Department of Mechanical and Aerospace Engineering

Methodology to assess cost optimality for retrofitting existing Scottish housing stock to meet EnerPHit energy efficiency standards

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Signed: Jennifer MacLean Date: 4th September 2015

Abstract

The need to ensure a sustainable and secure energy supply networks and to reduce the impact of CO_2 emissions, pollution and natural resource use has led to the introduction of tighter regulation of energy performance standards for buildings. These will increasingly be applied to existing buildings, necessitating the need for refurbishment work to reduce energy use of building stock as a whole.

Scotland contains a disproportionately high proportion of historic properties with listed status which significantly constrains energy efficiency retrofit options due to the fabric of the buildings and the legal requirement to preserve their appearance and character. These challenges also greatly increase the cost of applying energy efficiency measures or introducing the provision of renewable energy generation to historic properties. Partly as a result of this, Scotland experiences high levels of fuel poverty and ill health due to poor building fabric and design.

This thesis captures the technologies available to improve energy performance and occupant health within buildings. As there are currently no requirements to improve the energy performance of existing buildings in Scotland, modelling work on a case study was carried out in the PHPP spreadsheet to measure against Passive House and EnerPHit standards. A beta version of the spreadsheet was used to reflect incoming tightening of the requirements and allow renewables to be modelled effectively.

A technology selection table was developed in conjunction with a cost optimal methodology framework in order to enable effective and cost efficient retrofit options to be selected for other buildings being considered for improvements.

The case study demonstrated that it is only through the introduction of renewable generation capability that true financial as well as energy savings can be achieved over lifetime timescales. This is heavily influenced by fuel prices and renewables subsidies which are vulnerable to future increases or being withdrawn in the case of subsidies.

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Firstly, thank you to my supervisor Dr Paul Strachan for giving me a gentle initial shove in the right direction to get things going and helping to keep me focussed on the most important aspects of the project.

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And finally, a thank you to the team at the BBCs The Beechgrove Garden for giving me an alternative focus, a physical outlet whilst all this mental work has been going on and leaving me with a wonderful, uplifting garden to look out at during the final few weeks.

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Nomenclature

ach	Air changes per hour (1/h)
ASHP	Air Source Heat Pump
CFD	Computational Fluid Dynamics
COM	Cost Optimal Methodology
DECC	Department for Environment and Climate Change
DHW	Domestic Hot Water
EPC	Energy Performance Certificate
FIT	Feed-In Tariff
GSHP	Ground Source Heat Pump
NPV	Net present value (£)
PE	Primary Energy (kWh/m^2.a)
PER	Passive Energy Renewable (kWh/m^2.a)
PH	Passive House
PHPP	Passive House Planning Package
PSI (ψ)	Linear thermal transmittance of a thermal bridge (W/mK)
Q	Heat Transfer Rate (W)
RHI	Renewable Heat Incentive
SAP	Standard Assessment Procedure
TFA	Treated floor area (m^2)
TST	Technology Selection Table
U-value	Overall heat transfer coefficient or thermal transmittance (W/m^{2}K)

Chapter 1: Introduction

It is becoming more widely recognised that as CKD Galbraith (2015) stated "*Heat is the single biggest reason we use energy in our society*". This is backed up by statistics from the Department of Energy & Climate Change (2014) who reported that in 2011, space heating in the UK was responsible for around 60% of household total energy use, with this proportion showing a gradual upward trend and total space heating energy requirement across the UK increasing more rapidly. In the same year, around 18% of total household energy use was for domestic hot water production, although this shows a slowly falling trend. As housing accounted for 29.1% of total UK energy use in 2012 (DECC, 2014), improvements to building energy efficiency will play a large role in reducing overall demand for energy.

These factors, coupled with the need to ensure a sustainable and secure energy supply networks and to reduce the impact of CO_2 emissions, pollution and natural resource use has led to the introduction of tighter regulation of energy performance standards for buildings. These will increasingly be applied to existing buildings, necessitating the need for refurbishment work to reduce energy use of building stock as a whole.

Scotland contains an atypically high proportion of historic properties with listed status. This significantly constrains energy efficiency retrofit options due to both the fabric of the buildings and the legal requirement to preserve their appearance and character. These challenges also greatly increase the cost of applying energy efficiency measures or introducing the provision of renewable energy generation to historic properties. As a result of this and other economic factors, Scotland experiences high levels of fuel poverty and ill health due to poor building fabric and design.

This study as a whole will focus on domestic houses characterised as historic in rural areas. Flats, particularly those in urban areas are treated differently by legislation to houses and the energy efficiency challenges of these dwellings tend to be quite different.

Chapter 2 defines the aims of the project and the objectives employed to achieve these aims.

Chapter 3 introduces the factors and concepts identified during the literature review as significant to this project. It begins with an overview of the current housing stock in Scotland and the major issues which affect this stock. An introduction then follows to the legislation, regulations and standards applying to building energy use. This covers the current European Directive legislation and the widely recognised Passive House standard. The newer EnerPHit standard for retrofitted buildings is then described. The implications for applying energy efficiency measures to historic buildings is introduced along with the constraints imposed by the Listed Building system in Scotland. The concept of a Cost Optimal Methodology to assess the cost effectivity of building improvements is described. And finally the PHPP itself and its benefits and limitations are introduced.

Chapter 4 first describes the overall methodology and approach determined at the beginning of the project, before going on to identify the tasks involved and data required for the four principle project areas: application of building standards to modelling and analysis of results, energy efficiency improvement technology and constraints, development of a cost optimal methodology and verification of these tools through PHPP modelling of a case study.

Chapter 5 concentrates on the case study used for this project. It first gives an introduction to and background of the building modelled including the base case and actual retrofit activity applied to the property. It then looks in more detail at the modelling assumptions utilised for all the different categories of energy efficiency improvement before presenting the outputs from the modelling.

Chapter 6 looks in more detail at how the Technology Selection Table was put together and presents the final tool following verification with the case study example.

Chapter 7 describes the inputs and assumptions required in generating the Cost Optimal Methodology model, summarises the calculations used in the final model and presents the results of this methodology applied to the case study.

Chapter 8 contains analysis of the results from the case study energy performance from PHPP, the validity of the Technology Selection Table and the implications from the Cost Optimal Methodology applied to the case study. It concludes by drawing together inferences from these individual aspects for the improvement of energy efficiency amongst existing buildings for Scottish Housing stock as a whole.

Chapter 9 completes the study by providing suggestions for potential future work to improve the understanding of this topic through further building and energy modelling, appropriate selection of technology for building application and cost optimal methodology at a macroeconomic and energy policy level.

Chapter 2: Aims and Objectives

2.1. Aims

For this project, the main aim was to investigate the appropriate application of building energy consumption improvement technologies to existing buildings in Scotland. Additionally, the potential benefits of incorporating renewable energy solutions were to be assessed using a PHPP spreadsheet.

2.2. Objectives

The following objectives for the project were set:

- Develop a methodology for selecting and verifying a cost optimal retrofit solution for an existing building in Scotland
- Produce a guidance method and document to prioritise technology and renewable energy solutions when planning to upgrade an existing building to meet EnerPHit building standards
- Utilise the latest version of PHPP spreadsheet to benchmark and quantify the energy use changes resulting from the application of different energy efficiency technologies to an existing case study building

- Create analysis rules and tools to utilise the PHPP outputs in order to confirm the Cost Optimal retrofit solution for an individual building

Chapter 3: Literature Review

3.1. Scottish Housing Stock Overview

The Scottish Government (2014a) defines fuel poverty where *"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 (including Housing Benefit or Income Support for Mortgage Interest) on all household fuel use"*. So whilst there has been a reported 8% drop in the overall energy needs of the average house due to energy efficiency improvements since 2010, it is telling that levels of fuel poverty have risen to affect 39.1% of Scottish households in 2013. Whilst rising fuel prices across the board have undoubtedly contributed to this increase, it can be argued that the characteristics of the housing stock in Scotland also has a very significant contributory role.

According to The Scottish Government (2014a), 20% of all existing dwellings in Scotland were built prior to 1919 and these older properties are associated with higher levels of fuel poverty and lower levels of energy efficiency. To give an idea of the scale of the challenge faced by homeowners, policy makers and regulatory authorities – 77% of all Scottish housing was built before the introduction of energy efficiency standards in 1982. Of this stock, 59% are houses. It is these individual dwellings which this study was focused on, as they are self contained units for modeling and are predominantly occupied by owner occupiers who have direct control over their own building fabric, systems and energy bills.

Individuals are beginning to become more aware of their role in improving energy efficiency as increasing numbers of people are reporting monitoring their energy use very or fairly closely. There is however still a perception gap, as in The Scottish Government (2014a) the most common reasons given for having difficulty in heating homes is poor/inadequate heating and draughty buildings. In fact, poor building fabric, insulation levels and occupant behavior are most likely to be driving up the energy required to heat properties and therefore the installed heating system becomes inadequate.

3.2. Legislation, Regulations and Standards

3.2.1. European Directive

Requirements for energy efficiency measures in buildings in Scotland are ultimately driven by **The European Directive 2010/31/EU** (The European Parliament and the Council of the European Union, 2010) setting out energy efficiency and CO_2 targets which EU member states are required to interpret and enshrine in national regulation. According to The Scottish Government (2013a), this has been formalised with the introduction of Climate Change (Scotland) Act 2009 which imposed greenhouse gas reductions which are legally binding and must be implemented in a timely manner.

Whilst new construction is governed by the Energy Performance of Buildings (Scotland) Regulations (2008), very few of the regulations are actually directed at retrofitted or renovated buildings. New buildings and those undergoing major refurbishment must undergo energy efficiency calculation using the Standard Assessment Method (SAP) to generate an Energy Performance Certificate (EPC), but there are no current requirements for them to meet any specific energy performance standards. An EPC gives both an energy use banding (A-G, where A represents lowest and G highest relative energy use) and a rating within the band to give more specific knowledge of where in the band a property performs. It also produces a separate measure with similar banding and rating to represent CO_2 emissions for the property. The difference between the two is indicative of the relative efficiency and emissions of different fuels used.

The Scottish Government (2013a) report sets out specific recommendations on how to achieve their commitment to reduce CO_2 emissions by 42% by 2020 (from 1990 levels), balanced against financial pressures which have resulted from UK public finance cuts putting pressure on existing efficiency incentive programmes. Whilst these recommendations won't become legal until the 2015 revision of the Climate Change (Scotland) Act, it is anticipated that these are likely to include at least some aspects of the following becoming mandatory whenever a property is sold or undergoes a major refurbishment:

- **Measures based –** e.g. specific measures such as insulation of cavity walls and lofts, with set insulation depths and heating systems codified into building standards
- **SAP** energy report recommendations – some to become mandatory instead of the current advisory basis
- **Standards based** – e.g. introducing a requirement to meet a minimum EPC rating

3.2.2. Passive House Standard

Whilst not mandatory in any country, the Passive House standard developed in Germany in the early 1990s has become increasingly popular worldwide as a recognised benchmark standard for energy efficient, comfortable, healthy homes and is beginning to be more widely utilised in public buildings. It is claimed by the Passivhaus Institut (2014) that a building constructed according to PH guidelines can achieve energy savings from heating and cooling of 90% compared to typical housing stock and 75% when compared against typical new builds. In order to achieve the targets enshrined within the standard, features typical of a Passive House building are:

- **Insulation** – very low U-value structural components to minimise heat loss through the fabric of the building
- **Air leakage** – extremely airtight buildings which prevent heat losses due to uncontrolled air infiltration through the structure
- **Ventilation** – to maintain healthy air quality a MVHR system is in continuous operation to feed fresh air to all living spaces which has been pre-warmed using heat from extract air from warm, high moisture areas such as bathrooms and kitchens
- **Cooling** – shading and ventilation design to minimise solar heat gain during summer months and prevent overheating
- **Energy use** – kept to a minimum with use of highly efficient lighting and appliances with heat pumps used to reduce total electricity demand where practical

- **Thermal bridges** – eliminating cold spots and risk of local and fabric moisture problems by designing out thermally linked through penetrations to the building exterior

The specific requirements are applicable to new construction. To reflect targets to further reduce dependence on fossil fuel generation, draft classifications are introduced in Passive House Institute (2015) which propose to create three different stratified layers of passive house classification which are shown in the table below.

Table 1: Draft Passive House Energy Use Criteria (from Passive House Institute 2015)

Renewable Primary Energy (PER)			Classic	Plus	Premium
PER demand	kWh/m^2yr	<=	60	45	30
Renewable energy generation	kWh/m^2yr	<=	-	60	120

The convention of converting all requirements to the specific quantity per m^2 of the building treated ground floor area ensures that comparisons can directly be made between buildings and systems. PER demand incorporates all heating, cooling, hot water, auxiliary and domestic electricity usage within the thermal envelope of the property as well as any renewable energy generation on site.

The latest certification changes (which are due to go live in late 2015) move from PE (Primary Energy) to PER (Primary Energy Renewable) as one of the principal measurable certification criteria. This will result in changes to both predicted energy use from modelling and success in meeting certification criteria. Both PE and PER are intended to give a measure of the total energy requirement of a property as described above. Weighting factors to reflect the true energy requirements of different fuel types from PE have been updated in the PER metric to reflect the incorporation of renewable generation into the energy supply networks and new factors added to account for on site renewable generation.

3.2.3. EnerPHit

Recognising the need to improve energy efficiency throughout housing stock as a whole, the EnerPHit standard has been developed by the Passive House Institute for use on refurbished buildings. It has recently begun to be utilised on a number of properties in the UK. EnerPHit recognises that the constraints of working with existing materials and structures make it more difficult to achieve the stringent heating demand and continuous airtight layer construction of a new build passive house, the heating demand and airtightness targets are different.

To achieve certification, an EnerPHit property must achieve a specific space heating demand of no more than 25 kWh/m^2a (compared to 15 kWh/m^2a for full PH). Airtightness from a pressurised leakage test carried out on the building at 50 Pascals internal pressure must be lower than 1 air change per hour for EnerPHit (compared to 0.6 for full PH). The move from PE demand to PER requirements has led to a change in certification criteria for these values.

Using PE demand the total must be less than or equal to (Passive House Institute, 2015):

" $120 + [(Q_H - 15) \times 1.2] + Q_C - Q_{C,PH}$ *"*

Whereas using PER demand the total must be less than or equal to:

" $60 + [(Q_H - Q_{H,PH}) \times f_{OPER}] + [(Q_C - Q_{C,PH})/2]$

Where

Q_H *= heating demand*

$Q_{H,PH}$ *= passive house criterion for heating demand (25* kWh/m^2a *in cool, temperate climate zone)*

f_{OPER} *= weighted mean of the PER factors of the heating system of the building*

Q_C *= cooling demand*

$Q_{C,PH}$ *= passive house criterion for heating demand (15* kWh/m^2a*)*

If $(Q_H - Q_{H,PH})$ *or* $(Q_C - Q_{C,PH})$ *are negative then these terms are to be taken as zero"*

This change to the energy requirements for certification from Passive House to EnerPHit classifications make direct comparison of building energy use more complex.

