HISTORIC SCOTLAND

Technical Conservation Group

Technical Paper

Energy Modelling In Traditional Scottish Houses (EMITSH)

Heriot-Watt University analysis of potential CO2 savings of building variants

Tarbase Group report for Historic Scotland

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1. Introduction

When applying energy saving measures to solid wall houses, typical in many parts of Scotland, it is important to recognise that a subtly different approach might be required than that used for other sections of the housing stock. Thermal transmittances of solid sandstone, granite and similar materials are, compared to modern buildings, generally poor (depending on wall thickness) and the lack of a cavity results in cavity-wall insulation not being an option. When such buildings also have an aesthetic or historical value, any visible building fabric measure (such as external insulation, many glazing options and rooftop alterations) becomes problematic. The result is, when compared to very modern dwellings, a relatively inefficient building with potentially fewer energy-saving refurbishment options.

With solid wall dwellings making up a substantial part of the housing stock in Scotland (e.g. 23% of dwellings are traditional sandstone or granite construction[1]), this problem is symptomatic of a wider issue – a single stock-wide solution to achieving large-scale energy (and carbon) reductions in all UK housing is not possible. It is necessary to understand the specific housing type (be it a solid wall terraced flat or a modern detached house) before choosing a successful strategy to reduce the carbon emissions of a dwelling. This involves, firstly, understanding the electrical and thermal demand of the building which, as well as being affected by building size and construction, will vary with occupancy, demographic of owners and location.

Secondly, the fact that many interventions might be proposed (from improving lighting and building fabric to installing onsite generation) makes it vital that the cumulative effect of interventions be accounted for. The order that these refurbishments are carried out is also important – for example, changing the boiler before reducing the thermal demand would result in a poorly-sized boiler (at a greater cost) operating at reduced efficiency.

These issues are true for the entire housing stock. With the limitations on refurbishments for Scottish traditional houses in mind, the following exercise models the energy use of three specified existing building types based on three real-life case studies: a terraced flat, a rural cottage and a detached house. Once the thermal and electrical demand characteristics are defined, suitable refurbishment measures, covering all aspects of dwelling energy use, are suggested and quantified for specific scenarios. These intervention scenarios, producing a final potential carbon saving for each dwelling, are informed by previous research by Heriot-Watt University under “Tarbase”, a £1.4 million Carbon Vision Buildings project funded by the Carbon Trust and Engineering and Physical Sciences Research Council.

2. Tarbase methodology

The Tarbase project[2] looked at technologies and methods that might reduce the carbon emissions of specified domestic and non-domestic building variants by 50% or more, with the year 2030 as a target date. The domestic branch of this project involved the production of a steady-state methodology (hereon referred to as the Tarbase model, which includes a series of onsite generation models and assessment of other refurbishment technologies) that was used to analyse the energy use of several dwelling types in the UK. The Tarbase model, when compared to the standard BREDEM/SAP[3,4] approach (which Tarbase is partly based on), looks at electrical and thermal demand in greater depth, characterising the relationship between the building occupancy profile, internal heat gains and, subsequently, thermal requirements of the dwelling. The calculation method has the ability to improve any aspect of the building energy use, from individual appliances (e.g. using an LCD instead of a CRT television) and lighting as well changes to the building itself (the alterations for Tarbase were made with 2030 in mind – the chosen improvements for EMITSH are based on currently available technologies). There is also the option of changing the climate conditions, whether through geographical location or by applying future climate predictions. In addition, several onsite generation models were constructed to investigate the potential of solar thermal, solar photovoltaics (PV), micro and small-scale wind, micro and small-scale CHP and heat pump technologies (ground-source and air-source). These are also made available for the EMITSH project, subject to suitability with the chosen dwelling. With respect to micro-CHP options, current technologies have been discounted due to the relatively low electrical efficiencies available, and therefore carbon savings are generally very small when compared to very efficient gas boilers. However, this situation may change in the coming years if, for example, solid-oxide fuel-cell and internal combustion engine systems emerge at a commercial level with improved electrical efficiencies, where (for the former case) hydrogen is reformed from the existing gas supply and several thousand kWh of low-carbon onsite electricity could be generated as a result.

