EnerPHit standards. The cost efficient of this solution was still relatively high – 16.2 £/kg of CO2 reduce.

Accuracy, uncertainty and limitations

The accuracy of the final estimated energy consumption is affected by the multiple assumptions and simplification used during the construction of the base model as well as the final recommended solution. Additionally, the typical performance gap observed, when modelling building energy consumption, furthermore increases the uncertainty of the results.

In real life, many of the static, repetitive pattern based inputs used in the simulation are dynamic, stochastic and non-linear. For example, the weather data will differ on daily and annual basis, the infiltration rates are not depending just on air tightness of the building, but also on the ever changing wind speeds and temperature difference between indoor and outdoor spaces. Additionally, the occupancy related profiles are different for each day as well as each individual flat. Moreover, the heating and DHW input values and profiles are a simulation of the "perfect" controls system, which is hard to replicate in real life. However, for the purpose of comparing two different designs instead of modelled versus measured demand, the uncertainty levels are significantly reduced. Because, the relative difference between, for example, two insulation thicknesses, will not be affected by most of the assumed values used in the background calculations.

Lastly, to estimate the capital investment costs, relatively reliable costs of materials and equipment was obtained, however, the labour and access related costs were mostly based on *rule of thumb* approach and grey literature.

Although, the IESVE is a powerful tool, there are some limitation regards available inputs. For this paper most limitations were caused by lack of expertise of the user which led to the use of the less versatile *Apache* simulation module instead of the *ApacheHVAC* which offers significantly more customisation of the thermal conditioning systems and their controls.

Future work

The EnerPHit Classic compliance was met by comparing the outputs of the simulation with the upper limits of the standard. However, the official compliance with the EnerPHit standard is determined by the use of the Passive House Planning Package (PHPP 9) spreadsheet, therefore this building and the recommended retrofit measures should be run through this tool. Additionally, this would allow to calculate the recently incorporated Primary Renewable Energy (PER) of the building, as currently, the Primary non-renewable Energy (PE) was used for the compliance check.

In order to increase the solar gains in winter and reduce them in summer, a detailed analysis of the optimal window parameters for each of the building façade should be undertaken.

More accurate capital cost of the investment should be determined by acquiring real quotes from the companies in the industry.

Furthermore, as the high rise building insulation activity consists of applying almost identical "jacket" to all matching middle floor facades, the means of reducing the costs by simplifying and streamlining the design should be investigated. A similar approach to the *Energiesprong* could be implemented, were the external wall insulation, window and façade integrated PV system can be pre-fabricated in an off-site factory. Therefore, for a set of identical towers, the economies of the scale could allow to significantly reduce the costs for the large landlords.

Lastly, the lack of available funds required for these type of works is the main obstacle for most of the landlords. Therefore, more research is required to identify the relevant financing options available for these type of improvements.

In this chapter, in order to draw the final conclusions, the author discussed and evaluated the key findings of this paper. Additionally the required future work was suggested to furthermore increase the accuracy, reliability and relevance of this study.

6. Conclusions

The final chapter of this thesis will list the main conclusions drawn from this research.

First objective - to research the background of the domestic energy demand in Scotland and current situation regarding the fuel poverty as well as the policy environment, was fully met in the chapter 2 - *Literature review* of this paper.

The domestic energy demand reduction will play a pivotal role in reaching the GHS emission targets and tackling the fuel poverty in Scotland.

Second objective - to investigate the current industry practice as well as the state of the art solutions and technologies allowing to achieve low or net-zero energy efficiency standards such as EnerPHit, was partly met in the chapter 2 - *Literature review* of this paper.

There is no clear, generic solution or technology that can be applied to all properties in order to achieve the EnerPHit standards. A holistic, bespoke solution is required for each project.

Third objective - to model a high rise tower block using IESVE building simulation software and select and simulate potential retrofit solutions and their performance, was fully met in the chapter 3 - *Base model* of this paper.

The IESVE is a powerful tool for application of different *what-if* scenarios to a building design and comparison of the outputs.

The best performing retrofit solutions were the replacement of the existing heating system with an ASHP or GSHP.

Second best results were achieved by the replacement of the existing widows with low energy triple glassed windows.

Only a combination of increased EWI, roof insulation as well as low energy window replacement could reduce the heating demand below the target of 25 kWh/m²/y.

Fourth objective - to calculate the estimated costs and savings for viable solutions and compare and analyse the results, was fully met in the in the chapter 4 – *Potential retrofit solutions* of this paper.

For the total cost of £0.77m, the recommended system achieved a 70% reduction of heating demand, and 86% reduction of CO_2 emissions and running costs.

Fifth objective - to critically evaluate and discuss the findings in order to be able to conclude and recommend a solution, was fully met in the chapter 5 – *Discussion* of this paper.

The recommended system consists of a combination of building fabric thermal efficiency`s improvements as well as implementation of the MVHR, communal GSHP and BiPV systems.

The overheating was a significant issue in a naturally ventilated building undergoing deep retrofit, however, it can be eliminated with application of a seasonal ventilation profile or implementation of a MVHR system.