There are also alternative certification criteria related to the thermal and airtightness properties of the building components which are dependent on the climate zone in which the building is situated. These were not directly considered during this project.

Reviewing the UK case studies available on Low Energy Buildings (2015) demonstrated that concentrating on applying the underlying principles of focusing close attention to application of insulation and airtightness detailing alongside introducing MVHR technology and updating space heating technology can successfully result in achievement of EnerPHit standards across a wide variety of building constructions, styles and ages. Design strategies to achieve these goals are listed under:

- Space heating
- Water heating
- Fuel selection
- Renewable energy generation
- Passive solar
- Space cooling
- Daylighting
- Ventilation
- Airtightness
- Minimising thermal bridges (modeling)
- Insulation

3.3. Historic and Listed Buildings

From a total housing stock of around 2.4million (The Scottish Government, 2013b) in 2013, listed buildings represented around 2% of this total according to the 47,649 records quoted by Historic Scotland (2015a). They are categorised into:

- **Category A** – typically of national or international importance (8% of listed building total)
- **Category B** – generally of regional importance (50% of listed building total)

- **Category C** – either of local importance or simple traditional building (42% of listed building total)

Listed buildings represents properties from a broad range of historical ages, construction materials and styles, sizes and original function and therefore require to be considered on a case by case basis for the purposes of renovation or upgrading. In addition to formally listed buildings, the 20% of Scottish housing stock constructed prior to 1919 can largely also be classified as historic.

Although hugely individual, what the listed and historic buildings often share is the designation of being hard to treat in terms of energy efficiency improvement measures. This can be due to construction methods or materials (such as solid floors and walls) which present technical and practical difficulties when designing or applying energy efficiency improvements (such as wall insulation or an extensive MVHR ventilation ducting system). Additionally, due to strict planning approvals for listed buildings (plus some other properties in sensitive locations), changes which effect the appearance of the property or area, or significantly modify the construction materials or function of the property reduce the scope for making energy efficiency improvements.

An initial priority order for investment when upgrading historic buildings was suggested by Historic Scotland (2013a) in the figure below. The principal influencing factors were energy use and how the measures met up to the subsidy funding requirements of the Green Deal and other CO_2 reduction subsidy initiatives. Significant energy use reductions would be expected on selection of appropriate insulation.

1. Loft insulation
2. Flat roof insulation
3. Room-in-roof insulation
4. Cavity wall insulation
5. Internal or external solid wall insulation
6. Floor insulation
7. Cylinder jacket
8. Draught proofing
9. Low energy lighting
10. Cylinder thermostat
11. Heating controls (wet system)
12. Heating controls (warm air system)
13. Biomass boiler
14. Wood pellet stove and radiators
15. Biomass boiler (alternative)
16. Replacement condensing gas or boiler, same fuel
17. Condensing oil boiler (from warm air)
18. Condensing gas boiler (from gas fires)
19. Condensing gas boiler, fuel switch
20. Flue gas heat recovery in conjunction with new boiler
21. Replacement storage heaters
22. Replacement warm air unit
23. Solar water heating
24. Waste water heat recovery
25. Energy efficient glazing
26. Secondary glazing
27. Insulate doors
28. Photovoltaics
29. Wind turbine

Figure 1: Historic Scotland (2013a) recommended priority order for historic building energy efficiency upgrade

On historic buildings, simply applying insulation to existing walls can reduce energy bills at the expense of interfering with the healthy functioning of the natural building ventilation process, preventing the building from breathing and potentially trapping moisture within the walls to create fabric degradation and mould problems. The table below clearly illustrates the conflict between a traditional vapour permeable construction and a modern sealed envelope design.

Table 2: Traditional 'vs' modern construction principles (Historic Scotland, 2015b)

Traditional House	Modern House
Vapour permeable construction allows moisture within the building to dissipate. Moisture is absorbed into the fabric, can pass through, and then evaporates when drying conditions occur.	Modern construction relies on a sealed external envelope. Water finding its way into the construction does not readily evaporate. Vapour barriers within the construction prevent internal vapour loads from passing through the fabric.
Thick walls (0.6 metres or more), in Scotland usually stone, with a large volume of lime mortar and some voids, giving a high thermal mass.	Relatively slender wall construction (typically 0.3 metres) with vapour barriers and/or cavities.
May not have a damp-proof course although many buildings have a basic system (slate or bitumen).	Damp-proof course prevents moisture transfer from the ground.
Good ventilation within voids in walls, floors and roofs essential to disperse moisture from the construction. Chimneys and flues help to remove internally generated moisture.	Largely sealed structure, trickle ventilation in windows and mechanical extractor fans in areas of high vapour load.
Generally composed of a limited range of natural materials with no preservatives.	Most construction products are mass produced and many are man-made. Timbers are treated with preservatives.
Relatively low levels of insulation.	High levels of insulation are normally incorporated into the design.

Research raises a number of additional concerns arising from insulating and airtight sealing of historic properties. Notable amongst these according to Historic Scotland (2011a) is deterioration of indoor air quality due to accumulation of particulates, gases and contaminants. These have been linked to increase in lung cancer, allergies and hypersensitivity reactions – particularly amongst immune suppressed inhabitants. Therefore, it is vital that sufficient and appropriate ventilation is designed in at the same time as insulation and draft proofing measures.

3.4. Cost Optimal Methodology

In addition to the original legislative obligations to reduce building energy usage through energy efficiency measures, the Recast of The European Parliament and the Council of the European Union (2010) Directive requires that Member States "*assure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels*". This is to be achieved through the development of a Cost Optimal Methodology by Member States which is defined in the Directive as "*the energy performance level which leads to the lowest cost during the estimated economic lifecycle*". This calculation methodology can be carried out on two different levels:

- **Societal level:** Calculating costs and benefits from the ***macro***economic perspective
- **Private/end-users level:** Calculating financial cost from the **micro**economic perspective

As this project was focussed on assessing highly individual buildings in private ownership, then the second method was deemed most appropriate. Figure 2 below illustrates the calculation inputs and processes involved:

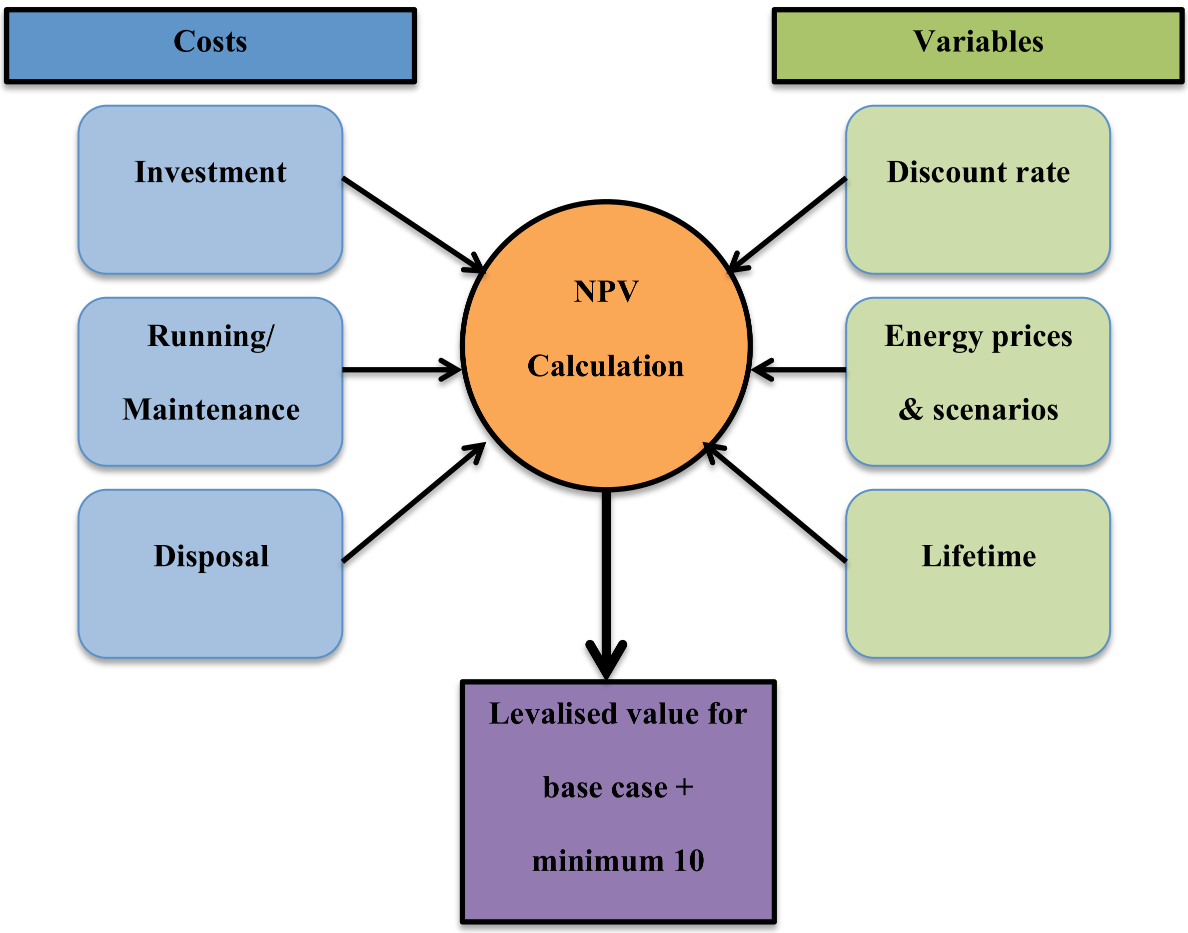


Figure 2: Cost Optimal Methodology Inputs and Processes

A typical resulting COM graph for a base model with variants calculated can be seen below.

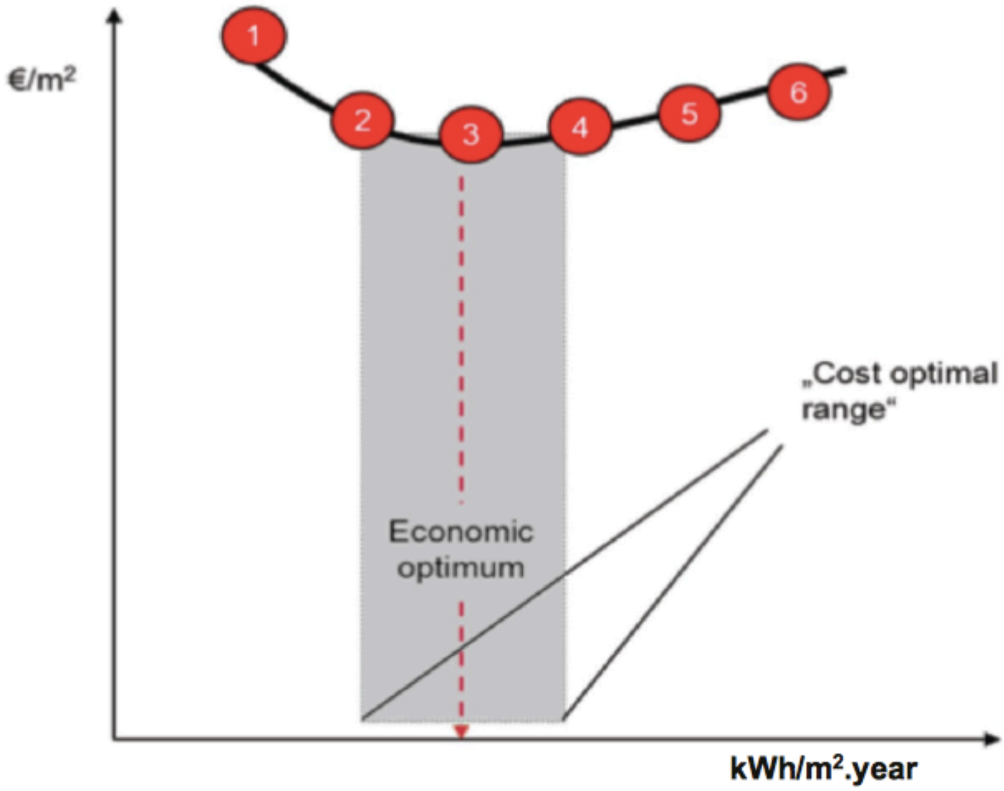


Figure 3: Typical Cost Optimal Methodology results (Source: Concerted Action Energy Performance of Buildings, 2013)

The cost optimal range shown is the minimum lifetime cost which meets the energy use requirements under consideration – i.e. to achieve EnerPHit, if the dotted red line represented 25 kWh/m^{2}year then option 4 would be moved out of the cost optimal range and rejected as a viable solution.

Some important additional factors were identified by The Buildings Performance Institute (2013) to ensure maximum benefit from the process of combining energy performance and cost optimal goals in the selection of retrofit packages:

1. Non economic factors such as associated improvements to indoor climate, changes to behaviour and building use required of occupants and the introduction of additional maintenance requirements should also be considered

2. There are implications for property values and the burden of cost and benefit for the householder and society with the introduction of additional energy efficiency requirements which must also be considered
3. Retain a holistic whole building perspective to prevent a component focus leading to piecemeal introduction of improvements, introducing additional costs and reducing the motivation and benefits from implementing more effective whole building solutions

3.5. PHPP Modelling

PHPP is an Excel spreadsheet based tool developed and distributed by The Passive House Institute for use in modelling energy use in buildings and comparing the results with the defined Passive House and EnerPHit building standards described in Section 3.2. above. Inputs in the form of geometric and thermal properties and characteristics are utilised in quasi steady-state heat flow calculations in order to produce energy use information. It has been widely used for many years by architects, planners and engineers to validate buildings in order to gain a coveted Passive House certification. Predictions of energy use from PHPP have favourably compared with measurements from real buildings. So, whilst more detailed dynamic energy modelling methods are available to produce a room by room assessment of heat flow, there is a high level of confidence that the simplified PHPP approach provides a good overview of building performance for initial validation purposes.

PHPP was of particular value for this project as it is sufficiently flexible to allow the modelling of the features of historic as well as new construction buildings. Moran et al (2013) reported successful use of PHPP for modelling a series of historic properties in Bath in order to assess a range of potential retrofit packages.

Whilst not yet commercially available, access was available for this project to a Beta educational and development version of PHPP - PHPP9. This new version more accurately reflects the true energy requirements of buildings through revised weighting factors for different fuel types which recognise the changing nature of energy supply networks with the incorporation of renewable energy generation.

The new version also introduces the ability to add micro renewable generation capability to buildings and to measure this against the new stratified sub-classifications of Classic, Plus and Premium status in accordance with the updated Passive House and EnerPHit standards due to be introduced in late 2015 and discussed in section 3.2.3. above.