The general Tarbase approach is to understand the specific building energy demand, then reduce it and, if suitable, look at possibilities for supplying these energy demands through onsite or near-site applications. The following points briefly highlight the main areas covered by the model, though more detail can be found elsewhere[2,5].

2.1 Appliances, cooking and lighting

Appliance, cooking and lighting technologies are given typical profiles (based on domestic energy surveys and empirical information collected by the project) and the contribution they make to the building space heating demand characterised by deciding whether they are used during times of occupancy and whether their use coincides with the heating season of the building.

Any selection of appliance (and cooking) technologies can be inputted into the model. Design lighting levels are assumed for the various areas of a dwelling (e.g. bedroom, lounge etc), with default occupancy hours per room (though these can be changed if desired). All the above are linked with the chosen number of occupants in the dwelling (inputted as number of adult males, adult females and children).

2.2 Domestic hot water usage

This is calculated from the British Gas domestic hot water energy formula[6], based on number of occupants and required return temperature of hot water (typically 55-60°C). The resulting requirement is then met by the chosen boiler system at a specified efficiency.

2.3 Building fabric

The main requirements to define the building are dimensions (ideally obtained from in-situ measurements), construction and glazing U-values (calculated from assumed or quoted materials), location (for climate file – though all buildings in EMITSH will be assuming an Edinburgh climate), orientation (to account for solar gain) and information relating to the position of the dwelling relative to other buildings (e.g. detached, semi-detached, terraced etc). Wall thickness is also used to estimate the degree of thermal bridging that might occur.

2.4 Space heating requirement

The BREDEM/SAP model is a steady-state approach where the heat loss through the building elements is calculated (from U-value and building dimension information) and, by comparing with average external temperatures, the annual space heating requirement is calculated. This must also account for infiltration and (if present) ventilation, sometimes defined as ventilation conductance (with higher air changes requiring larger heating loads). The Tarbase model takes a similar approach but assigns design comfort temperatures to the various rooms and calculates an area-weighted average dwelling comfort temperature. The chosen boiler system, with specified efficiency and fuel type, is then used to estimate the final space heating energy consumption.

3. Chosen building variants

The individual assessment of the three building variants will now be carried out. This involves defining the current (or baseline) electrical and thermal energy use that can then be altered through the carbon-saving refurbishments of section 4.

3.1 Terraced Flat (variant 1)

The terraced flat, modelled on a Georgian Edinburgh tenement as shown in Figure 1, was visited and building data (such as appliances present, lighting technology and room dimensions) recorded. The building uses a gas boiler for space heating and hot water. Tables 1 and 2 show some of the building information, with assumed comfort temperatures (used in the modelling) also listed. The building is assumed to be occupied by two adults and a child.

Figure 1 – Georgian Edinburgh flat used for variant 1

Table 1 – Building dimensions of variant 1

Height (roof apex) (m)	5.5
Width (North and South walls) (m)	9.5
Length (West and East walls) (m)	14
height to soffit (m)	3.5
Floor to ceiling height (m)	3.2
Number of storey's	1

Table 2 – Room information of variant 1

Room	Floor area (m^2)	Comfort temperature (°C)
Hall	12.0	21.5
Lounge	27.3	21.5
Storage	5.5	18
Box room	8.5	21.5
Kitchen	12.2	18
Bedrooms	40.4	18
Bathroom	3.75	26.5

Table 3 – Summary of building fabric data of variant 1

	U-value (W/m^2K)	Area (m^2)	Glazing					Doors/other opening		External surface? (Y/N)
			Material	*U-value ($W/m^2 K$)*	*Frames*	*External shading*	*Area (m^2)*	*U-value ($W/m^2 K$)*	*Area (m^2)*	
N wall	1.5	33.3	single	5.1	wood	1	7.6			y
S wall	1.5	33.3	single	5.1	wood	1	6.6	3.23	1.76	y
E wall*	0.7	63	single	5.1	wood	1	0.0			n
W wall	1.5	63	single	5.1	wood	2	2.2			y
TOTAL WALLS	1.2	192.5		5.1			16.4	3.23	1.76	
Roof	0.18	133	single	5.1	wood	4	0.16			y
Floor	adiabatic	133								n

**East wall faced communal corridor area and is given "effective" U-value of 0.7 based on SAP 2005*[4]

Table 3 shows some of the assumed building fabric information for the building. It also includes glazing dimensions (as measured) with external shading characterised from being almost completely unshaded (graded "1") to having more than 80% of the available sky shaded ("4"). This informs the solar gain calculations. The sash windows (Figure 2) are single-glazed with the wall construction 600mm sandstone (calculated as having a U-value of 1.5W/m^2K).