The addition of a MVHR system was the only solution allowing to tackle the excess humidity frequency issues and still comply with all other requirements of the EnerPHit standard.

The hypothesis of this thesis was confirmed - EnerPHit deep retrofit of high rise residential buildings can be achieved in an economically viable way whilst significantly reducing the CO_2 footprint and running costs of the building.

References

Abi-Ghanem, D. & Haggett, C., 2011. Shaping people's engagement with microgeneration technology: The case of solar photovoltaics in UK homes. In: P. Devine-Wright, ed. *Solar Energy and Microgeneration.* London and Washington: Earthscan, pp. 149-165.

Abualqumboz, M. & Rodley, D., 2018. Mathematical modelling of smart solar heating system with the deployment of borehole thermal energy storage to increase renewable heat share in Dundee, UK.. *Energy Procedia,* Volume 151, pp. 37-46.

Agostini, A., Giuntoli, J. & Boulamanti, A., 2014. *Carbon accounting of forest bioenergy. Conclusions and recommendations from a critical literature review,* Luxembourg: Publications Office of the European Union.

Ahn, K. U. et al., 2016. Issues to Be Solved for Energy Simulation of An Existing Office Building. *Sustainability,* Volume 345, p. 8.

Andreadis, G., Roaf, S. & Mallick, T., 2013. Tackling fuel poverty with building-integrated solar technologies: The case of the city of Dundee in Scotland. *Energy and Buildings,* Volume 59, pp. 310-320.

Antonelli, L., 2015. *Manchester social housing gets passive regeneration.* [Online] Available at: https://passivehouseplus.ie/magazine/upgrade/manchester-social-housing-gets-passive-regeneration
[Accessed 05 07 2019].

Armstrong, P. M., Bhagavathy, S. M., Kang, R. & McCulloch, M., 2019. Pitfalls in decarbonising heat: A misalignment of climate policy and product energy labelling standards. *Energy Policy,* Volume 131, pp. 390-398.

Asaee, R. S., Ugursal, I. V. & Beausoleil-Morrison, I., 2017. Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock. *Applied Thermal Engineering,* Volume 111, pp. 936-949.

Averfalk, H. & Werner, S., 2017. Essential improvements in future district heating systems. *Energy Procedia,* Volume 116, pp. 217-225.

BEIS, 2017. *The Clean Growth Strategy Leading the way to a low carbon future.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf
[Accessed 18 07 2019].

BEIS, 2018. *A SUMMARY OF CHANGES FROM SAP 2012 TO SAP10,* Londong: BRE.

BEIS, 2018. *Consultation on the Feed-in Tariffs Scheme,* London: BEIS.

BEIS, 2018. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings,* Watford: BRE Garston.

BizEE Software Limited, 2019. *Custom Degree Day Data.* [Online]
Available at: https://www.degreedays.net/
[Accessed 02 08 2019].

Bornatico, R., Pfeiffer, M., Witzig, A. & Guzzella, L., 2012. Optimal sizing of a solar thermal building installation using particle swarm optimization. *Energy,* 41(1), pp. 31-37.

BPC Ventilation LTD, 2019. *BPC Ventilation LTD.* [Online]
Available at: https://www.bpcventilation.com/nuaire-wm1
[Accessed 15 08 2019].

British Standards, 2005. *Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,* London: BSi.

British Standards, 2017. *BS EN 12831-3:2017 Energy performance of buildings — Method,* London: The British Standards Institution.

Brocklebank, I., Styring, P. & Beck, S., 2018. Heat mapping for district heating. *Enegy Procedia,* Volume 151, pp. 47-51.

Building Research Establishment, 2019. *BREEAM.* [Online]

Available at: https://www.breeam.com/

[Accessed 02 07 2019].

Burford, N., Onyango, V. & Wright, F., 2019. LZCGT impact on GHG reductions in Scotland's new domestic buildings. *Energy Policy,* Volume 129, pp. 34-52.

Cabrol, L. & Rowley, P., 2012. Towards low carbon homes – A simulation analysis of building-integrated air-source heat pump systems. *Energy and Buildings,* Volume 48, pp. 127-136.

CCL Components Ltd, 2019. *CCL Components.* [Online]

Available at: https://www.cclcomponents.com/

[Accessed 17 08 2019].

Chaudry, M. et al., 2015. Uncertainties in decarbonising heat in the UK. *Energy Policy,* Volume 87, pp. 623-640.

Chiacchio, F. et al., 2018. On the use of dynamic reliability for an accurate modelling of renewable power plants. *Energy,* Volume 151, pp. 605-621.

CIBSE, 2017. *HVDH Domestic Heating Design Guide.* London: DBSP.

CIBSE, 2017. *HVDH Domestic Heating Design Guide.* London: DBSP.

CIBSE, 2018. *Combustible cladding in high-rise residential buildings.* [Online]
Available at: https://www.cibse.org/news-and-policy/december-2018/combustible-cladding-in-high-rise-residential-buil
[Accessed 15 08 2019].