Chapter 4: Methodology

4.1. Overall methodology and approach

In order to effectively meet the aims and objectives set for the project, the tasks and information required and the sequence in which they should be performed had first to be determined. The methodology which was developed and utilised through the course of the project is shown in the figure below:

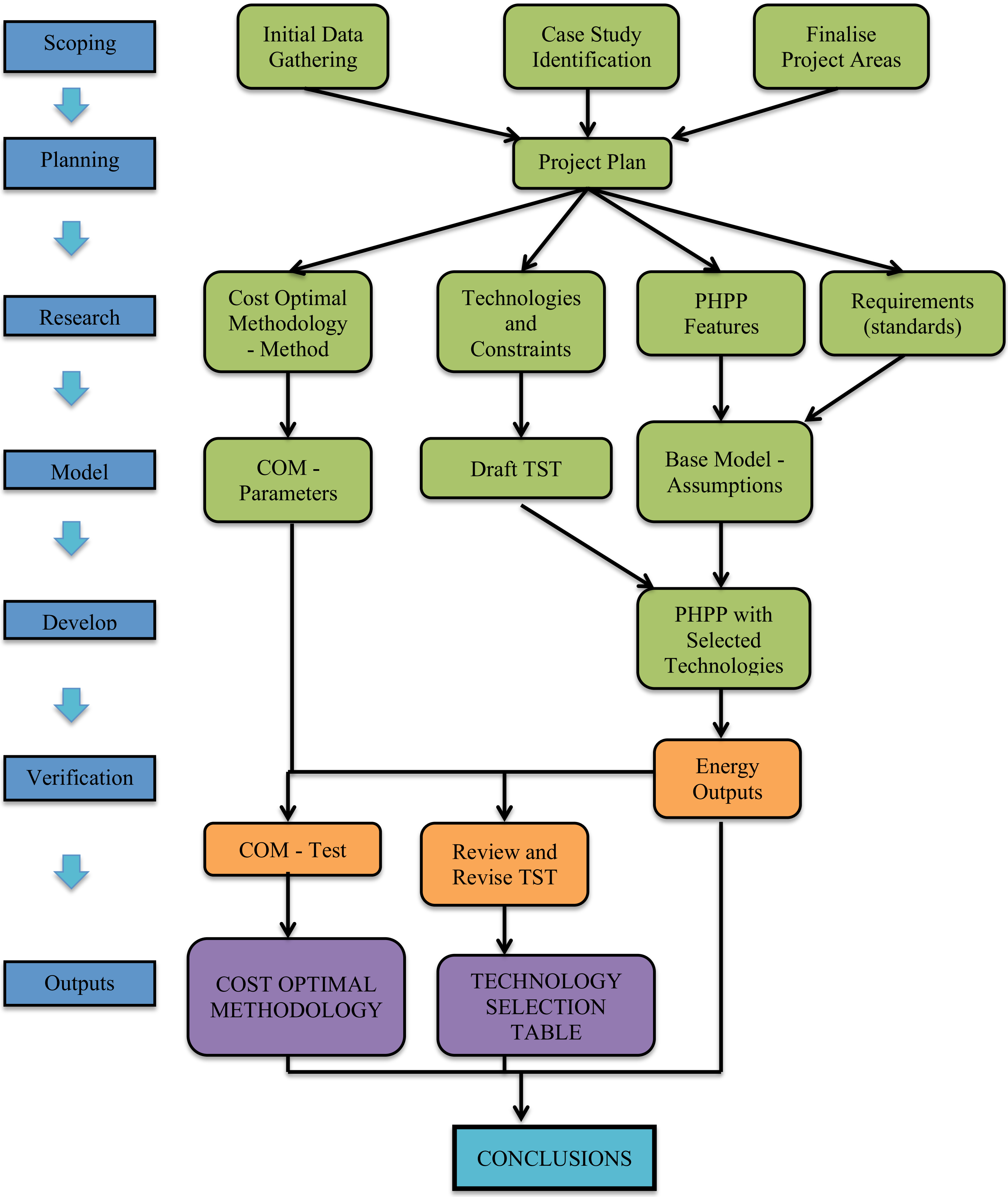


Figure 4: Project Methodology

The boxes on the left represent the phases of the project, with the tasks associated with these phases and the flow and associations between then shown to the right. It is important to note that the case study was required primarily as a vehicle to visualise the impact of energy efficiency technologies on buildings and to be able to test and refine the COM and TST models.

4.2. Application of standards

Understanding of the Passive House and EnerPHit standards for energy requirements in buildings was vital for the project. Both because they generate the specific output metrics and calculation methods from PHPP and more significantly, to create knowledge of desirable features and outcomes when selecting technologies and measuring their impact through the COM model. Understanding and summary of standards and their impacts and applicability was achieved through research.

4.3. Technology and constraints

The starting point for this strand of the project was also research along the following two main lines:

- Energy efficiency technologies and components
- Historic building types, construction, regulation and retrofit experience

This generated a vast range of technology, component and building variants which required cross referencing and prioritisation in order to simplify and manage potential variables within the TST model and its use in generating assumptions and specific details used within PHPP model scenarios.

An important aspect of the verification process for the TST was reviewing the energy outputs generated by the PHPP modelling against EnerPHit standards and COM outputs for the different technologies. Combining these two numerical factors with the more subjective benefits and constraints to arrive at the final TST is described in more detail is Section 6.1 below.

4.4. Cost Optimal methodology

Before any form of model could be proposed, research was required to understand the terminology of a COM model, the types of models previously produced and the parameters and data inputs needed to construct and populate a new model. Key at this point was to distinguish between a macro and micro economic approach as described in Section 3.4. above and the decision to utilise a micro economic format for all further work.

Once the model was constructed, the next stage was to verify the model by inputting energy outputs for each technology scenario from PHPP into the COM model. Plotting the results and comparing against expectations highlighted by research completed this process. Finalising the specific COM model for an individual historic property undergoing energy efficiency renovation to meet EnerPHit standards using TST options and scenarios was the final stage.

4.5. PHPP case study

At the outset of the project, there were a number of potential case study options available. Setting the aims and objectives to create tools to assist in updating historic properties to meet EnerPHit guidelines led to the selection of the "Pink House" described in more detail in Section 5 below as a vehicle for the case study.

Research focussed on the practical use of PHPP spreadsheet in order to be able to model specific technologies. As PHPP is a commercial product, free access to full documentation was not available. However, combining use of available documentation from an earlier software version and literature searching of previous case studies and examples in conjunction with interrogation of design information direct from the case study building facilitated the completion of a base model and set of assumptions.

Refining assumptions according to different technology options identified in conjunction with the draft TST generated a full set of PHPP models. A summary of the main parameters used for each variation can be found in Table 14a-c in Appendix I.

An analysis of the energy performance of the case study building can be found in Section 8.1. below. Whilst the details of these results are of interest for model validation purposes, the principal objective from the modelling was to generate a range of energy outputs for use to verify and revise the COM and TST.

Chapter 5: Case Study

5.1. Introduction

A suitable case study for this project was one which consisted of a domestic historic building undergoing or planned to undergo a major renovation in order to improve the energy performance of the building to reduce energy bills and improve interior comfort plus ease of heating. One such building which was close to completion of its renovation at the start of the project was suggested by Kirsty Maguire Architects who have experience of designing new build properties to Passive House standard and were therefore well placed to advise on practical aspects of technology and design features of different elements.

The property in question, the “Pink House” in St Monans, Fife is pictured below in Figure 5.

Figure 5: Case study building photograph – the “Pink House”

It is a small (51m^2 total floor slab area) traditional property constructed in the 1780s between two larger dwellings with a solid floor and wall construction, a pantile roof and originally had an un-insulated, unheated loft space. The main living space is on the first floor and the principal entrance is via steps to a porch area projecting from the front of the building. This entrance is above a store area which has a metal column supported metal ceiling. All windows were traditional sash and case with wooden frames. It is a ‘B’ listed property and was therefore was required to retain its historic characteristics in terms of exterior appearance. The property is connected on both sides to larger houses of a similar construction.

Renovation work included removing and rebuilding the roof at a higher level, allowing a mezzanine 2nd floor sleeping area to be created with the roof being insulated and forming part of the thermal envelope, complete with new double glazed velux and dormer windows to increase the flow of natural daylight into the property. Internal insulation was applied to the front and rear main external walls, the windows refurbished and a modern, efficient gas boiler installed to replace an older existing model. Whilst the retrofit wasn’t designed to meet full EnerPHit standards, it utilised a number of key features and components and it was possible to visualise how further changes could have been made had certain restrictions not been in place.

From the initial research carried out and with preliminary familiarisation to PHPP complete, a set of 25 scenarios were generated which formed the basis of the case study modelling and the subsequent TST validation and COM analysis. A summary of these cases is listed below in Table 3. Case study numbers remain the same through the remainder of the report.

Table 3: Case study scenario numbers and descriptions

Case Number	Summary Description
1	**Pre-retrofit** – all unimproved
2	**Base** – some insulation, windows renovated/double glazed, efficient gas boiler
2a	**Base + biomass** – as base, biomass replaces gas boiler
3	**Base - thermal bridges** – as base with thermal bridging elements in construction eliminated
3a	**Base – thermal bridges + biomass** – as 3, biomass replaces gas boiler
4	**Complete insulation** – full wall, roof and floor insulation including in porch area
4a	**Complete insulation + biomass** – as 4, biomass replaces gas boiler
5	**Base + windows** – as base, full PH standard triple glazed units in all windows
5a	**Base + windows + biomass** – as 5, biomass replaces gas boiler

6a	**Base + MVHR** – MVHR system with base heating and insulation standards
6b	**Base + MVHR + insulation – thermal bridges** – as 6a with complete insulation and elimination of thermal bridges in construction
6c	**Base + MVHR + windows + insulation – thermal bridges** – as 6b with full PH standard triple glazed units in all windows
7a	**Base + ASHP + MVHR** – as 6a with gas boiler replaced by ASHP as heat supply
7b	**Base + ASHP + MVHR + insulation – thermal bridges** – as 6b with gas boiler replaced by ASHP as heat supply
7c	**Base + ASHP + MVHR + windows + insulation – thermal bridges** – as 6c with gas boiler replaced by ASHP as heat supply
8	**Base + Solar thermal** – as 2 with DHW/space heating supplied by solar collector
8a	**Base + ASHP + MVHR + Solar thermal - boiler** – as 7a with DHW/space heating supplied by solar collector
8b	**Base + ASHP + MVHR + insulation + Solar thermal – thermal bridges – boiler** – as 7b with DHW/space heating supplied by solar collector
8c	**Base + ASHP + MVHR + windows + insulation + Solar thermal – thermal bridges – boiler** – as 7c with DHW/space heating supplied by solar collector
9	**Base + PV** – as 2 with electricity supplemented by PV generation
9a	**Base + MVHR + PV** - MVHR system with base heating and insulation standards and electricity supplemented by PV generation
9b	**Base + MVHR + insulation + PV – thermal bridges** - as 6b with electricity supplemented by PV generation
9c	**Base + MVHR + windows + insulation + PV – thermal bridges** - as 6c with electricity supplemented by PV generation
10	**Base + MVHR + ASHP + windows + insulation + Solar thermal + PV – thermal bridges – boiler** – all technologies applied with boiler replaced by ASHP, MVHR and Solar thermal
11	**Base + MVHR + ASHP + windows + insulation + double Solar thermal + double PV – thermal bridges** – as 11 with solar collector and PV areas doubled

5.2. Assumptions for modelling

Whilst in reality planning and physical restrictions would complicate or directly preclude the installation of certain technology types on the real case study building (external insulation eliminating thermal bridges, MVHR system, modern triple glazed windows, heat pump installation and the installation of solar thermal or PV). In order to better understand the direct energy use and cost impacts of all the available technologies, each was modelled individually for the purposes of the case study and validation of the COM and TST.

Following the generation of the case study scenarios, more detailed research was required to ensure that the correct parameters were used within the PHPP model in order to generate accurate and meaningful energy outputs. Section 5.2.1. below describes the physical construction of the property prior to renovation and identifies the modelling aspects which remained unchanged through subsequent modelling iterations. Subsequent sections describe the assumptions which were made for each aspect of the modelling – they distinguish parameters applied for the original base case from those utilised on later scenario variants. Data sources for specific characteristics are also provided where relevant.

5.2.1. Base Case

The location of the building is St Monans in Fife. Within PHPP, there are a wide range of climate datasets available to ensure that the correct climate zone and conditions are applied to ensure accurate heat flow calculations. Data for Dundee was selected and applied to all variants of the model.

Standard interior winter (20^0C) and summer (25^0C) temperatures were set to represent a realistic expectation of heating requirement in the winter and overheating limits in the summer.

With the heavy stone walls of the property and it being enclosed directly on either side, the specific capacity was set to the maximum of 204 Wh/k per m^2 of treated floor area. This specific capacity impacts the heating and cooling rate of the building. With a high specific capacity, the building would expect naturally to have a slow thermal response rate to any changes in internal or external temperature.

Modelling assumed that the building was south facing. In reality it is set ~15^0 from south, so this was taken to be a reasonable simplification.

No specific shading objects were created in the model. Shading reduction factors of 1 (for unshaded front facing walls and roof surfaces), 0.7 (for rear facing dormer surfaces) and 0.4 for the rear walls as these are situated in an area surrounded by densely packed other buildings.

No cooling system was specified for the model. An initial trial modelling run did not identify any issues with overheating and therefore this variable was eliminated as not being required for this particular case study.

5.2.2. Treated Floor Area

Treated floor area (TFA) is the reference area used in PHPP to calculate specific energy requirements. It differs slightly from the floor area used in SAP calculations to produce EPCs in the UK and therefore caution should be taken in comparing energy use information produced from these two different sources. TFA is used to calculate the volume of air which requires heating. The definition of TFA (Passive House Institute, 2007) given is: "*The floor area is determined using the clear width between building elements (e.g. plaster to plaster). The base areas of baseboards, non-detachable bath or shower tubs, built-in furniture etc. are part of the floor area*". Internal walls, window and door niches do not form part of the TFA. Only rooms within the thermal envelope can contribute to the TFA. In this instance, the front porch area of the building was included, although the external steps to the first floor door were not.

TFA changed between the pre-retrofit model and the modified building due to the addition of the mezzanine floor area which meant that the entire building envelope up to the rafters was then part of the thermal envelope. Previously there was a ceiling with an unheated loft space above which was counted as being outside the thermal envelope. Within the mezzanine level there were some areas that were given a 50% area reduction factor as their clear height was between 1m and 2m. Areas with ceiling heights of less than 1m were excluded from the TFA calculation.

Detail drawings of the pre and post renovation model were used in conjunction with the above guidance to calculate TFA for input to PHPP.