Figure 2 – sash windows and solid sandstone of flat (variant 1)

Table 4 – Appliance list (and refrigeration) for variant 1

	Number	Total electical consumption (kWh/yr)
Clock radio	1	20
laptop	1	33
broadband	1	31
VCR	1	84
Digibox	1	95
DVD non record	1	15
Hairdryer	1	60
Hair straightners	1	60
fridge freezer	1	328
Sec Lighting	4	188
TV - CRT	1	128
CD Player	1	120
WSH/Mch	1	293
Kettle	1	164
Microwave	1	85
Oven - electric	1	253
Hob - gas	1	379
Phone	1	35
Smoke Alarms	1	13
gas boiler electricity consumption	1	400
external power supplies	2	306
irons	1	75
toaster	1	12
vacuum cleaner	1	83
food processor	1	1
extractor fan kitchen	1	20
extractor fan bathroom	1	20
burglar alarm	1	9
electric shower	1	300
TOTAL		**3611**

Table 4 is composed through an onsite audit and previous work from the Tarbase project. It lists all the identified electrical appliances/equipment, with energy consumption calculated from typical figures for the described items (for assumed operating patterns). Table 5 takes the areas of Table 2 and applies design illuminances and estimated hours of activity in the various rooms to calculate the lighting energy consumption (where GLS, or General Lighting System, refers to incandescent bulbs and CFL refers to Compact Fluorescent Lighting). Bulb type is based on the site visit whereas utilisation factor (in effect the percentage of generated light that reaches the horizontal floor area) and ballast factor (representing losses from the fixture itself) are estimated from design guides[7].

With this information, Table 6 is produced showing the annual energy consumption and CO_2 emissions of the different categories of energy use in the dwelling. CO_2 emissions have been calculated using carbon intensities of $0.52kgCO_2/kWh$[8] for grid electricity and $0.19kgCO_2/kWh$ for gas[4].

Table 5 – Lighting usage in variant 1

Dwelling area	Design illuminance (lux)	Light required (lumens)	Use per day (hrs)	Bulb-type	Utilisation factor	Ballast factor	Daily energy consumption (Wh)	Annual energy consumption (kWh)
Hall	150	1797	4	GLS	0.7	0.9	553	301
Lounge	150	4095	3.9	CFL	0.7	0.9	290	158
Storage	150	825	3.5	CFL	0.7	0.9	53	29
Box room	100	850	1.9	CFL	0.7	0.9	29	16
Kitchen	300	3660	1.5	CFL	0.7	0.9	100	54
Bedrooms	50	2020	0.9	GLS	0.7	0.9	140	76
Bathroom	150	563	0.5	CFL	0.7	0.9	5	3
Total Dwelling Energy Consumption per Annum								**637**

Table 6 – Total energy consumption and CO_2 emissions of variant 1 (pre-refurbishment)

	Energy consumption ($kWh/m^2/yr$)	CO_2 emissions ($kgCO_2/m^2/yr$)
Appliances	24.7	11.4
Refrigeration	2.5	1.3
Lighting	4.8	2.5
Space heating	139.8	26.6
Hot water	18.8	3.6
TOTAL	191	45

It is useful at this stage to ascertain the causes of the building CO_2 emissions. It is possible, through the use of Table 3, to produce Figure 3, showing the percentage of space heating that is assigned to different factors, namely heat loss through building elements (and thermal bridging) and air changes through infiltration and ventilation.