Climate Emergency UK, 2019. *List of Councils who have declared a Climate Emergency.* [Online]
Available at: https://www.climateemergency.uk/blog/list-of-councils/
[Accessed 15 07 2019].

Coakley, D., Raftery, P. & Keane, M., 2014. A review of methods to match building energy simulation modelsto measured data. *Renewable and Sustainable Energy Reviews,* Volume 37, pp. 123-141.

Collective Architecture Ltd, 2016. *WOODSIDE.* [Online]
Available at: https://www.collectivearchitecture.com/downloads/RE-CYCLING.pdf
[Accessed 20 07 2019].

da Cunha, J. P. & Eames, P., 2018. Compact latent heat storage decarbonisation potential for domestic hot water and space heating applications in the UK. *Applied Thermal Engineering,* Volume 134, pp. 396-406.

Day, T., 2006. *TM41: Degree Days: Theory & Application.* London: CIBSE.

DECC, 2011. *Renewable Heat Incentive,* London: DECC.

DECC, 2011. *MCS 022: GROUND HEAT EXCHANGER LOOK-UP TABLES,* London: Department of Energy and Climate Change.

DECC, 2013. *Microgeneration Installation Standard: MIS3005,* London: Department of Energy and Climate Change.

Department for Business, Energy & Industrial Strategy, 2019. *The future for small-scale low- carbon generation,* London: Crown.

Department for Education, 2016. *Guidelines onventilation,thermal comfort and indoor air quality inschools,* Londong: Department for Education.

Department for Transport, 2019. *Electric Vehicle Charging in Residential and Non-Residential Buildings.* [Online]

Available at:

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/818810/electric-vehicle-charging-in-residential-and-non-residential-buildings.pdf

[Accessed 22 07 2019].

Donaldson, R. & Lord, R., 2014. Challenges for the Implementation of the Renewable Heat Incentive – An example from a school refurbishment geothermal scheme. *Sustainable Energy Technologies and Assessments,* Volume 7, pp. 30-33.

Donaldson, R. & Lord, R., 2018. Can brownfield land be reused for ground source heating to alleviate fuel poverty?. *Renewable Energy,* pp. 344-355.

Dunn, T., 2019. *Renewable energy system installation costs* [Interview] (7 August 2019).

ECD Architects LTD, 2018. *Wilmcote House. A new model for tackling estate refurbishment and fuel poverty.* [Online]

Available at: https://cdn01.rockwool.co.uk/siteassets/rw-uk/why-stone-wool/case-studies/wilmcote-house-continued/ecd-wilmcote-house-project-booklet.pdf?f=20190103033900

[Accessed 19 07 2019].

energie sprong uk, 2019. *energie sprong uk.* [Online]

Available at: https://www.energiesprong.uk/

[Accessed 19 07 2019].

Energy Saving Trust, 2019. *Domestic charge point funding.* [Online]
Available at: https://www.energysavingtrust.org.uk/scotland/grants-loans/domestic-charge-point-funding
[Accessed 23 07 2019].

energysprong, 2019. *Energysprong works!.* [Online]
Available at: https://energiesprong.org/wp-content/uploads/2019/04/Energiesprong-works_DEF.pdf
[Accessed 19 07 2019].

Eteiba, M. B., Barakat, S., Samy, M. M. & Wahba, W. I., 2018. Optimization of an off-grid PV/Biomass hybrid system with different battery technologies. *Sustainable Cities and Society,* Volume 40, pp. 713-727.

Eyre, N., 2011. Effciency, demand reduction or. *ECEEE,* pp. 1391-1399.

Feliciano, D., Slee, B. & Smith, P., 2014. The potential uptake of domestic woodfuel heating systems and its contribution to tackling climate change: A case study from the North East Scotland. *Renewable Energy,* Volume 72, pp. 344-353.

Fletcher, M. J., Johnston, D. K., Glew, D. W. & Parker, J. M., 2017. An empirical evaluation of temporal overheating in an assisted living Passivhaus dwelling in the UK. *Building and Environment,* Volume 121, pp. 106-118.

Fosas, D. et al., 2018. Mitigation versus adaptation: Does insulating dwellings increase overheating risk?. *Building and Environment,* Volume 141, pp. 740-759.

Freeman, J., Whitmore, J., Blair, N. & Dobos, A. P., 2014. *Validation of Multiple Tools for Flat Plate Photovoltaic Modeling Against Measured Data,* Denver : National Renewable EnergyLaboratory.

Gillard, R., Snell, C. & Bevan, M., 2017. Advancing an energy justice perspective of fuel poverty: Household vulnerability and domestic retrofit policy in the United Kingdom. *Energy Research & Social Science,* pp. 53-61.

Glasgow City Council, 2017. *SG 5: Resource Management.* [Online]
Available at: https://www.glasgow.gov.uk/article/20790/SG-5-Resource-Management
[Accessed 08 07 2019].