Pre-retrofit *(Case 1)* TFA = 51.0m^2

Post-retrofit *(all remaining cases)* TFA = 59.8 m^2

5.2.3. Walls

From visiting the property, studying drawings and communication with the architect, it was clear that none of the standard building material options within PHPP could be selected to give an accurate representation of the thermal properties of the walls. However Historic Scotland (2011b) contained results of actual measurements of U-values of a number of historic properties which had been successfully retrofitted with insulation to reduce their energy use and then re-measured. The constructions most closely matching the walls of the Pink House were selected and their pre and post retrofit thermal characteristics used in PHPP.

Pre-retrofit *(Case 1)* U = 1.3 W/m^{2}K (Historic Scotland, 2011b) for all external walls – Old masonry construction 700mm thick

Post-retrofit *(all other cases)* U = 0.24 W/m^{2}K (from drawings) for front and rear walls of main building – existing walls + sheet insulation. As pre-retrofit material for porch exterior walls.

Due to the roof being rebuilt with the addition of a dormer window and removal of the loft space, there were changes in the total surface area of the building and correspondingly, the thermal building envelope. Elements of the front and rear walls were below ground level and these were had to be identified separately for the purposes of heat flow calculation as they were externally exposed to the ground instead of ambient air. A summary of the pre and post-retrofit wall areas and total thermal envelope is given in Table 4 below:

Table 4: Wall areas for PHPP model

Parameter	Pre-retrofit area (Case 1), m^2	Post-retrofit area (all other cases), m^2
Total thermal envelope	202	227
External wall – ambient	67.8	74.4
External wall – ground	20.8	20.8
External wall – to neighbours*	92.6	92.6

* PHPP uses this area for heating load calculation only as zero heat loss through party walls is assumed

All wall areas were manually identified and calculated from drawings.

5.2.4. Floors

Similarly to walls, a U-value from a matching construction type in Historic Scotland (2011b) was selected to represent the thermal performance for the floor slab – in this instance to give values for both the pre and post retrofit cases.

Pre-retrofit *(Case 1)* U = 3.9 W/m^{2}K (Historic Scotland, 2011b) – traditional loose stone floor.
Post-retrofit *(all other cases)* U = 0.8 W/m^{2}K (Historic Scotland, 2011b) – traditional loose stone floor with aerogel insulation.

Total floor slab surface area remained consistent for all cases at 50.9m^2.

The other floor area to be modelled was the unusual construction with a metal base plate with timber on top which made up the bottom surface of the porch area. For the later cases with full insulation, a more conventional insulated floor construction was selected.

Pre-retrofit *(Case 1, 2, 2a, 3, 3a, 6a, 7a, 8, 8a, 9 and 9a)* U = 2.383 W/m^{2}K over an area of 4.7m.
Post-retrofit *(Case 4, 4a, 5, 5a, 6b, 6c, 7b, 7c, 8b, 8c, 9b, 9c, 10,11)* U = 0.7 W/m^{2}K (Historic Scotland, 2011b) – suspended timber floor with wood fibre insulation.

All floor areas were manually identified and calculated from drawings.

5.2.5. Roof

For the pre-retrofit case, it was the ceiling of the main building and the porch roof which made up the top of the thermal envelope. Once retrofitted, the main roof (including dormer surfaces and rooflight surface) plus porch roof made up the top of the thermal envelope. The only change is for those cases with full insulation (5, 5a, 6c, 7c, 8c, 9c, 10 & 11) where the porch roof is now assumed to be made from the same material as the main roof.

Ceiling, U = 1.5 W/m^{2}K (Historic Scotland, 2011b) – traditional ceiling.
Porch roof, U = 1.9 W/m^{2}K (Historic Scotland, 2011b) – traditional coomb construction.
Main roof, U = 0.12 W/m^{2}K (from drawings) – new board insulation construction finished with pantiles.
Dormer surfaces, U = 0.151 W/m^{2}K (from drawings)
Rooflight surfaces, U = 0.141 W/m^{2}K (from drawings)

Pre-retrofit *(Case 1)* = 50.9 m^2 ceiling + 3.1 m^2 porch roof
Post-retrofit *(Case 2, 2a, 3, 3a, 4, 4a, 6a, 6b, 7a, 7b, 8a, 8b, 9a, 9b)* = 51.6 m^2 main roof + 3.1 m^2 porch roof + 12.9 m^2 dormer surfaces + 11.4 m^2 rooflight surfaces
Full insulation *(Case 5, 5a, 6c, 7c, 8c, 9c, 10 & 11)* = 54.7 m^2 main roof + 12.9 m^2 dormer surfaces + 11.4 m^2 rooflight surfaces

All roof areas were manually identified and calculated from drawings.

5.2.6. Infiltration

In order to achieve full Passive House or EnerPHit certification standards, buildings need to be designed and constructed to provide an extremely high degree of airtightness to prevent unintended heat losses due to cold air infiltration into the heated parts of the building and warm air infiltration from the interior to the colder interior. To ensure that occupants are then supplied with a constant and sufficient flow of fresh air to maintain healthy levels of pollutant gases, dust and contaminants, an MVHR system would then be used. This is a constant flow system drawing in outside air, heating it in a heat exchanger unit using warm, moist air extracted from areas such as kitchens and bathrooms and supplying it via a ventilation system to all main living spaces. Additionally, ventilation between living spaces to ensure internal flow pathways are maintained is provided.

Although PHPP would more usually be expected to produce models with full passive house ventilation systems, it is also increasingly being used to model existing buildings prior to the installation of passive house components. Therefore it was possible to make a reasonable approximation of the conditions representing an un-insulated historic building with a leaky fabric and trickle ventilation only to reduce risk of condensation.

Moran et al (2013) successfully used infiltration rates of 10 ach based on CIBSE guidelines and previous measurements from historic buildings and therefore this was selected as the initial value base case (Case 1) for the pressure test result as no physical measurement process had been undertaken at the property. Proper installation of internal insulation, along with refurbishment of existing historic windows and a well constructed modern insulated room would be expected to have a dramatic reduction on infiltration rates. Further improvements can be achieved by completing the internal insulation with the elimination of thermal bridges (continuous insulation around the entire perimeter with internal elements such as floors and window/door openings designed with thermally insulated fixers which do not penetrate the external surfaces). And by replacing both the traditional windows and the real retrofit double glazed units with full passive house standard triple glazed units, it would be reasonable to anticipate that infiltration rates could be brought down to well within certification targets.

Infiltration rates were therefore set within PHPP as follows:

Pre-retrofit *(Case 1)* = 10 ach
Post-retrofit standard insulation and windows *(Case 2, 2a, 3, 3a, 6a, 7a, 8, 8a, 9, 9a)* = 2 ach
Post-retrofit with complete insulation *(Case 4, 4a, 6b, 7b, 8b, 9b*) = 1 ach
Post-retrofit with upgraded PH standard windows *(Case 5, 5a)* = 1 ach
Post-retrofit with complete insulation and upgraded PH standard windows *(Case 6c, 7c, 8c, 9c, 10, 11)* = 0.5 ach

5.2.7. Ventilation

With PHPP 9 it is now possible to select a ventilation system as "only window ventilation" and enter data for window opening times and parameters. These include how far they open and if they are tilt types. There are separate inputs for inline windows all on the same side of the building and cross ventilation with windows on opposite sides of the building. According to David H Clarke (2013) there is *"Good evidence for high ACH rates for natural ventilation using trickle vents and open windows".*

David H Clarke (2013) also gives clear guidelines for fresh air requirements for mechanical ventilation systems, with 8-10 l/s/person being recommended. This is comfortably in line with the 100 m^3/h extract (and therefore supply) requirements for a building with one kitchen and one bathroom recommended within PHPP.

There is a large database of components available within PHPP. Reviewing the MVHR systems which would supply 100 m^3/h, a Danfoss w1 unit was selected for modeling purposes and combined with an ASHP for those modeling cases which required it.

Pre-retrofit *(Case 1),* only window ventilation, inline windows.
Post-retrofit *(Case 2, 2a, 3, 3a, 4, 4a, 5, 5a, 8, 9*), only window ventilation, inline and cross flow windows.
Post-retrofit with MVHR *(Case 6a, 6b, 6c)*, inline and cross flow windows plus balanced PH ventilation with heat recovery.
Post-retrofit with MVHR and ASHP *(Case 7a, 7b, 7c, 8a, 8b, 8c, 9a, 9b, 9c, 10, 11)*, inline and cross flow windows plus balanced PH ventilation with heat recovery.

Air supply and extract lines lengths were estimated from drawings. The size and properties of the tubing were obtained from Nuaire (2014) and added to the PHPP model.

5.2.8. Glazing

Window sizes were available from drawings for both the traditional windows which were refurbished as part of the retrofit process and the new double-glazed velux and dormer windows added to the room with the retrofit. PHPP contains thermal properties for glazing and frames for a wide range of windows. Therefore it was possible to select appropriate components to match each of the specified windows already created in the model.

Pre-retrofit *(Case 1)*, all 6 existing windows single glazing in wooden frames.
Post-retrofit *(Case 2, 2a, 3, 3a, 4, 4a, 6a, 6b, 7a, 7b, 8, 8a, 8b, 9, 9a, 9b)*, 6 existing windows single glazing in wooden frames + 3 double glazing (4/12/4) windows in PH compatible frames.
Post-retrofit with new windows *(Case 5, 5a, 6c, 7c, 8c, 9c, 10, 11)*, all 9 windows triple glazing low e in PH compatible frames.

5.2.9. Doors

Door sizes were taken from drawings. Thermal properties were used as follows:
Pre-retrofit & post-retrofit with existing doors *(Case 1, 2, 2a, 3, 3a, 4, 4a, 6a, 6b, 7a, 7b, 8, 8a, 8b, 9, 9a, 9b)*, U = 3.9 W/m^{2}K (Historic Scotland, 2011b) – traditional doors.
Post-retrofit with new doors *(Case 5, 5a, 6c, 7c, 8c, 9c, 10, 11)*, U = 0.8 W/m^{2}K (Historic Scotland, 2011b) – insulated traditional doors.

5.2.10. Thermal bridges

The scope and timescales of the project did not permit the detailed modelling of all the thermal bridges found on the case study property.

PHPP automatically calculates PSI (ψ) values for windows based on the design of frame selected.

It was possible to identify representative linear thermal transmittance (ψ) values which would apply to the different types of thermal bridge elements present in the case study building from Table 3 of BRE (2006) and the lengths over which the bridging losses applied by reference to drawings.

5.2.11. Heating and DHW system

Prior to retrofit, the property was heated with an old, inefficient gas boiler feeding radiators and a DHW storage tank with poor insulation which was situated within the unheated loft space. This system was replaced with an efficient combination gas boiler (Worcester Bosch Greenstar 30SI Compact) which was A-rated for efficiency, offering conversion efficiencies of more than 90%. The rated output of the new boiler is 24kW (Greenstar Si Compact Overview, 2015). However, selecting "Improved gas condensing boiler" and "Natural gas" from PHPP Boiler tab suggested a 15kW unit as standard and the suitability of this capacity of unit was verified by the success at meeting the space heating and DHW requirements of the building.

For the pre-retrofit model a "Low temperature gas boiler" was selected in the PHPP Boiler tab, with operational efficiencies significantly reduced and standby heat loss rate increased to present a more realistic scenario better reflecting the age deteriorated performance commonly observed on very old boilers. It was important that a DHW storage tank was specified and situated outside the thermal envelope with poor levels of insulation on the tank and the pipes. Using a storage tank also resulted in significantly longer pipe supply lines for the entire system when compared to a gas combination boiler or biomass system and introduced additional standby heat losses into the loft space.

To model an alternative Biomass system "Wood pellets (only indirect heat emission)" was selected in the PHPP Boiler tab to give a comparable 15kW unit to the gas boiler unit.

For all cases where space heating and DHW was supplied by some form of boiler, "Heating boiler" had to be selected in the PHPP PER tab as the primary heat generator. In addition, pipe run length, size and thermal properties were required to allow PHPP to calculate the full impact of heat supply and distribution.

5.2.12. Heat pumps

Details for a standard range of heat pumps is available in PHPP with the ability to create user defined pumps with thermal and COP data from actual operational products if desired. A standard air/water pump taking its heat from outdoor air was selected to represent the ASHP for this model.

GSHP parameters are included and can easily be modelled in this version of PHPP. To reduce the amount of variables under investigation, this possibility was omitted for the purposes of this study, as it was perceived that the types of impacts of a GSHP would generally be similar to an ASHP, with reduced electricity use for the same heat production due to higher value COP.

5.2.13. Solar thermal provision

PHPP contains solar capture and conversion characteristics for Standard flat plate, Improved flat plate or Evacuated tube type solar thermal collectors. In order to reflect best performance for current technology to capture the maximum impact that Solar thermal could offer to a retrofit project, an Evacuated tube collector type was selected. This was situated in the front roof element to ensure it was south facing and on a suitably incline (42^0 from horizontal) to effectively capture and convert solar radiation into heated water to supply the space heating and DHW systems. For the available 30 m^2 roof area, a 5.5 m^2 collector was suggested by PHPP. As a collector of this size was not able to cover the heat demands of the building, it was applied in conjunction with the existing space heat/DHW supply system under consideration.

Solar thermal supplementing gas boiler *(Case 8)*
Solar thermal supplementing ASHP + MVHR system *(Case 8a, 8b, 8c)*
Solar thermal + PV supplementing ASHP + MVHR system *(Case 10, 11*)*
* double 11 m^2 collector area used in this scenario.

5.2.14. PV provision

The Amorphous-Si style of PV panels was selected in the PHPP PV tab. Considering the available roof area, as system comprising of 5 cells (which would cover approximately 7.5 m^2) was selected. The addition of PV played no role in the heating or DHW supply system for the building and therefore it was treated by PHPP as a supplementary electricity generation source. It was applied to the scenarios 9, 9a, 10 and 11 (15 m^2 of PV).

5.2.15. Domestic appliance usage and occupation

The model was constructed using an occupancy rate of 2 people for all scenarios. Occupancy rate impacts causal heat gains to the property from the body heat of the occupants and to assess the hygiene requirement for fresh air against the supply rate of the system specified.

Occupant behaviour (lighting, heating thermostat settings, technology use etc…) can have an extremely significant impact on the final real energy demand of a building and is often the reason for deviation between predicted and actual energy performance which can very by a factor of 3 or 4 for identical properties. These changes can be reflected in the Electricity tab in PHPP, although it was not used as a variable during this study. Less efficient lighting was assumed for the pre-retrofit base case, with all other parameters remaining the same for the other scenarios. The following assumptions were made:

- Dishwashing and clothes washing using DHW
- Clothes were line dried internally
- Refrigeration was with an electric fridge freezer
- Cooking was with electricity

5.4. Results

To assist in visualising the differences between the final modelling cases, refer to Table 3 in Section 5.1. above. Two graphs are shown below to illustrate the energy performance results of the different case study scenarios. Figure 6 shows how much space heating is required in each case, the calculated PER demand from modelling, what the PER demand requirement the property is aiming to achieve and the gap between the requirement and the actual property. Figure 7 illustrates some details of thermal performance – heat production through Solar thermal, PV, biomass and ASHP, plus heat losses caused by the windows.