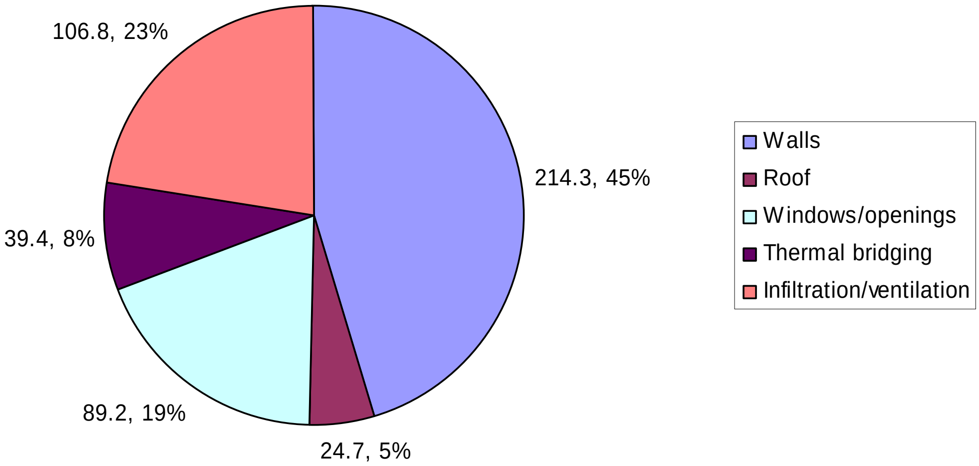

Figure 3 – Heat loss (W/K) and percentage contribution to space heating load of different building elements and processes for variant 1 (NB – there are no losses through the floor as it is assumed to be adiabatic with the adjoining flat below)

Figure 3 can be used with the space heating figures to assign CO_2 emissions to different building elements. When compared with all other energy uses in the building, as shown in Figure 4, it is possible to identify the features of the building that are responsible for CO_2 emissions. Figure 4 lists the different causes of building CO_2 emissions (cumulatively) in order of magnitude from left to right (with heat loss through walls having the highest level of CO_2 emissions associated with it).

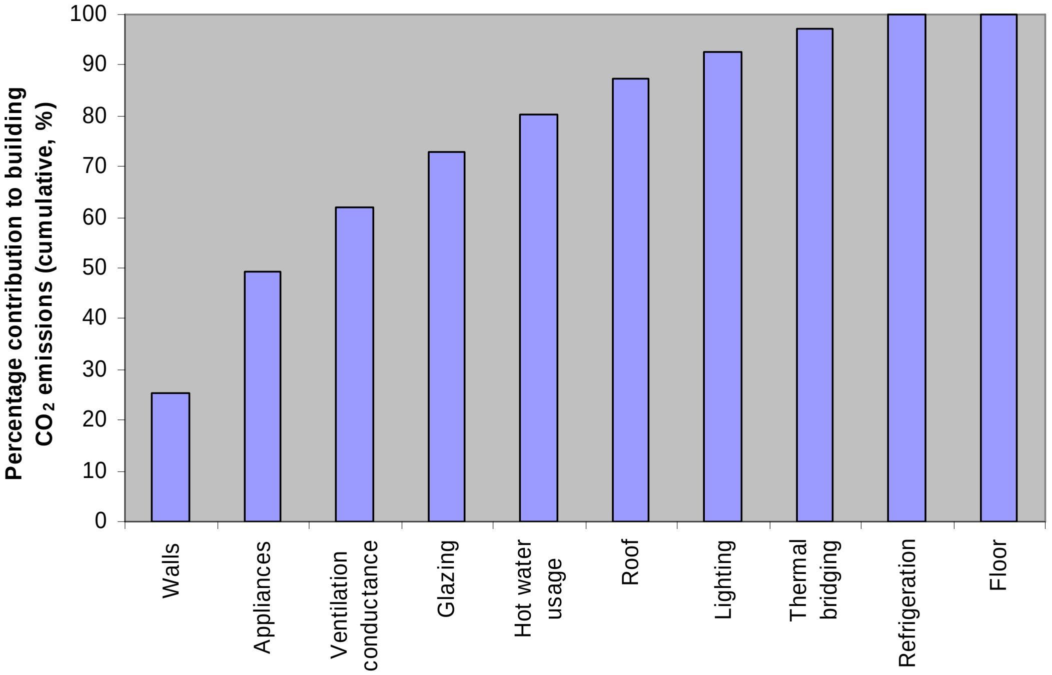

Figure 4 – Causes of building CO_2 emissions as percentage of total building emissions for variant 1 prior to refurbishments (shown cumulatively)

This demonstrates the areas where carbon-saving interventions might be applied. However, as a listed historic building, certain categories in Figure 4 will generally be difficult to reduce in practice. This is reflected in the chosen refurbishments in section 4.