Green Building Store, 2016. *Large-scale EnerPHit retrofit in Longsight, Manchester.* [Online]
Available at: https://www.greenbuildingstore.co.uk/erneley-close-enerphit-mvhr-triple-glazed-timber-windows/
[Accessed 05 07 2019].

Greenage, 2016. *How much does external wall insulatio costs?.* [Online]
Available at: https://www.thegreenage.co.uk/how-much-does-external-wall-insulation-cost/
[Accessed 17 08 2019].

Gupta, R. & Gregg, M., 2018. Modeling and Mapping Domestic Energy Refurbishment Measures on a Community Scale. In: P. Droege, ed. *Urban Energy Transition.* London: Elsevier Ltd, pp. 661-676.

Gupta, R., Kapsali, M. & Howard, A., 2018. Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK. *Energy and Buildings,* Volume 174, pp. 548-562.

Hardy, A. & Glew, D., 2019. However, SAP calculations are applied only to ‘regulated energy’ in Building Standards which excludes significant electrical energy required for additional water heating on white goods and other appliances that tend to have a cold supply in the UK. *Energy Policy,* Volume 129, pp. 1168-1178.

Hooper, T. et al., 2018. Do energy scenarios pay sufficient attention to the environment? Lessons from the UK to support improved policy outcomes. *Energy Policy,* Volume 115, pp. 397-408.

House of Commons Committee of Public Accounts, 2018. *Renewable Heat Incentive in Great Britain,* London: House of CommonsCommittee of Public Accounts.

Huang, B. J., Lee, J. P. & Chyng, J. P., 2005. Heat-pipe enhanced solar-assisted heat pump water heater. *Solar Energy,* Volume 78, p. 375–381.

IES Ltd, 2019. *Integrated Environmental Solutions Limited.* [Online]
Available at: https://www.iesve.com/software
[Accessed 12 08 2019].

IESVE, 2019. *How do I account for thermal bridging?.* [Online]
Available at: https://www.iesve.com/support/knowledgebase/faq/2430
[Accessed 02 08 2019].

Illsley, B., Jackson, T. & Lynch, B., 2007. Addressing Scottish rural fuel poverty through a regional industrial symbiosis strategy for the Scottish forest industries sector. *Geoforum,* 38(1), pp. 21-32.

Imperial College London, 2019. *Accelerated electrification and the GB electricity system,* London: Vivid Economics Limited.

Insulation shop Ltd, 2019. *Insulationshop: Roof Insulation.* [Online]
Available at:
https://www.insulationshop.co/roof_insulation_rigid_wool_knauf_xtratherm.html
[Accessed 08 08 2019].

IPCC, 2018. *2018: Summary for Policymakers. In: Global warming of 1.5°C.,* Geneva: World Meteorological Organization.

Jacobs, P. et al., 2015. *Transition Zero,* s.l.: Mei.

Ji, J. et al., 2008. Experimental study of photovoltaic solar assisted heat pump system. *Solar Energy,* 82(1), pp. 43-52.

Johnson, H. et al., 2005. The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates.. *Euro Surveillance : Bulletin Europeen sur les Maladies Transmissibles = European Communicable Disease Bulletin,* 10(7), pp. 168-171.

Judkoff, R., Wortman, D. & O`Doherty, B., 2008. *A Methodology for Validating Building Energy Analysis Simulations,* Springfield: National Renewable Energy Laboratory.

Kearns, A., Whitley, E. & Curl, A., 2019. Occupant behaviour as a fourth driver of fuel poverty (aka warmth & energy deprivation). *Energy Policy,* pp. 1143-1155.

Kelly, N., 2006. The role of energy efficiency in reducing Scottish and UK CO2 emissions. *Energy Policy,* 34(18), pp. 3505-3515.

Kelly, N. J. & Cockroft, J. P., 2011. Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data. *Energy and Buildings,* 43(1), pp. 239-245.

Kelly, N. J., Tuohy, P. G. & Hawkes, A. D., 2014. Performance assessment of tariff-based air source heat pump loadshifting in a UK detached dwelling featuring phase change-enhancedbuffering. *Applied Thermal Engineering,* Volume 71, pp. 809-820.

Li, H. & Sun, Y., 2019. Performance optimization and benefit analyses of a photovoltaic loop heat pipe/solar assisted heat pump water heating system. *Renewable Energy,* Volume 134, pp. 1240-1247.

Ling-Chin, J. et al., 2019. UK policies and industrial stakeholder perspectives on building thermal performance. *Energy Procedia,* Volume 158, pp. 3375-3380.

Liu, S., Shukla, A. & Zhang, Y., 2014. Investigations on the integration and acceptability of GSHP in the UK dwellings. *Building and Environment,* Volume 82, pp. 442-449.

Li, Y., Kubicki, S., Guerriero, A. & Rezgui, Y., 2019. Review of building energy performance certification schemes towards future improvement. *Renewable and Sustainable Energy Reviews,* Volume 113, pp. 109-244.

Lund, H., Duic, N., Østergaard, P. A. & Mathiesen, B. V., 2018. Future district heating systems and technologies: On the role of smart energy systems and 4th generation district heating. *Energy,* 165(A), pp. 614-619.