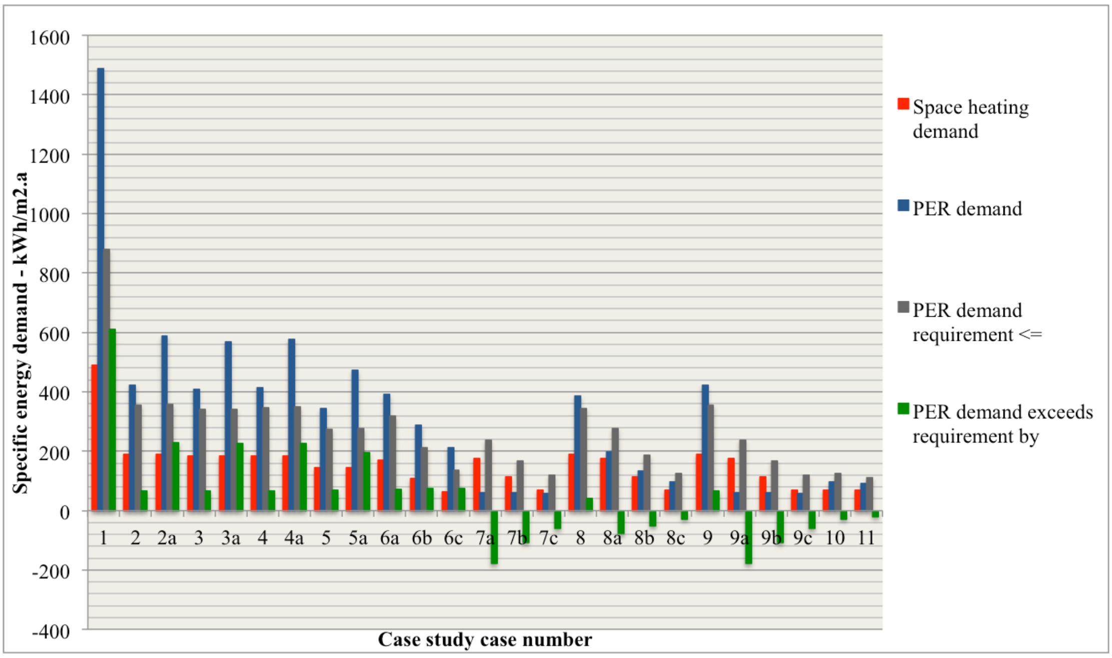


Figure 6: Thermal and total energy demand for case study models

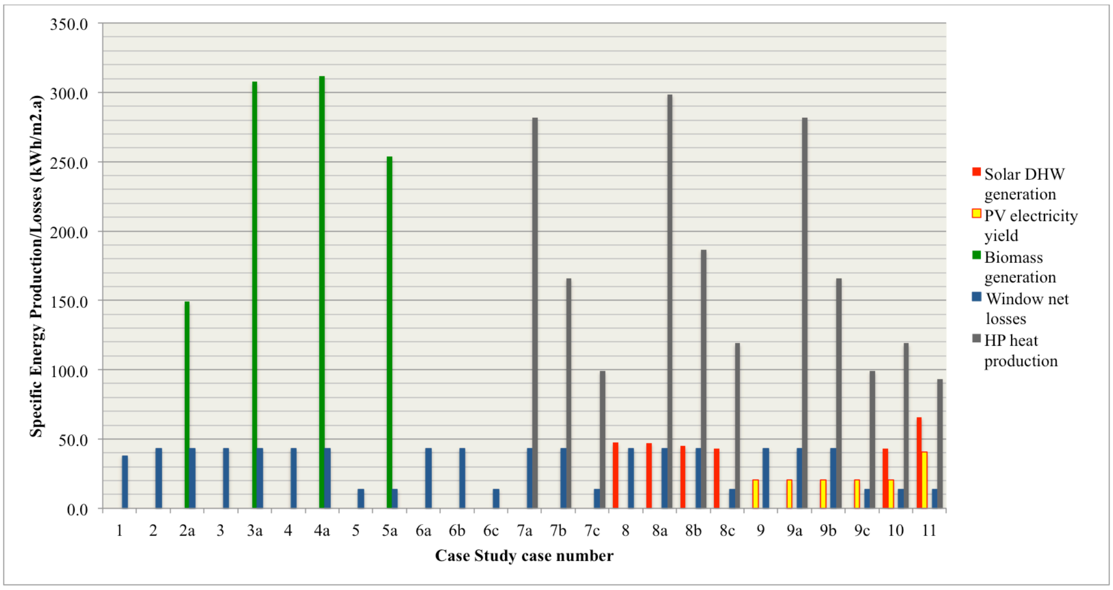


Figure 7: Technology energy contributions for case study models

Looking at PER demand requirements alone there are significant variations. The lowest PER demand requirements are for cases 7c (ASHP + MVHR + full insulation + new windows – thermal bridges) and 9c (as 7c, with the addition of Solar thermal heat collection) which would need to achieve 119 kWh/m^{2}a to obtain an EnerPHit certification. In both instances, the modelled demand is 51% less than that, which suggests that these retrofit packages offer an attractive energy efficiency improvement opportunity. Removing the additional insulation, modified windows and reinstating thermal bridges (mapping to case 2 and case 9 respectively), results in a big shortfall between PER demand requirement and that calculated, illustrating the energy performance benefits of these technologies.

In terms of space heating requirements, none of the modelled scenarios resulted in a building which achieved the EnerPHit target of 25 kWh/m^2a. Even the most efficient models required more than twice this amount of energy to effectively heat their interiors. However, it would appear that use of an MVHR system in conjunction with full insulation, fully upgraded windows and elimination of thermal bridges results in the lowest space heating requirement. The space heating performance when an ASHP system is added with or without Solar thermal and/or PV delivers an almost identical result.

The overall impact on energy performance broken down by technology use is shown in Table 5 below. Comparison between the most energy effective scenarios with the rankings achieved when the scenarios are modelled using the COM will be shown in Section 8.1. of this report.

Table 5: Technology impact on energy performance

Technology (scenario from – to)	PER	Space Heating	Thermal Performance Factors
Roof insulation + basic insulation + new gas boiler (1 – 2)	↓72%	↓61%	-
Eliminate thermal bridges (2 – 3)	Virtually unchanged		
Full wall and floor insulation (2 – 4)	Virtually unchanged		
Full triple glazed windows (2 – 5)	↓19%	↓24%	↓68% Window losses
Biomass (2 – 2a)	↑39%	-	Biomass generation dominates
(3 – 3a)	↑39%	-	
(4 – 4a)	↑39%	-	
(5 – 5a)	↑38%	-	
MVHR alone (2 – 6a)	↓7%	↓11%	-
+ full insulation (2 – 6b)	↓32%	↓43%	
+ full insulation + windows (2 – 6c)	↓50%	↓66%	↓68% Window losses
ASHP + MVHR (6a – 7a)	↓85%	↑3%	HP generation dominates
+ full insulation (6b – 7b)	↓79%	↑5%	
+ full insulation + windows (6c – 7c)	↓73%	↑6%	
Solar thermal (7a – 8a)	↑232%	-	HP gen dominates – significant Solar thermal contribution
+ full insulation (7b – 8b)	↑125%	-	
+ full insulation + windows (7c – 8c)	↑66%	-	
PV (7a – 9a)	-	-	HP gen dominates – smaller PV contribution
+ full insulation (7b – 9b)	-	-	
+ full insulation + windows (7c – 9c)	-	-	
Full retrofit (2 – 10)	↓77%	↓41%	Generation >> losses
Full retrofit + double Solar thermal + double PV (10 – 11)	↓59%	-	↓HP ↑Solar

Chapter 6: Technology Selection Table

6.1. Process and Findings

Figure 1 from 3.2. above was the basis for the initial TST list and application order of technologies to be assessed and ranked in order to generate a meaningful guideline for selection for future buildings. Drawing from EnerPHit guidelines, additional categories of “Eliminate Thermal Bridges”, MVHR, ASHP and GSHP were added to ensure that a wide and representative range of energy efficiency and renewable energy solutions were considered. The following ranking categories were determined as significant in terms of their impact on the desirability and success of retrofit to historic buildings. They were then applied to each of the technologies in turn to quantify the potential benefit:

Table 6: TST Impact and Ranking Categories

Category	Description
NPV	Net Present Value of investment in technology over a 20 year life span. Obtained from results of PHPP modelling input to COM
Energy use (EU)	Effect on PER demand and space heating/DHW results from PHPP modelling
Comfort (Com)	Evidence based assessment of likely improvement to the comfort of building occupants following the implementation of technology
Air quality (AQ)	Evidence based assessment of likely impact on building air quality through the application of technology
Listed building constraints (LBC)	Technical and regulatory/planning restrictions on the use of technologies on historic buildings

Reviewing case study energy performance and COM results and using evidence from literature review, a High, Medium or Low impact was assigned to each category for each model along with commentary describing the principle observations and restrictions. The results of this verification process are shown below:

Table 7a: Technology Evaluation – Roof Insulation

Roof Insulation		
Category	**Ranking**	**Commentary**
NPV	H	Not individually quantified. Initial investment costs moderate
EU	H	• Large contributor to reduction in PER (71%) and SH (61%) demand from pre to post retrofit in case study • ***Critical*** in case study instance where post retrofit the roof forms the top of the thermal envelope
Com	H	A well insulated roof can prevent large thermal upflow and drafts
AQ	L	N/A
LBC	L	Typically internal – planning authorities may restrict choice of materials for listed buildings

Table 7b: Technology Evaluation – Wall Insulation

Wall Insulation		
Category	**Ranking**	**Commentary**
NPV	L	65% lifetime cost increase
EU	L	2% PER reduction
Com	M	• Ventilation reduction and poor air flow within the building
AQ	L	• Installation may change mode of operation from vapour permeable to sealed envelope, reducing natural ventilation to create air quality problems + potential fabric degradation from moisture trapped inside walls • Cavity wall insulation where the breathable air space is filled is particularly problematic in this regard
LBC	M	• Listed status likely to restrict use to interior insulation which reduces available room space inside building

It is recommended that detailed ventilation flow design and calculations are carried out prior to implementation to prevent creating a warm building at the expense of occupant health and building fabric degradation. MVHR or simple exhaust system should be considered as a priority if insulating walls.

Table 7c: Technology Evaluation – Floor Insulation

Floor Insulation		
Category	**Ranking**	**Commentary**
NPV	M	Inexpensive. Not modelled as a separate case
EU	L	Difficult to quantify
Com	H	Can play a major role in reducing drafts and reducing occupant discomfort due to cold floors
AQ	L	N/A
LBC	L	Material selection and construction method may be restricted on listed buildings

Table 7d: Technology Evaluation – Tank & Pipe Insulation

Tank & Pipe Insulation		
Category	**Ranking**	**Commentary**
NPV	H	Through reduction in energy costs
EU	H	83% reduction in DHW heat loss to uninsulated loft space with post-retrofit modelled case provides significant contribution to reduction in PER demand
Com	M	Improving probability of achieving a comfort level of warmth inside the property
AQ	L	N/A
LBC	L	N/A

Table 7e: Technology Evaluation – MVHR

MVHR		
Category	**Ranking**	**Commentary**
NPV	L	• 3% increase across lifetime • Requires maintenance & filter changes to ensure hygiene & unit performance are maintained • Historic properties with solid walls/floors & large numbers of small rooms may add to cost
EU	M	• 7% PER reduction • Highly effective when utilised with a heat pump to reduce energy demand for heating the incoming air
Com	H	Consistent temperature and humidity maintained within building and drafts eliminated
AQ	H	Elimination of internal moisture problems and consistently high levels of ventilation maintained
LBC	M	Additional complexity and restrictions may result from solid walls and floors as ventilation flows are required into and between all rooms

Table 7f: Technology Evaluation – Biomass Boiler

Biomass Boiler		
Category	**Ranking**	**Commentary**
NPV	L	Variable impact in case study model – high sensitivity to RHI subsidy levels
EU	L	No impact on space heating demand. Significantly increases PER demand
Com	M	Efficient boiler delivery ensures comfortable internal temperatures are maintained
AQ	L	N/A
LBC	L	N/A

Biomass is theoretically "carbon neutral", but requires inefficient land use to generate fuel which has to be delivered and loaded physically. Fuel storage requires additional space. Only recommended where other heating fuels are not available or other systems are not feasible.

Table 7g: Technology Evaluation – Gas Boiler

Gas Boiler		
Category	**Ranking**	**Commentary**
NPV	M	More cost effective over lifetime + less expensive to install and maintain than biomass boiler
EU	H	Significantly higher efficiency and controllability than electric storage heaters
Com	M	Efficient boiler delivery ensures comfortable internal temperatures are maintained
AQ	M	Consistent temperatures reduce likelihood of moisture problems
LBC	L	N/A

Not feasible if property does not have access to the gas grid. Recommended as a base case if no other heating/DHW solution is selected, existing boiler is old and installation is practical.

Table 7h: Technology Evaluation – GSHP

GSHP		
Category	**Ranking**	**Commentary**
NPV	H	• Not directly modelled in available version of PHPP. Expected to be similar to ASHP figures of 146% reduction (net cost saving) over lifetime • Some regular maintenance required
EU	H	• ASHP showed an 86% reduction. Improved COP (more heat generated for lower electricity input) for GSHP would be expected to give an even larger EU reduction • More efficient than ASHP in winter as ground temperature remains higher than air
Com	H	Continuous supply of warm air to ensure comfort when distributed using MVHR
AQ	M	Used with MVHR system will ensure ventilation and moisture levels are maintained
LBC	H	Heat exchanger unit and the drilling required for heat supply lines highly likely to prevent permissions being received for historic properties

Table 7i: Technology Evaluation – ASHP

ASHP		
Category	**Ranking**	**Commentary**
NPV	H	• 146% reduction to give a real NPV cost saving over lifetime • Some regular maintenance required
EU	H	86% reduction
Com	H	Continuous supply of warm air to ensure comfort when distributed using MVHR
AQ	M	Used with MVHR system will ensure ventilation and moisture levels are maintained
LBC	H	Heat exchanger unit highly likely to prevent permissions being received for historic properties

Table 7j: Technology Evaluation – Solar DHW

Solar DHW		
Category	**Ranking**	**Commentary**
NPV	H	• 34% reduction over lifetime • Even greater benefits achievable when coupled with MVHR
EU	M	• 8.5% PER reduction • Even greater benefits achievable when coupled with MVHR
Com	L	N/A
AQ	L	N/A
LBC	H	High visual impact - planning restrictions highly likely to preclude use on historic buildings

Requires suitable roof space for installation – ideally ±45^0 orientation from south facing with sufficient space and strength to accommodate the collector and ancillaries. Storage tank also required.