3.2 Cottage (variant 2)

The cottage variant, modelled on a property in the Borders (see Figure 5) is a mid-1800’s construction with a more recent (circa 1950) bathroom and kitchen extension. The building is situated in a rural location and is off the gas grid, using an oil boiler for space heating and hot water. Tables 7 to 9 show building information used in the calculations. The definitions used are as discussed for variant 1. The building is assumed to be occupied by two adults.

Figure 5 – Cottage (with extension) used for variant 2

Table 7 – Building dimensions of variant 2

Height (roof apex) (m)	5
Width (North and South walls) (m)	5.5
Length (West and East walls) (m)	10.7
height to soffit (m)	2.5
Floor to ceiling height (m)	2.5
Number of storey's	2

Table 8 – Room information of variant 2

Room	**Floor area (m^2)**	**Comfort temperature (°C)**
Hall	4.7	21.5
Living area 1	18.1	21.5
Living area 2	14.0	21.5
Landing	2.2	21.5
Kitchen	8.7	18
Bedrooms	23.7	18
Bathroom	2.9	26.5

Table 9 – Summary of building fabric data of variant 2

	U-value* (W/m^2K)	**Area (m^2)**	**Glazing**					**Doors/other opening**		**External surface? (Y/N)**
			Material	***U-value (W/m^2K)***	***Frames***	***External shading***	***Area (m^2)***	***U-value (W/m^2K)***	***Area (m^2)***	
N wall	1.5	11.3	double	2.75	pvc	1	0.0			y
S wall	1.57	11.3	double	2.75	pvc	1	2.6	3	2.16	y
E wall	1.52	36.4	single	5.1	wood	1	1.4			y
W wall	1.22	36.4	double	2.75	pvc	1	6.9			y
TOTAL WALLS	1.4	95.3		3.0			10.9	3	2.16	
Roof	2.108	79.0	single	5.1	wood	1	0.3			y
Floor	1.2	43.7								y

**U-values are average surface values and account for the different constructions (e.g. E walls are part sandstone, part brick cavity)*

Unlike the previous variant, the cottage had a variety of wall constructions. For the main building, the west wall was red brick, with an estimated U-value of $1.1 W/m^2K$ from a previous study[9]. The other main building wall construction is 500mm sandstone (Figure 6) at a calculated U-value of $1.5 W/m^2K$ (similar to the aforementioned measurements for this material). The extension is assumed to be cavity wall and, if constructed in 1950, would have a U-value in the region of

1.6W/m^{2}K[4]. The roof surfaces are a combination of pitched slate roof (main building) and flat, asphalt roof (extension). The pitched loft contains heated space which is accounted for in the heat loss calculations. The surface U-values in Table 9 are averaged over these surfaces – for example, there is 27m^2 of east-facing sandstone and 8m^2 of east-facing cavity wall and so the average U-value for east-facing walls will reflect this.

The floor is assumed to be a partly suspended floor (present due to a substantial slope of the ground beneath). Heat loss through this surface accounts for ground transmittance calculations (based on CIBSE Guide A suggestions[10]).

Figure 6 – window and sandstone wall of cottage (variant 2)

Figure 6 shows a detail of the single-glazed timber-frame windows in use. These are present in the front (East) of the building. The other windows are double-glazed uPVC-framed windows, and this is accounted for in the glazing U-values of Table 9 (where, again, the U-value is an area-weighted average).

Table 10 – Appliance list (and refrigeration) for variant 2

	Number	Total electical consumption (kWh/yr)
Clock radio	1	20
VCR	1	84
Hairdryer	1	30
fridge freezer	1	328
TV - CRT	1	128
CD Player	1	100
WSH/Mch	1	215
Kettle	1	136
Oven - electric	1	207
Hob - electric	1	225
boiler pump electricity consumption	1	400
irons	1	75
toaster	1	12
vacuum cleaner	1	83
food processor	1	1
extractor fan kitchen	1	20
electric shower	1	300
TOTAL		2364

The cottage was unoccupied so an assumed activity and occupancy has been applied, based on Tarbase assumptions for a retired couple. The corresponding appliance list is given in Table 10, where the specification involves a relatively low density of IT equipment and consumer electronics. Lighting usage is given in Table 11, with the site visit recording only incandescent lighting in use.