MacKay, D., 2009. *Sustainable Energy without the Hot Air.* Cambridge: UIT Cambridge Ltd.

Marczinkowski, H. M. & Østergaard, P. A., 2019. Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands Samsø and Orkney. *Energy,* Volume 175, pp. 505-514.

Ma, Z., Bao, H. & Roskilly, A. P., 2018. Feasibility study of seasonal solar thermal energy storage in domestic dwellings in the UK. *Solar Energy,* 162(1), pp. 489-499.

McCabe, A., Pojani, D. & Goenou, A. B. v., 2018. The application of renewable energy to social housing: A systematic review. *The application of renewable energy to social housing: A systematic review,* Volume 114, pp. 549-557.

McLeod, R. S., Hopfe, C. J. & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment,* Volume 70, pp. 198-209.

MCS, 2019. *MCS Product search.* [Online]
Available at: https://www.microgenerationcertification.org/consumers/product-search/
[Accessed 17 08 2019].

Mitsubishi Electric Corporation, 2012. *Mitsubishi Electric library.* [Online] Available at: https://library.mitsubishielectric.co.uk/pdf/book/Ecodan_CAHV-P500YA-HPB_Databook#page-1
[Accessed 17 08 2019].

Moore, N., Haines, V. & Lilley, D., 2015. Improving the installation of renewable heating technology in UK social housing properties through user centred design. *Indoor Built Environment,* pp. 970-985.

Morrison, C. & Shortt, N., 2008. Fuel poverty in Scotland: Refining spatial resolution in the Scottish Fuel Poverty Indicator using a GIS-based multiple risk index. *Health & Place,* pp. 702-717.

Mould, R. & Baker, K. J., 2017. Documenting fuel poverty from the householders' perspective. *Energy Research & Social Science,* pp. 21-31.

Munro, F. R., 2019. Renewable energy and transition-periphery dynamics in Scotland. *Environmental Innovation and Societal Transitions,* Volume 31, pp. 273-281.

Nageler, P. et al., 2018. Validation of dynamic building energy simulation tools based on a real test-box with thermally activated building systems (TABS). *Energy and Buildings,* Volume 168, pp. 42-55.

National Records of Scotland, 2018. *Winter Mortality in Scotland 2017/18,* Edinburgh: National Records of Scotland.

Office for Low Emission Vehicles, 2019. *Electric Vehicle Homecharge Scheme Guidance for customers: January 2019.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/772404/evhs-guidance-for-customers-v-2.3.pdf
[Accessed 22 07 2019].

Ofgem , 2019. *Feed-in Tariffs: Essential guide to closure of the scheme.* [Online]

Available at: https://www.ofgem.gov.uk/publications-and-updates/feed-tariffs-essential-guide-closure-scheme

[Accessed 05 07 2019].

Ofgem, 2016. *Ofgem's Future Insights Series The Decarbonisation of Heat,* London: Ofgem.

Ofgem, 2019. *Environmental Programmes.* [Online]

Available at: https://www.ofgem.gov.uk/environmental-programmes/

[Accessed 20 07 2019].

Ofgem, 2019. *Non-Domestic RHI tariffs.* [Online]

Available at: https://www.ofgem.gov.uk/publications-and-updates/non-domestic-rhi-tariff-table

[Accessed 17 08 2019].

Ofgem, 2019. *Tariffs and payments: Domestic RHI.* [Online]

Available at: https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-domestic-rhi/current-future-tariffs

[Accessed 17 08 2019].

Passive House Institute, 2015. *About Passive House - What is a Passive House?.* [Online]

Available at:

https://passivehouse.com/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm

[Accessed 01 07 2019].

Passive House Institute, 2016. *Criteria for the Passive House, EnerPHit andPHI Low Energy BuildingStandard.* [Online]

Available at: https://passiv.de/downloads/03_building_criteria_en.pdf

[Accessed 07 19 2019].

Passivehaus Trust, 2019. *The UK Passive House Organisation.* [Online]

Available at: http://www.passivhaustrust.org.uk/

[Accessed 01 07 2019].

Peng, Z., Herfatmanesh, M. R. & Liu, Y., 2017. Cooled solar PV panels for output energy efficiency optimisation. *Energy Conversion and Management,* Volume 150, pp. 949-955.

Petrichenko, K., Ürge-Vorsatz, D. & Cabeza, L. F., 2019. Modeling global and regional potentials for building-integrated solar energy generation. *Energy and Buildings,* Volume 198, pp. 329-339.

Pointner, H. & Steinmann, W. D., 2016. Experimental demonstration of an active latent heat storage concept. *Applied Energy,* Volume 168, pp. 661-671.

Pretlove, S. & Kade, S., 2016. Post occupancy evaluation of social housing designed and built to Code for Sustainable Homes levels 3, 4 and 5. *Energy and Buildings,* Volume 110, pp. 120-134.

Qadrdan, M. et al., 2019. Gas and electricity supply implications of decarbonising heat sector in GB. *Energy,* Volume 169, pp. 50-60.