Table 7k: Technology Evaluation – Improved Windows

Improved Windows		
Category	**Ranking**	**Commentary**
NPV	M	• 9% reduction when moving to full PH standard triple glazed units • Investment cost increased and fuel savings reduced if window choice is limited to slimline double glazing units or secondary glazing due to planning restrictions
EU	H	• 19% PER reduction • PER reductions will be reduced if window choice is limited to less energy efficient units due to planning restrictions
Com	M	Reduces drafts and cold spots (with associated moisture problems) around windows
AQ	L	N/A
LBC	H	Very strict requirements and constraints imposed by planning authorities on historic buildings which can severely restrict options

Table 7l: Technology Evaluation – PV

PV		
Category	**Ranking**	**Commentary**
NPV	H	168% reduction over lifetime giving net cost saving – largest demonstrated benefit of any modelled technology
EU	H	53% PER reduction
Com	L	N/A
AQ	L	N/A
LBC	H	High visual impact - planning restrictions highly likely to preclude use on historic buildings

Table 7m: Technology Evaluation – Eliminate Thermal Bridges

Eliminate Thermal Bridges		
Category	**Ranking**	**Commentary**
NPV	L	With careful attention to detail during design and construction there should be negligible impact on investment costs
EU	M	• 3.5% PER reduction • Likely to become proportionally more significant as the building envelope as a whole becomes more efficient
Com	M	Can reduce drafts and prevent unintended air flows + eliminate moisture problems
AQ	L	N/A
LBC	M	Solid walls and floor + restrictions on material and construction choices may make design constraints more challenging on historic buildings

Should always be given close attention during the detailed design phase and during the construction phase of the retrofit.

Applying a 3 to all High, 2 to all Medium and 3 to all Low impacts for each technology produced a ranking number (highest to lowest) to determine the order for the final TST. The commentary for the specific impact categories and the general guidance for selection for each technology could then be created. Equal weighting ensures that financial, environmental, occupant comfort and health are considered alongside feasibility for the building type in question to arrive at the holistic best solution for that particular circumstance.

6.2. Final Technology Selection Table

This table is intended for use at an early design stage to aid the individual approaching a retrofit/renovation project on a historic property to make an initial evaluation of which energy efficiency and renewable energy generation technologies should be considered and evaluated for inclusion on the project and to identify potential constraints which should be built into the project plan.

The user should begin at the top of the table and work methodically through the options to rule each one in or out prior to moving on to evaluate the next. On selection of technologies, rough estimates of investment and running costs can be calculated from the tables in section 7.1 before performing detailed material selection, design work and detailed energy modelling of the building under consideration and proceeding to the next stages of the project.

Table 8: Final Technology Selection Table

Technology	Benefits	Constraints	Requirements	Select
GSHP	Significant energy use & cost benefits Constant heat availability Better COP than ASHP	Piling & exchanger unit likely to preclude use on historic buildings	MVHR unit to distribute incoming & extract air Regular maintenance	☐
ASHP	Significant energy use & cost benefits Constant heat availability	Heat exchanger unit likely to preclude use on historic buildings	MVHR unit to distribute incoming & extract air Regular maintenance	☐
MVHR	Elimination of internal moisture problems Maintains high air quality Highly effective with heat pump to reduce heating demand	Solid floors & walls in historic properties may limit design options & increase system complexity, particularly in properties with many small rooms	Regular maintenance & filter changes required to maintain hygiene & system performance Supply/extract access required to and between all rooms	☐
Roof Insulation	Very significant contributor to reduction in heating demand Prevention of thermal upflow and drafts	Selection of material appropriate to property	Critical when thermal envelope extends into roof space	☐
Tank & Pipe Insulation	Significant reduction in heat loss during distribution	None	Critical if storage tanks/pipes are sited outside thermal envelope	☐
Gas Boiler	Lower cost to install & maintain than biomass boiler Compact Significantly higher efficiency & controllability than electric storage heaters Can power DHW in addition of space heating to radiators or underfloor heating	Gas grid availability	Recommended if existing system is old/inefficient	☐
Improved Windows	Reduces heat loss through building fabric Reduces drafts & cold spots near windows	Materials & appearance prescribed in historic properties – likely to result in thermally inferior window properties at increased investment cost	Careful design & installation to prevent thermal bridging around frames	☐

Solar DHW	Good contribution to water heating needs to reduce overall energy requirements Very significant cost benefits over lifetime	Visual appearance restricts use on historic buildings	Suitable roof – ideally ±45^0 of north for maximum gain Sufficient space to accommodate collector, storage tank & ancillaries	☐
Floor Insulation	Low initial cost impact Draft reduction + warm floors improve occupant comfort	Material selection for compatibility with existing floors in historic buildings	Careful design & installation to prevent thermal bridging around perimeter	☐
Thermal Bridges (eliminate)	Prevention of local comfort (drafts) & moisture (condensation, mould, building fabric deterioration) issues	Solid walls & floors with restrictions on material selection in historic buildings increases design constraints	Part of good practice during the design process	☐
Biomass Boiler	Theoretically "carbon neutral"	Fuel storage requirement Regular delivery and supply of fuel required Highly sensitive to generation subsidies	Only recommended where other heating solutions not available or feasible	☐
Wall Insulation	Reduced heat loss and improved occupant comfort	High lifetime cost Historic building status limits application of internal insulation Building breathability issues can cause air quality, moisture & fabric degradation problems – particularly if cavity wall insulation is utilised	Ventilation must be carefully considered & improved	☐

Chapter 7: Cost Optimal Methodology

7.1. Inputs and assumptions

7.1.1. Overall approach

In order to assess the lifecycle cost of each of the case study scenarios, it was necessary to create summary tables detailing the presence/size/quantity of each technology. These can be found in Table 14a-c in Appendix I for reference.

Reference to review of good practise by The Buildings Performance Institute Europe (2013) determined that in order to compare economic lifecycle costs effectively, the following information was required:

- Initial investment costs (purchase and retrofitting costs summarised for all technologies applied)
- Running costs (including replacement costs for building elements if the end of their lifetime fell within the overall economic lifecycle under consideration + benefits of earnings from energy produced)
- Energy costs (to consider ongoing changes to energy prices)

Initial scoping ruled out the following costs which are included as an option in the original guidance:

- Disposal costs (currently limited information available on end of lifecycle residual value and the true financial and energy costs of disposal of materials and equipment at the end of its lifecycle)
- Cost of greenhouse gas emissions (this is only required when carrying out a macroeconomic analysis at a EU Member State level when the state would bear these costs in relation to their entire housing stock)

Various suggestions were forthcoming as to a suitable time period over which the economic lifecycle should be analysed. True lifespan of the newest insulation materials is unknown. Therefore a lifespan of 20 years was selected which would be expected to ensure that all installed plant and materials would last for the entire period.

In line with recommendations from The Buildings Performance Institute Europe (2013), sufficient technology variants had already been modelled to more than match the requirement to compare lifecycle costs for a base case (the pre-retrofit building) with a minimum of 10 variants. Unlike the examples viewed during the literature survey which featured variants exhibiting stepped change in U-value for insulation of walls, roofs and floors, the constraints of the historic property construction for the case study gave a single variant for each area of insulation, installed in conjunction with other discrete technologies. Therefore, a less continuous relationship between building specific energy demand and lifecycle cost should be anticipated.

As all variants consist of equal TFA, when analysing costs, the model simply plots PER Demand (kWh/m^2.a) against NPV (£). PER Demand is kept in units related to area in order to test energy demand against EnerPHit requirements directly along the x-axis of the graph.

A spreadsheet was created containing the energy output results from PHPP for each scenario along with the cost data for each technology, the lifecycle parameters and the parameter summary information collected in Table 15a-c in Appendix I. All COM calculations were performed in this spreadsheet.

7.1.2. Technology costs

Two different sources were used to populate the technology cost part of the model. As cost information was drawn directly from case studies of real life historic properties, costs of window refurbishment, double glazing, triple glazing, door upgrade, wall insulation, roof insulation and floor insulation costs were drawn from Historic Scotland (2013a).

For heating, distribution and renewable energy generation systems, data from The Buildings Performance Institute Europe (2013) was used as the basis, as the base costs are due to the technology rather than the specific building in which they are installed. However, some of the costs given per kW or m^2 were for plant units considerably larger than those required for the case study building. Therefore a multiplier of 2 was used for the costs of gas and biomass boilers, heat pumps and solar thermal collectors. These costs were also multiplied by 0.733 to convert them from € to £.

Table 9: Investment costs utilised in model. (Historic Scotland (2013a) and The Buildings Performance Institute Europe (2013))

Equipment	Type	Unit	Cost	
			Investment	Annual
External wall area	Insulated	m^2	£181.50	£0
Floor slab area	Insulated	m^2	£75	£0
Roof area	Insulated	m^2	£86	£0
Door upgrade	Insulated	m^2	£481	£0
Windows	Refurbished	Each	£300	£0
	Double glazed	m^2	£687	£0
	Triple glazed	m^2	£858.75	£0
Gas boiler	New	kW	£227.23	£469.12 (per unit)
Biomass boiler	New	kW	£806.30	£806.30 (per unit)
ASHP	New	kW	£476.45	£531.42 (per unit)
Air ducts	For MVHR	m^2 TFA	£25.66	£0
Ventilation plant	For MVHR	m^2 TFA	£14.66	£0.51
Ventilation plant	For ASHP	m^2 TFA	£18.32	£0.55
Heat distribution system	For gas or biomass boiler	m^2 TFA	£21.99	£0
Solar thermal collector	Evacuated tube	m^2	£806.30	£3.97
PV system	Amorphous-Si	m^2	£249.22	£0.73

For each case study scenario the total initial investment was summed separately from the total annual maintenance and repair cost and these two parameters recorded in the spreadsheet under the titles of Upgrade Investment (UI) and Annual Cost (AC).

7.1.3. Fuel costs

The following fuel costs per kWh were obtained from the Biomass Energy Centre.

Table 10: Fuel costs used in COM

Fuel	Price (p/kWh)
Gas	4.9
Electricity	15
Wood pellets	4.4

Using the energy use outputs captured from PHPP as previously mentioned in Section 5.4. above, the following calculations were performed and the results summed to give a figure of total fuel cost in £ per year for each case study scenario.

GAS = (Space heating+DHW) x (Gas/100)
ELEC = (Total electricity demand) x (Electricity/100)
BIO = (Biomass generation) x (Wood pellets/100)

The results were recorded in the spreadsheet under the title of fuel cost (fc).

7.1.4. Energy subsidies

For certain forms of renewable energy generation, there are government subsidies available in the UK to offset the cost of grid connected or islanded energy use.
For the technology systems employed on the case studies, the Domestic Renewable Heat Incentive (RHI) is applicable to biomass generation, ASHP heat output and solar thermal generation. Solar PV generation falls under the remit of the Feed-in Tariff (FIT) scheme.

Ofgem (2015a&b) provided the numerical value of these subsidies at the current time which are shown in the table below.

Table 11: Subsidy levels for renewable energy generation

Generation	Tariff (p/kWh)
Biomass	7.14
ASHP	7.42
Solar thermal	19.51
Solar PV	11.63

PHPP energy use outputs as in Section 7.1.3. above were utilised in the following calculations and the results summed to give a figure of total subsidy value in £ per year for each case study scenario.

BIO = (Biomass generation) x (Biomass/100)
ASHP = (HP generation) x (ASHP/100)
SOLAR THERMAL = (Solar heat contribution) x (Solar thermal/100)
SOLAR PV = (PV electricity yield) x (Solar PV/100)

The results were recorded in the spreadsheet under the title of fuel cost (sv).

7.2. NPV Calculations

In order to give accurate lifecycle costs which reflect the changing value of money over time and the fact that costs are incurred at different time points during the retrofit lifecycle, a Net Present Value (NPV) assessment of the costs and benefits was required.

This required setting a time period (20 years as already discussed above), an appropriate discount rate to track the effect of the decreasing value of money over time and an interest rate to reflect the likely development of energy prices over time. EU studies on COM gave 3% as an appropriate discount rate and 2.8% as a suitable energy price development rate (Source: The Buildings Performance Institute Europe, 2013). Whilst subsidy values are set and remain valid for only 7 years, for the purposes of this calculation it assumed that the new rates will remain broadly similar once the old ones expire.

Therefore the parameters for the NPV model were as follows:

- **Upgrade Investment, UI** – from PHPP energy outputs and calculated technology costs for the specific scenario
- **Annual Cost, AC** – from PHPP energy outputs and calculated technology costs for the specific scenario
- **Subsidy value, sv** – from PHPP energy outputs and calculated subsidy payments for the specific scenario

- **Fuel cost, fc** – from PHPP energy outputs and calculated fuel costs for the specific scenario
- **Time, t** – 20 years
- **Discount rate, i** – 0.03
- **Energy price development rate, e** – 0.028

These was used to calculate total NPV of upgrade investment, running costs, subsidy value and fuel costs using the following formulas:

$UI_{tot} = UI/(1+i)^t$

$AC_{tot} = \Sigma AC/(1+i)^t$

$sv_{tot} = \Sigma sv/(1+i)^t$

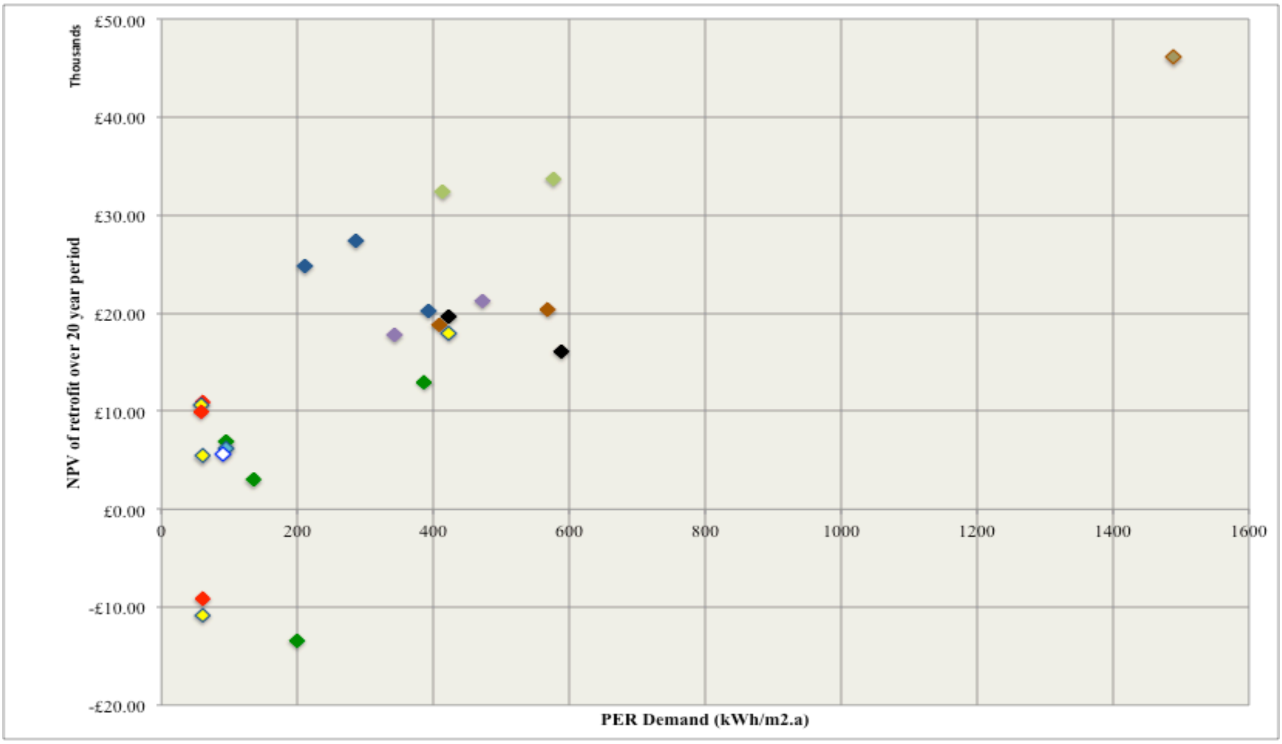
$fc_{tot} = \Sigma fc(1+e)^t/(1+i)^t$

The final operation within the spreadsheet is to generate an overall NPV value for the PHPP modelling scenario in question.