Table 11 – Lighting usage in variant 2

Dwelling area	Design illuminance (lux)	Light required (lumens)	Use per day (hrs)	Bulb-type	Utilisation factor	Ballast factor	Daily energy consumption (Wh)	Annual energy consumption (kWh)
Hall	150	705	4	GLS	0.7	0.9	217	118
Living area 1	150	2720	3.9	GLS	0.7	0.9	816	444
Living area 2	150	2099	3.9	GLS	0.7	0.9	630	343
Landing	100	219	4	GLS	0.7	0.9	68	37
Kitchen	300	2610	1.5	GLS	0.7	0.9	301	164
Bedrooms	50	1185	0.9	GLS	0.7	0.9	82	45
Bathroom	150	435	0.5	GLS	0.7	0.9	17	9
Total Dwelling Energy Consumption per Annum								**1160**

As previously described, this information is used to generate Table 12, showing the assumed annual energy consumption and carbon emissions of the dwelling (for the defined occupancy). As with all variants, a grid carbon intensity of 0.52kgCO_2/kWh is used. For all heating (space and hot water), it is assumed that 90% of the generation comes from the oil boiler (at a carbon intensity of 0.265kgCO_2/kWh) and 10%[4] comes from open log fires (0.025kgCO_2/kWh) used intermittently in the house.

Table 12 – Total energy consumption and CO_2 emissions of variant 2 (pre-refurbishment)

	Energy consumption (kWh/m^2/yr)	CO2 emissions (kgCO_2/m^2/yr)
Appliances	27.6	14
Refrigeration	4.4	2
Lighting	15.6	8
Space heating	275.2	66
Hot water	26.2	6
TOTAL	349.1	97

These estimations would suggest that space heating is the main problem, implying that building fabric and boiler improvements might be the most appropriate measures. The composition of the space heating load is demonstrated in Figure 7.

The cottage has several double-glazed windows (see Table 11) and so glazing heat loss is calculated as having less of an impact, proportionately, for the heating demand than for variant 1. The cottage roof is poorly insulated and so there is a substantial proportion of heat loss due to this element. This problem will be exacerbated by the room in the loft, which will tend to restrict the available space for roof insulation and also create a heated area that is close to the actual roof construction (with little or no insulation in between). Therefore, it is suggested that dealing with the heat loss through the roof and walls should be the primary concern.

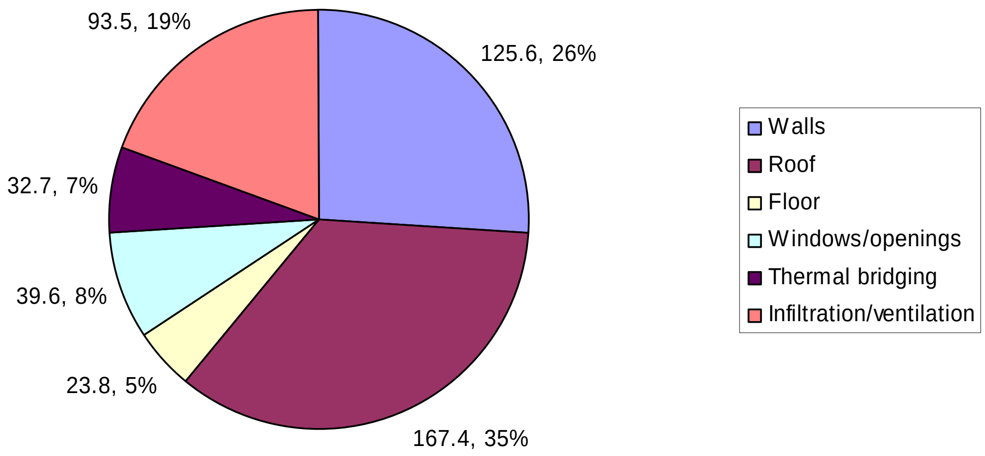

Figure 7 – Heat loss (W/K) and percentage contribution to space heating load of different building elements and processes for variant 2

Looking at all areas of energy use, and corresponding carbon dioxide emissions, Figure 8 confirms the above suggestion, with heat loss through roof and walls causing the highest contribution to building CO_2 emissions. Although IT equipment and consumer electronics have been assumed to be relatively low in this dwelling (based on occupancy type), the total appliance usage is still significant in terms of total CO_2 emissions.