Renaldi, R. & Friedrich, D., 2019. Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK. *Applied Energy,* Volume 236, pp. 388-400.

Rodrigues, L. et al., 2018. Theoretical and experimental thermal performance assessment of an innovative external wall insulation system for social housing retrofit. *Energy and Buildings,* Volume 162, pp. 77-90.

Sameni, S. M. T., Gaterell, M., Montazami, A. & Ahmed, A., 2015. Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment,* Volume 92, pp. 222-235.

Scarpa, M., Tambani, C. & Schibuola, L., 2018. CO2 based ventilation control in energy retrofit: An experimental assessment. *Energy*, Volume 143, pp. 606-614.

Schibuola, L., Scarpa, M. & Tambani, C., 2018. Innovative technologies for energy retrofit of historic buildings: An experimental validation. *Journal of Cultural Heritage,* Volume 30, pp. 147-154.

Scottish Government, 2002. *The Scottish Fuel Poverty Statement,* Edinburgh: Scottish Government.

Scottish Government, 2011. *Technical Handbook - Domestic Section 6.* [Online] Available at: https://www.webarchive.org.uk/wayback/archive/20141201091407mp_/http:/www.scotland.gov.uk/Resource/0046/00462652.pdf
[Accessed 01 07 2019].

Scottish Government, 2011. *Technical Handbook Domestic Section 7.* [Online] Available at: https://www.webarchive.org.uk/wayback/archive/20160105072529mp_/http://www.gov.scot/Resource/0039/00392411.pdf
[Accessed 01 07 2019].

Scottish Government, 2017. *Building Standards technical handbook 2017: domestic buildings.* [Online]

Available at: https://www.gov.scot/publications/building-standards-2017-domestic/
[Accessed 28 06 2019].

Scottish Government, 2017. *Scottish Energy Strategy: The future of energy in Scotland,* Edinburgh: Scottish Government.

Scottish Government, 2017. *Scottish House Condition Survey,* Edinburgh: Scottish Government.

Scottish Government, 2018. *Consultation Analysis: Energy Efficiency Standard for Social Housing post-202 (EESSH2),* Edinburgh: Scottish Government.

Scottish Government, 2018. *Consultation Analysis: Energy Efficient Scotland.*
[Online]
Available at:
https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2018/11/consultation-analysis-energy-efficient-scotland-making-homes-buildings-warmer-greener-more-efficient/documents/consultation-analysis-energy-efficient-scotla
[Accessed 03 07 2019].

Scottish Government, 2018. *Home Energy Efficiency Programmes Scotland: annual review 2016-2017,* Edinburgh: Scottish Government.

Scottish Government, 2018. *Scottish house condition survey: 2017 key findings.*
[Online]
Available at: https://www.gov.scot/publications/scottish-house-condition-survey-2017-key-findings/pages/4/
[Accessed 25 07 2019].

Scottish Government, 2019. *Reaching net zero.* [Online]

Available at: https://www.gov.scot/news/reaching-net-zero/

[Accessed 14 07 2019].

Shi, G. H., Aye, L., Li, D. & Du, X. J., 2019. Recent advances in direct expansion solar assisted heat pump systems: A review. *Renewable and Sustainable Energy Reviews,* Volume 109, pp. 349-366.

Shrestha, P., 2018. *Energy Live News.* [Online]

Available at: https://www.energylivenews.com/2018/07/20/uk-to-scrap-feed-in-tariff-scheme-in-april-2019/

[Accessed 25 07 2019].

Singh, R. M., Sani, A. K. & Amis, T., 2019. An overview of ground-source heat pump technology. *Managing Global Warming,* pp. 455-485.

Sovacool, B. K., Lipson, M. M. & Chard, R., 2019. Temporality, vulnerability, and energy justice in household low carbon innovations. *Energy Policy,* pp. 495-504.

Sovacool, B. K., Sidortsov, R. V. & Jones, B. R., 2013. *Energy Security, Equality and Justice.* London: Routledge.

Stafford, A., Gorse, C. & Shao, L., 2011. *The Retrofit CHallange: Delivering Low Carbon Building,* London: The Centre fro Low Carbon Futures.

Streicher, K. N., Parra, D., Buerer, M. C. & Patel, M. K., 2017. Techno-economic potential of large-scale energy retrofit in the Swiss residential building stock. *Energy Procedia,* Volume 122, pp. 121-126.

Sunamp Ltd, 2019. *Sunamp.* [Online]

Available at: https://www.sunamp.com/

[Accessed 29 06 2019].

Suzer, O., 2019. Analyzing the compliance and correlation of LEED and BREEAM by conducting a criteria-based comparative analysis and evaluating dual-certified projects. *Building and Environment,* Volume 147, pp. 158-170.

Swan, W. & Brown, P., 2013. Retrofit innovation in the UK social housing sector. In: W. S. a. P. Brown, ed. *Retrofitting the Built Environment.* s.l.:John Wiley & Sons Ltd, pp. 36-52.