$NPV = UI_{tot} + AC_{tot} + fc_{tot} - sv_{tot}$

7.3. Results from case study

Figure 8 below summarises the results of the cost optimal methodology applied to the case study outputs. These results were instructive in modifying the priority order for the Technology Selection Table, as in some instances, small improvements to energy performance from applying a technology are negated by the high investment cost and cumulative discount effect to the energy saving or available subsidies. The graph is shown to give a general impression only. As PER demand requirements are different for each modelling case it is not possible to generate a single plot which allows direct comparison of the success against both PER and NPV targets.



Key

- Pre-retrofit
- Base post-retrofit
- Thermal bridges eliminated
- Complete insulation
- PH windows
- MVHR
- ASHP
- Solar thermal
- PV
- Full retrofit
- Double solar thermal & PV

Figure 8: Cost Optimal Methodology graph for case study

More detailed results are available in Table 12 below. The case numbers are colour coded to match the graph data points above. All NPV values are the total cost for retrofitting and running the building over the full 20 year period. They have not been transformed relative to the base case as it is instructive to understand the absolute cost magnitude as well as the relationship to the base case for each technology. Only the cases marked with a ✔ meet the EnerPHit PER demand target and only these cases should be considered when identifying a truly cost optimal retrofit solution.

Table 12: COM results

Case	PER (kWh/m^2a)			NPV (£)	Comment
	Demand	Target	Met?		
1	1489	880	✗	46112	Driven by high heating costs
2	423	356	✗	19640	Reduces gap to PER and cost targets
2a	588	358	✗	16129	Includes biomass which increases PER, but offers slight NPV improvement
3	409	342	✗	18857	Little effect
3a	569	342	✗	20374	Includes biomass which increases PER and slightly worsens NPV
4	414	347	✗	32405	Significantly increased NPV over 2 – no cost benefit from additional insulation
4a	576	349	✗	33747	Includes biomass which increases PER and slightly worsens NPV
5	343	275	✗	17803	Small cost benefit despite significant PER improvement
5a	472	277	✗	21299	Includes biomass which increases PER and worsens NPV
6a	392	319	✗	20309	Small overall effects on NPV (increase) and PER (decrease)
6b	287	212	✗	27361	Some NPV increase and PER decrease
6c	212	137	✗	24787	Appreciable NPV increase despite significant PER decrease
7a	60	238	✓	-9116	Represents net NPV cost benefit with very significant PER decrease
7b	60	168	✓	10872	Very significant NPV cost benefit with very significant PER decrease
7c	58	119	✓	10663	Significant NPV cost benefit with maximum PER decrease
8	387	345	✗	12999	Small PER benefit with significant NPV cost benefit
8a	199	277	✓	-13405	Maximum NPV cost benefit though PER deteriorates
8b	135	186	✓	3002	Significant NPV improvement with PER deterioration
8c	96	124	✓	6881	Significant NPV improvement and PER deterioration
9	423	356	✗	17971	PER neutral with modest NPV improvement
9a	60	238	✓	-10785	COST OPTIMAL SOLUTION –

					maximum PER benefit for NPV saving
9b	60	168	✓	5412	PER neutral with significant NPV saving
9c	58	119	✓	9991	PER neutral with modest NPV saving
10	96	124	✓	6209	Significant PER and NPV benefits
11	91	111	✓	5633	Additional PER and NPV benefits from doubling generation

Separating the effects of specific technologies gives the overall impacts shown in Table 13 below which were fed back into the TST rankings to assist to improve the quality of retrofit decision making.

Table 13: COM – impacts of specific technologies

Technology	Energy Use Impact	Cost Optimality Impact
Wall Insulation	Significant improvement	Moderate improvement
Roof Insulation	Very significant improvement	Significant
Floor Insulation	Modest improvement	Minimal improvement
Thermal Bridge Elimination	Very little impact	Very little impact
Gas Boiler	Significant improvement	Moderate improvement
Biomass Boiler	Negative impact	Sensitive to subsidy and fuel prices
Windows	Significant impact	Small improvement
MVHR	Significant positive benefits	Negative impact until used with ASHP which leads to significant cost benefit
ASHP	Limited benefit due to electricity requirements, significantly more energy effective with installed renewables	Significant benefits
Solar Thermal	Modest improvement	Greatest improvement
PV	Neutral	Modest improvement

Taken as a whole, the three most effective retrofit packages in terms of both energy performance and cost optimality benefits are as follows (all have basic retrofit insulation and window improvements applied):

1. PV panels with ASHP and MVHR system

2. ASHP and MVHR system used in conjunction with a modern gas boiler
3. Solar thermal heat collection with ASHP and MVHR system

The expected energy performance and fuel cost benefits would be expected to be even greater for all these cases if the ASHP was replaced with a GSHP.

Chapter 8: Analysis and Conclusions

8.1. Case Study energy performance

From an energy performance perspective, all of the most energy efficient solutions incorporate full PH standard triple glazed windows and MVHR units. These give dramatic reductions in both space heating and PER demand which would result in huge annual fuel bill savings for those currently experiencing fuel poverty due to living in a historic, hard to heat property. It is instructive to note that these solutions are amongst the most difficult to introduce to a historic property as up until now they have routinely been precluded by planning regulations.

It has previously been noted that none of the retrofit packages proposed come even close to achieving the full EnerPHit certification standard for space heating demand. Whilst this is disappointing, it can perhaps be explained, at least partly by the fact that the surface area of the property is large compared to its enclose volume which significantly increases the overall rate of heat loss, even on the best insulated property. The U-values of the renovated walls are still high at 0.23 W/m^2K when measured against the EnerPHit component standard for opaque building envelope elements of 0.15 W/m^2K (Passive House Institute, 2012), which is also indicative of increased heat loss through the walls. For this particular case study with such substantial, solid walls, it would be unlikely to be feasible be able to improve this further by adding sufficient additional insulation to significantly impact heat loss without very substantially affecting internal floor space ability and impairing functioning of the vapour permeability of the walls. However, on historic buildings with a lighter construction, greater improvements in the insulating properties of the exterior may be more easily achievable.

8.2. Validity of Technology Selection Table

The best feature of the TST is that it objectively draws together energy, cost, comfort, air quality and listed building considerations in order to offer a potential solution which takes a whole building holistic approach rather than the "one size fits all" single technology focussed initiatives often promoted to householders. Whilst the basis for its construction was numerical, the table itself is not. This potentially opens its use up to a wide range of people who may lack the technical skills to carry out a formal numerical analysis. The benefits and constraints columns very rapidly allows some technologies to be ruled in or out, at the same time identifying requirements and areas needing deeper investigation in the requirements column.

Its current weakness is the confidence levels surrounding its recommendations due to it having only taken inputs from one case study example. The benefits, constraints and requirements themselves are sound as they have been generated through extensive research. But testing with a wider range of case study properties would significantly increase confidence in the priority order for application.

8.3. Cost Optimal Methodology discussion

When plotting the COM model results it became apparent that a lack of range of options for insulation material to allow sufficient comparative data points to be compared effectively for each technology type had been calculated. This limits the confidence levels in the conclusions drawn from the results. However, the COM model does provide evidence that incentivising the installation of renewable energy technologies on historic properties through promotion of domestic generation subsidies could improve the cost benefits to those undertaking the initial investment.

At the heart of the top ranked retrofit packages identified from the COM model, there always appears an ASHP with MVHR for distribution of ventilation air, regardless of the quantity or type of renewable generation technology which may or may not be incorporated. This is good news for any householder in a similar property taking a similar approach as this is likely to lead to good internal comfort levels and long term benefits from a consistently high air quality.

8.4. Conclusions

There is some commonality between the recommendations arising from energy performance, TST and COM perspectives – namely MVHR, a baseline level of insulation and inclusion of some form of heat pump in any retrofit package. However, selecting an improved standard of window is a major feature of demonstrated good energy performance, whilst it appears midway down the list of recommendations from the TST and have strong negative desirability connotations when considering lifecycle costs. Conversely, strong drivers towards the use of renewable energy generation are illustrated by energy performance improvements (and to a lesser extent, the COM), although they only appear towards the bottom of the list of recommendations on the TST.

When considering historic buildings, the features and constraints affecting that specific building need to be weighed up in a holistic manner against the aims and requirements of the retrofit project. For an individual householder, the lifecycle approach COM recommendations will be of little immediate benefit for high price tag options such as biomass boiler systems, whole house wall insulation and ultra efficient windows if they are unable to finance the initial investment. Therefore, introducing substantial financial incentives with long term commitment applied across the housing sector as a whole may be required to achieve any significant increase in the rate of housing energy efficiency improvements in Scotland.

The quantity of research available implicating modern buildings in occupant ill health due to the sealing in of contaminants and moisture should act as a reminder that having energy (and cost) saving as the dominant primary goal may create an unintended set of consequences further down the timeline. It is vital that at both a strategic and household level the comfort, health and long term building fabric consequences should be built into decision making to achieve a holistically optimum energy saving solution.

The patterns of heat demand and energy production shown by the case study can not be accepted as a universal truth when viewed in isolation, although they do demonstrate practical examples of the validity of the principles researched and promoted by the Passive House Institute and other organisations working on the development of standards for low energy buildings.

Whilst there has been no direct calculation of CO_2 emissions savings generated by the introduction of energy efficiency measures in this study, viewed holistically the prominence of renewable energy technologies in the recommendations is an indicator that these measures would lead to emissions reductions over extended timescales which is desirable in terms of meeting legal commitments towards carbon reduction goals.

As, if is likely, energy use and emissions reduction targets become increasingly stringent, regulatory and societal pressures to reduce energy use and the reliance on fossil fuels will increase. In turn, this may increase the possibility of changes to planning requirements for listed buildings which will make it much more achievable to introduce renewable energy systems and the more effective energy efficiency improvement technologies on these properties.

Chapter 9: Further Work

The project met its aims and objectives in full and the results and analysis above together with concepts from the initial research phase raised a number of further questions and areas for investigation in the future. These suggestions for further work are organised into the three broad areas considered by the project itself.

In addition, carrying out modelling case studies on a varied selection of historic buildings in PHPP in order to categorise the relationship between construction style and materials against energy efficiency technology types would be extremely useful. Developing the validation of the TST and COM against these results would significantly strengthen confidence in the applicability of these tools.

9.1. Building and energy modelling

There were a whole range of model variables which were excluded from this project which would be instructive to study further. Introducing additional technologies such as GSHP and district heating systems would be of value. As would modelling a discrete range of different insulation levels, and separately varying the capacity of installed generation. Looking at the effect of occupation levels and additionally occupant behaviour and domestic energy use specifically in historic buildings would also add to the body of knowledge and understanding.

Old buildings with high thermal mass may be restricted to using internal insulation which isolates the thermal mass, preventing it effectively being used to stabilise and control internal temperature. If there are high thermal gains, this may result in overheating problems in summer conditions. More detailed case study modelling using a dynamic simulation tool such as ESP-r would be valuable to further understand this effect and consider the ways in which it could be mitigated or exploited.

Extending this theme would be to look at how climate affects the performance and cost impacts of particular technologies. The need for cooling was ruled out at a very early stage for this Scottish case study, but even with a similar building type the results could be very different if it was situated in a different part of the UK or the world. As well of being purely of academic interest, if predicted significant global temperature rises occur, the need for space cooling may become more relevant even in Scotland.

Accurate estimation of air infiltration rates and the true impact of these uncertain air and heat flows in historic buildings would add value to future EnerPHit renovations. A CFD package could be used to visualise air flow pathways in detail to build understanding.

9.2. Technology Selection Table

Develop the level of detail contained within the TST in order to generate break out tables covering further detailed selection criteria for the individual technologies and provide more specific conditions which need to be satisfied and recorded in order for the technology selection and package to be validated.

9.3. Cost optimal methodology

Two key areas for further development work for the existing COM model are disposal costs and sensitivity analysis. It is key moving forward that as a society we comprehend the true energy, resource and cost implications of materials, technologies and systems. Literature review to improve information on methods and costs of disposal for the technologies under investigation prior to feeding these new variables and testing sensitivity to technology price development, fuel costs, energy subsidies and economic variables such as interest rates.

9.3.1. Macroeconomic analysis

This study focussed on a microeconomic approach to energy efficiency retrofitting. To gain a better understanding of the potential costs and benefits across the Scottish historic housing stock as a whole, the cost of CO_2 emissions could be incorporated into the main model and tested against a suite of reference buildings representative of the sector.

9.3.2. Energy policy influence

There is scope to carry out a specific sensitivity analysis linked to energy policy scenarios, where a range of investment incentives with associated with particular fuel, generation and efficiency equipment types is considered. The robustness of the energy and COM benefits for different technologies could therefore be determined.