The Microgeneration Certification Scheme, 2019. *MCS Certified Product - Solar Assisted Heat Pump.* [Online]
Available at: https://www.microgenerationcertification.org/consumers/product-search/?product_type_id=6778
[Accessed 29 06 2019].

The Ministry of Housing, Communities and Local Government, 2019. *Local authority housing statistics:Year ending March 2018, England.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/773079/Local_Authority_Housing_Statistics_England_year_ending_March_2018.pdf
[Accessed 15 08 2019].

The Times, 2019. *Gas boilers will be banned in new homes from 2025.* [Online]
Available at: https://www.thetimes.co.uk/article/gas-boilers-will-be-banned-in-new-homes-from-2025-s7kbtb6jq
[Accessed 01 07 2019].

The Zero Carbon Hub, 2015. *Overheating in Homes: the Big Picture,* London: Zero Carbon Hub.

Tingley, D. D., Hathway, A. & Davison, B., 2015. An environmental impact comparison of external wall insulation types. *Building and Environment,* Volume 85, pp. 182-189.

Touchie, M. F. & Pressnail, K. D., 2014. Evaluating a proposed retrofit measure for a multi-unit residential building which uses an air-source heat pump operating in an enclosed balcony space. *Energy and Building,* Volume 85, pp. 107-114.

U.S. Green Building Council, 2019. *Green building leadership is LEED.* [Online]
Available at: https://new.usgbc.org/leed
[Accessed 03 07 2019].

UK Government, 2006. *A Decent Home:Definition andguidance forimplementation.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/7812/138355.pdf
[Accessed 15 08 2019].

UK Government, 2013. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings.* [Online]
Available at: https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf
[Accessed 01 07 2019].

UK Government, 2018. *Electricity generation and supply figures for Scotland, Wales, Northern Ireland and England, 2014 to 2017.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770766/Regional_Electricity_Generation_and_Supply.pdf
[Accessed 06 07 2019].

UK Government, 2018. *Energy Consumption in the UK,* London: UK Government.

UK Government, 2019. *Annual domestic energy bills.* [Online]
Available at: https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics
[Accessed 08 08 2019].

UK Government, 2019. *Greenhouse gas reporting - Conversion factors 2019.* [Online]
Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019
[Accessed 15 08 2019].

UN Climate Change, 2019. *UN Climate Chief Urges Action on Climate Emergency.* [Online]
Available at: https://unfccc.int/news/un-climate-chief-urges-action-on-climate-emergency
[Accessed 08 07 2019].

United Nations Environment Program, 2010. *Common Carbon Metricfor measuring Energy Use & reporting Greenhouse Gas Emissions from building operations,* s.l.: UNEP SBCI.

Valentin Software GmbH, 2019. *PV*SOL premium.* [Online]
Available at: https://www.valentin-software.com/en/products/photovoltaics/57/pvsol-premium
[Accessed 15 08 2019].

Walker, J. S., 2009. *Private landowners' engagement with woodfuel production: a scoping study in Fife, a scoping study in Fife.,* Fife: Forestry Commission.

Waser, R. et al., 2018. Compact latent heat storage decarbonisation potential for domestic hot water and space heating applications in the UK. *Applied Energy,* 231(1), pp. 116-126.

Watson, S. D. & Buswell, L. R., 2019. Decarbonising domestic heating: What is the peak GB demand?. *Energy Policy,* Volume 126, pp. 533-544.

Windows Guide, 2019. *How Much Do Windows Cost? Replacement Window Prices 2019.* [Online]
Available at: https://www.windowsguide.co.uk/window-prices
[Accessed 17 08 2019].

Wu, R., Mavromatidis, G., Orehounig, K. & Carmeliet, J., 2017. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. *Applied Energy,* Volume 190, pp. 634-649.

Xu, J., Wang, R. & Li, Y., 2014. A review of available technologies for seasonal thermal energy storage. *Solar Energy,* Volume 103, pp. 610-638.

Yingchun, J., Angela, L. & Swan, W., 2019. Building dynamic thermal model calibration using the Energy House facility at Salford. *Energy and Buildings,* Volume 15, pp. 224-234.

Zimmermann, M. & Pye, S., 2018. Inequality in energy and climate policies: Assessing distributional impact consideration in UK policy appraisal. *Energy Policy,* Volume 123, pp. 594-601.

Appendix

Appendix 1 Ground collector length calculation for the base model.