References:

Biomass Energy Centre *Fuel Prices per kWh* Available at www.biomassenergycentre.org.uk (Accessed July 2015)

BRE (2006) *Assessing the effects of thermal bridging at junctions and around openings. IP 1/06* Available from www.brepress.com (Accessed June 2015)

CKD Galbraith (2015) *Energy Matters 2015* Available at https://www.linkedin.com/company/745686?trk=tyah&trkInfo=clickedVertical%3Acompany%2CclickedEntityId%3A745686%2Cidx%3A1-1-1%2CtarId%3A1441104797678%2Ctas%3Ackd%20g (Accessed June 2015)

Concerted Action Energy Performance of Buildings (2013) *Implementing the Energy Performance of Buildings Directive* Available at http://www.epbd-ca.org/Medias/Pdf/CA3-BOOK-2012-ebook-201310.pdf (Accessed August 2015)

David H Clark (2013) *Information paper – 20. Ventilation rates in offices – mechanical and natural.* Available at http://www.cundall.com/Cundall/fckeditor/editor/images/UserFilesUpload/file/WCIYB/IP-20%20-%20Ventilation%20rates%20in%20offices%20-%20mechanical%20and%20natural.pdf (Accessed August 2015)

DECC (2014) *United Kingdom housing energy fact file* Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf (Accessed August 2015)

Historic Scotland (2011a) *Historic Scotland Technical Paper 12* Available at http://www.historic-scotland.gov.uk/technicalpaper12.pdf (Accessed July 2015)

Historic Scotland (2011b) *Historic Scotland Technical Paper 10* http://www.historic-scotland.gov.uk/technicalpaper10.pdf Available at (Accessed June 2015)

Historic Scotland (2015a) *What is listing?* Available at http://www.historic-scotland.gov.uk/index/heritage/historicandlistedbuildings/listing.htm (Accessed: July 2015)

Historic Scotland (2015b) *Maintaining your home* Available at http://www.historic-scotland.gov.uk/maintaining-your-home.pdf#xml=http://web1:10700/texis/webinator/pubssearch/pdfhi.txt?pr=publications&prox=page&rorder=500&rprox=500&rdfreq=500&rwfreq=500&rlead=500&rdepth=0&sufs=0&order=r&id=49d802ec7 (Accessed July 2015)

Low Energy Buildings (2015) *Low Energy Buildings Database* Available at www.lowenergybuildings.org.uk (Accessed July 2015)

Moran, F., Blight, T., Natarajan, S., Shea, A. (2013) *The use of Passive House Planning Package to reduce energy use and CO_2 emissions in historic buildings*

Nuaire (2014) *Five things you should know before ducting your MVHR system* Available at http://www.nuaire.co.uk/blog/residential/five-things-you-should-know-before-ducting-your-mvhr-system/ (Accessed July 2015)

Ofgem (2015a) *General eligibility checklist – Domestic Renewable Heat Incentive* Available at www.ofgem.gov.uk (Accessed July 2015)

Ofgem (2015b) *Feed-in Tariff (FIT) Scheme* Available at www.ofgem.gov.uk (Accessed July 2015)

Passive House Institute (2007) *Passive House Planning Package 2007. Requirements for Quality-Approved Passive Houses. Technical Information PHI-2007/1(E)*

Passive House Institute (2012) *Certification Criteria for EnerPHit Insulation Systems* Available at http://passiv.de/downloads/03_certification_criteria_enerphit-ds_en.pdf (Accessed August 2015)

Passive House Institute (2015) *Criteria for the Passive House, EnerPHit and PHI*

Low Energy Building Standard Available at http://www.passipedia.org/_media/picopen/phi_building_criteria_draft.pdf (Accessed June 2015)

Passivhaus Institut (2014) *Passipedia – The Passive House Resource* Available at http://www.passipedia.org (Accessed May 2015)

The Buildings Performance Institute Europe (2013) *Implementing the Cost Optimal Methodology in EU Countries. Lessons learned from three case studies* Available at http://bpie.eu/documents/BPIE/publications/cost_optimal_methodology/BPIE_Implementing_Cost_Optimality.pdf (Accessed July 2015)

The European Parliament and the Council of the European Union. (2003). *Directive 2002/91/EC. In Official Journal of the European Communities (pp. 65-71)*

The European Parliament and the Council of the European Union (2010) *Directive 2010/31/EC*

The Scottish Government (2012a) *Consultation Document on Directive 2010/31/EC on the Energy Performance of Buildings (Recast) – Scottish Government Response* Available at http://www.gov.scot/Resource/0039/00396545.pdf (Accessed July 2015)

The Scottish Government (2013a) *A Low Carbon Building Standards Update for Scotland 2013 Update* Available at www.scotland.gov.uk/sullivanreport (Accessed June 2015)

The Scottish Government (2013b) *Estimates of Households and Dwellings in Scotland, 2012* Available at http://www.gov.scot/News/Releases/2013/06/stats-households270713 (Accessed August 2015)

The Scottish Government (2014a) *Scottish House Conditions Survey 2013* available at http://www.scotland.gov.uk/SHCS (Accessed June 2015)

Worcester Si Compact Overview (2015) Available at https://www.worcester-bosch.co.uk/products/boilers/directory/greenstar-si-compact (Accessed July 2015)

Appendix I. Summary data for case study models

Table 14a: Parameter summary for case study models – a

Description	Type	Unit				Case				
			1	2	2a	3	3a	4	4a	5
Treated floor area		m^2	51.0	59.8	59.8	59.8	59.8	59.8	59.8	59.8
Thermal bridges eliminated?		y/n	n	n	n	y	y	n	n	n
Air leakage rate		1/h	10	2	2	2	2	1	1	1
External wall area	existing	m^2	181.1	99.9	99.9	99.9	99.9	0.0	0.0	99.9
External wall area	insulated	m^2	0.0	82.0	82.0	82.0	82.0	181.1	181.1	82.0
Floor slab area	existing	m^2	55.6	55.6	55.6	55.6	55.6	0.0	0.0	55.6
Floor slab area	insulated	m^2	0.0	0.0	0.0	0.0	0.0	55.6	55.6	0.0
Roof area	existing	m^2	54.0	3.1	3.1	3.1	3.1	0.0	0.0	3.1
Roof area	insulated	m^2	0.0	75.9	75.9	75.9	75.9	79.0	79.0	75.9
Door area	existing	m^2	3.2	3.2	3.2	3.2	3.2	0.0	0.0	0.0
	insulated	m^2	0.0	0.0	0.0	0.0	0.0	3.2	3.2	0.0
	new	m^2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2
Window numbers	trad	No.	7	0	0	0	0	0	0	0
	refurb	No.	0	6	6	6	6	6	6	0
	double glazed	No.	0	3	3	3	3	3	3	0
	triple glazed	No.	0	0	0	0	0	0	0	9
Gas boiler	existing	kW	24	0	0	0	0	0	0	0
	new	kW	0	24	0	24	0	24	0	24
Biomass boiler	new	kW	0	0	24	0	24	0	24	0
MVHR unit	new	No.	0	0	0	0	0	0	0	0
ASHP unit	new	kW	0	0	0	0	0	0	0	0
Solar thermal collector	evacuated tube	m^2	0	0	0	0	0	0	0	0
PV panels number	amorph-Si	m^2	0	0	0	0	0	0	0	0

Table 14b: Parameter summary for case study models - b

Description	Type	Unit	Case							
			5a	6a	6b	6c	7a	7b	7c	8
Treated floor area		m^2	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
Thermal bridges eliminated?		y/n	n	n	y	y	y	y	y	n
Air leakage rate		1/h	1	2	1	0.5	2	1	0.5	2
External wall area	existing	m^2	99.9	99.9	0.0	0.0	99.9	0.0	0.0	99.9
External wall area	insulated	m^2	82.0	82.0	181.1	181.1	82.0	181.1	181.1	82.0
Floor slab area	existing	m^2	55.6	55.6	0.0	0.0	55.6	0.0	0.0	55.6
Floor slab area	insulated	m^2	0.0	0.0	55.6	55.6	0.0	55.6	55.6	0.0
Roof area	existing	m^2	3.1	3.1	0.0	0.0	3.1	0.0	0.0	3.1
Roof area	insulated	m^2	75.9	75.9	79.0	79.0	75.9	79.0	79.0	75.9
Door area	existing	m^2	0.0	3.2	0.0	0.0	3.2	0.0	0.0	3.2
	insulated	m^2	0.0	0.0	3.2	0.0	0.0	3.2	0.0	0.0
	new	m^2	3.2	0.0	0.0	3.2	0.0	0.0	3.2	0.0
Window numbers	trad	No.	0	0	0	0	0	0	0	0
	refurb	No.	0	6	6	0	6	6	0	6
	double glazed	No.	0	3	3	9	3	3	0	3
	triple glazed	No.	9	0	0	0	0	0	9	0
Gas boiler	existing	kW	0	0	0	0	0	0	0	0
	new	kW	0	24	24	24	0	0	0	24
Biomass boiler	new	kW	24	0	0	0	0	0	0	0
MVHR unit	new	No.	0	1	1	1	1	1	1	0
ASHP unit	new	kW	0	0	0	0	5	5	5	0
Solar thermal collector	evacuated tube	m^2	0	0	0	0	0	0	0	5.5
PV panels number	amorph-Si	m^2	0	0	0	0	0	0	0	0

Table 14c: Parameter summary for case study models - c

Description	Type	Unit	Case									
			8	8a	8b	8c	9	9a	9b	9c	10	11
Treated floor area		m^2	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
Thermal bridges eliminated?		y/n	n	y	y	y	n	y	y	y	y	y
Air leakage rate		1/h	2	2	1	0.5	2	2	1	0.5	0.5	0.5
External wall area	exist	m^2	99.9	99.9	0.0	0.0	99.9	99.9	0.0	0.0	0.0	0.0
External wall area	ins	m^2	82.0	82.0	181.1	181.1	82.0	82.0	181.1	181.1	181.1	181.1
Floor slab area	exist	m^2	55.6	55.6	0.0	0.0	55.6	55.6	0.0	0.0	0.0	0.0
Floor slab area	ins	m^2	0.0	0.0	55.6	55.6	0.0	0.0	55.6	55.6	55.6	55.6
Roof area	exist	m^2	3.1	3.1	0.0	0.0	3.1	3.1	0.0	0.0	0.0	0.0
Roof area	ins	m^2	75.9	75.9	79.0	79.0	75.9	75.9	79.0	79.0	79.0	79.0
Door area	exist	m^2	3.2	3.2	0.0	0.0	3.2	3.2	0.0	0.0	0.0	0.0
	ins	m^2	0.0	0.0	3.2	0.0	0.0	0.0	3.2	0.0	0.0	0.0
	new	m^2	0.0	0.0	0.0	3.2	0.0	0.0	0.0	3.2	3.2	3.2
Window numbers	trad	number	0	0	0	0	0	0	0	0	0	0
	refurb	number	6	6	6	0	6	6	6	0	0	0
	dbl glz	number	3	3	3	0	3	3	3	0	0	0
	tpl glz	number	0	0	0	9	0	0	0	9	9	9
Gas boiler	exist	kW	0	0	0	0	0	0	0	0	0	0
	new	kW	24	0	0	0	24	0	0	0	0	0
Biomass	new	kW	0	0	0	0	0	0	0	0	0	0

boiler												
MVHR unit	new	number	0	1	1	1	0	1	1	1	1	1
ASHP unit	new	kW	0	5	5	5	0	5	5	5	5	5
Solar thermal collector	evac tube	m^2	5.5	5.5	5.5	5.5	0	0	0	0	5.5	11
PV panels number	amor-Si	m^2	0	0	0	0	7.5	7.5	7.5	7.5	7.5	15

Table 15a: Case study energy output and NPV summary - a

Output	**Case**							
	1	2	2a	3	3a	4	4a	5
Space heating demand ($kWh/m^2.a$)	489	190	190	183	183	185	185	144
PER demand ($kWh/m^2.a$)	1489	423	588	409	569	414	576	343
PER req <= ($kWh/m^2.a$)	880	356	358	342	342	347	349	275
PER demand > requirement by ($kWh/m^2.a$)	609	67	230	67	227	67	227	68
Total electricity demand ($kWh/m^2.a$)	36.3	20.3	30.9	20.2	30.6	20.2	30.6	19.7
Solar DHW generation ($kWh/m^2.a$)	0	0	0	0	0	0	0	0
PV electricity yield ($kWh/m^2.a$)	0	0	0	0	0	0	0	0
Biomass generation ($kWh/m^2.a$)	0	0	149	0	307.8	0	311.8	0
HP heat production ($kWh/m^2.a$)	0	0	0	0	0	0	0	0
Window net losses ($kWh/m^2.a$)	37.9	43.2	43.2	43.2	43.2	43.2	43.2	13.7

NPV output (£)	46112	19640	16129	18857	20374	32405	33747	17803

Table 15b: Case study energy output and NPV summary - b

Output	**Case**							
	5a	6a	6b	6c	7a	7b	7c	8
Space heating demand ($kWh/m^2.a$)	144	170	108	64	176	113	68	190
PER demand ($kWh/m^2.a$)	472	392	287	212	60	60	58	387
PER req <= ($kWh/m^2.a$)	277	319	212	137	238	168	119	345
PER demand > requirement by ($kWh/m^2.a$)	195	73	75	75	-178	-108	-61	42
Total electricity demand ($kWh/m^2.a$)	29.1	23.2	22.4	21.9	19.7	19.7	19.7	21
Solar DHW generation ($kWh/m^2.a$)	0	0	0	0	0	0	0	47.3
PV electricity yield ($kWh/m^2.a$)	0	0	0	0	0	0	0	0
Biomass generation ($kWh/m^2.a$)	253.8	0	0	0	0	0	0	0
HP heat production ($kWh/m^2.a$)	0	0	0	0	281.6	166	99.1	0
Window net losses ($kWh/m^2.a$)	13.7	43.2	43.2	13.7	43.2	43.2	13.7	43.2
NPV output (£)	21299	20309	27361	24787	-9116	10872	10663	12999

Table 15c: Case study energy output and NPV summary - c

Output	**Case**								
	8a	8b	8c	9	9a	9b	9c	10	11
Space heating demand ($kWh/m^2.a$)	176	113	68	190	176	113	68	68	68
PER demand	199	135	96	423	60	60	58	96	91

(kWh/m^2.a)									
PER req <= (kWh/m^2.a)	277	186	124	356	238	168	119	124	111
PER demand > requirement by (kWh/m^2.a)	-78	-51	-28	67	-178	-108	-61	-28	-20
Total electricity demand (kWh/m^2.a)	20.7	20.7	20.7	20.3	19.7	19.7	19.7	20.7	20.7
Solar DHW generation (kWh/m^2.a)	47	45	43.1	0	0	0	0	43.1	65.7
PV electricity yield (kWh/m^2.a)	0	0	0	20.3	20.3	20.3	20.3	20.3	40.6
Biomass generation (kWh/m^2.a)	0	0	0	0	0	0	0	0	0
HP heat production (kWh/m^2.a)	298.7	186.6	119	0	281.6	166	99.1	119	93.3
Window net losses (kWh/m^2.a)	43.2	43.2	13.7	43.2	43.2	43.2	13.7	13.7	13.7
NPV output (£)	-13405	3002	6881	17971	-10785	5412	9991	6209	5633