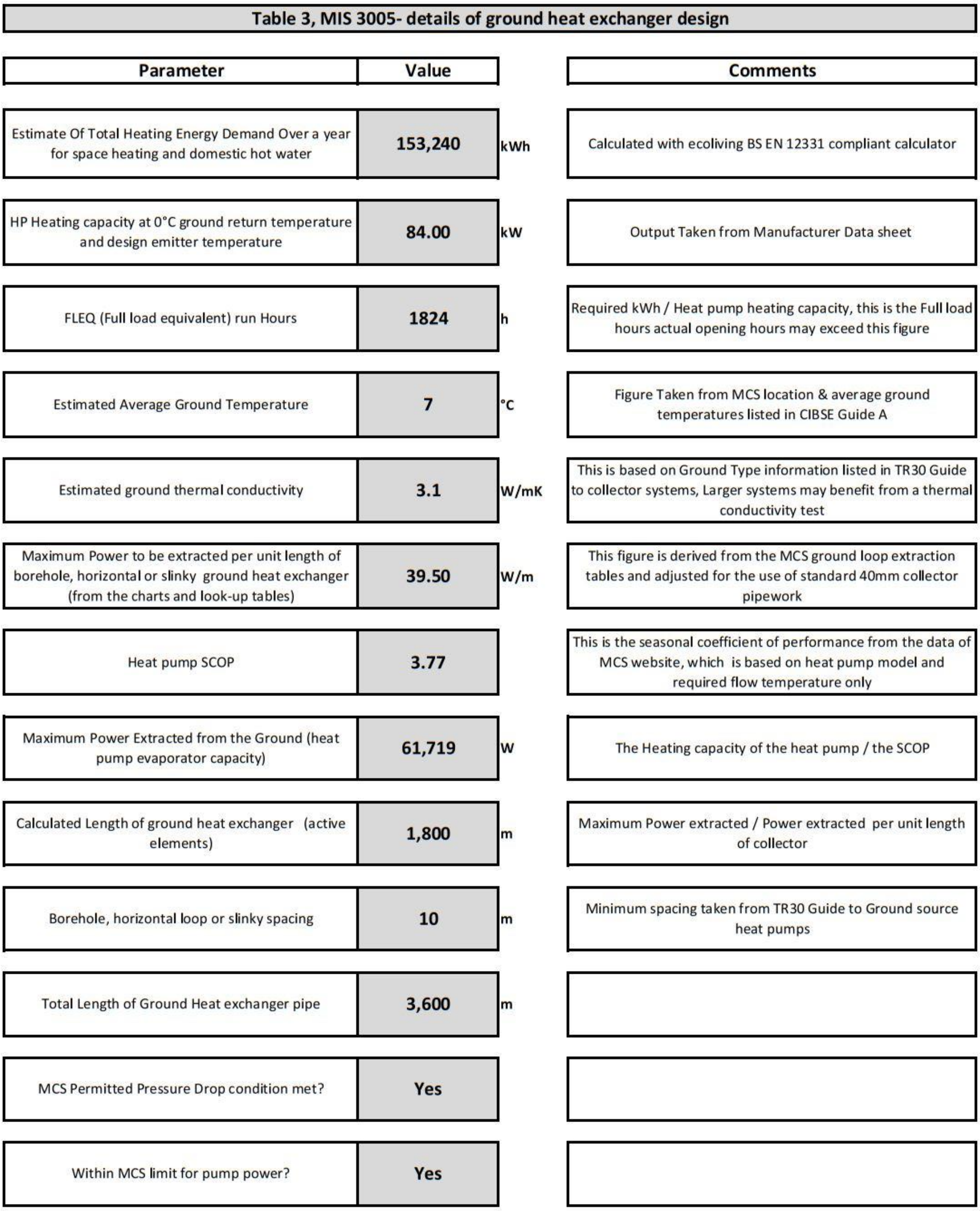


Table 3, MIS 3005- details of ground heat exchanger design

Parameter	Value		Comments
Estimate Of Total Heating Energy Demand Over a year for space heating and domestic hot water	153,240	kWh	Calculated with ecoliving BS EN 12331 compliant calculator
HP Heating capacity at 0°C ground return temperature and design emitter temperature	84.00	kW	Output Taken from Manufacturer Data sheet
FLEQ (Full load equivalent) run Hours	1824	h	Required kWh / Heat pump heating capacity, this is the Full load hours actual opening hours may exceed this figure
Estimated Average Ground Temperature	7	°C	Figure Taken from MCS location & average ground temperatures listed in CIBSE Guide A
Estimated ground thermal conductivity	3.1	W/mK	This is based on Ground Type information listed in TR30 Guide to collector systems, Larger systems may benefit from a thermal conductivity test
Maximum Power to be extracted per unit length of borehole, horizontal or slinky ground heat exchanger (from the charts and look-up tables)	39.50	W/m	This figure is derived from the MCS ground loop extraction tables and adjusted for the use of standard 40mm collector pipework
Heat pump SCOP	3.77		This is the seasonal coefficient of performance from the data of MCS website, which is based on heat pump model and required flow temperature only
Maximum Power Extracted from the Ground (heat pump evaporator capacity)	61,719	W	The Heating capacity of the heat pump / the SCOP
Calculated Length of ground heat exchanger (active elements)	1,800	m	Maximum Power extracted / Power extracted per unit length of collector
Borehole, horizontal loop or slinky spacing	10	m	Minimum spacing taken from TR30 Guide to Ground source heat pumps
Total Length of Ground Heat exchanger pipe	3,600	m	
MCS Permitted Pressure Drop condition met?	Yes		
Within MCS limit for pump power?	Yes		