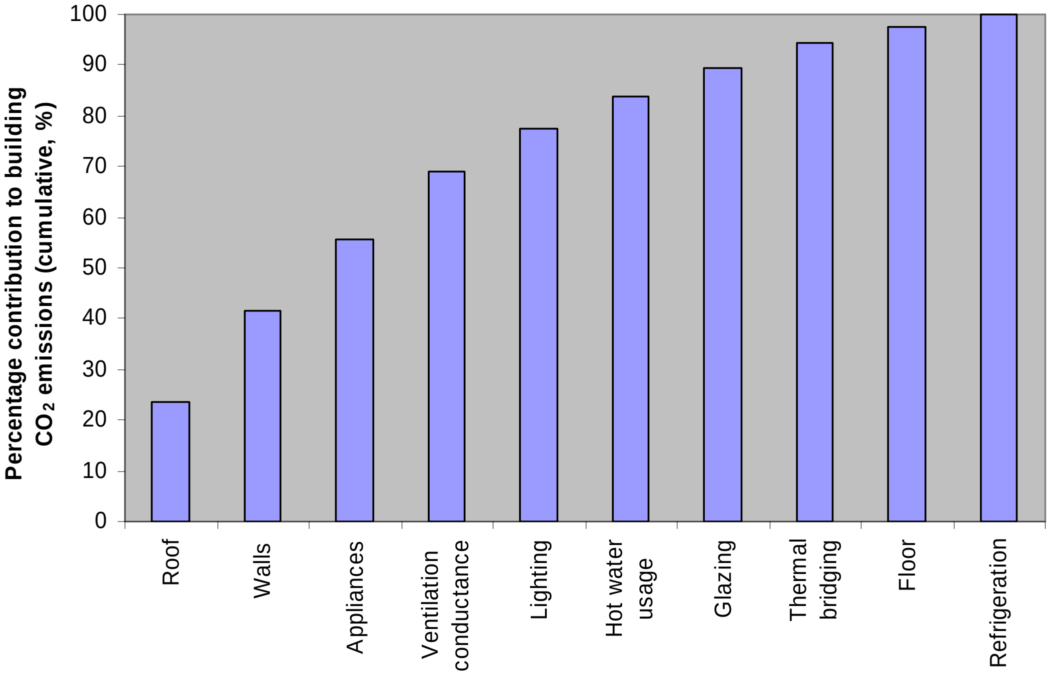

Figure 8 – Causes of building CO_2 emissions as percentage of total building emissions for variant 2 prior to refurbishments (shown cumulatively)

3.3 Detached house (variant 3)

The final variant is a detached house in Fife (Figure 9), situated in a coastal village. The C-listed building is of sandstone construction with a render applied to the external surface. The building is connected to the gas grid, providing hot water and space heating. Tables 13 to 15 show building information used in the calculations. The building is occupied by two adults and two children.

Figure 9 – Detached house used for variant 3

Table 13 – Building dimensions of variant 3

Height (roof apex) (m)	7
Width (North and South walls) (m)	10.08
Length (West and East walls) (m)	6.88
height to soffit (m)	2.5
Floor to ceiling height (m)	2.5
Number of storey's	2

Table 14 – Room information of variant 3

Room	**Floor area (m^2)**	**Comfort temperature (°C)**
Hall	13.5	21.5
Living area	16.2	21.5
Dining room	13.8	21.5
Landing	6.0	21.5
Kitchen	8.7	18
Bedrooms	32.8	18
Bathrooms	6.7	26.5

Table 15 – Summary of building fabric data of variant 3

	U-value (W/m^2K)	**Area (m^2)**	**Glazing**					**Doors/other opening**		**External surface? (Y/N)**
			Material	***U-value (W/m^2K)***	***Frames***	***External shading***	***Area (m^2)***	***U-value (W/m^2K)***	***Area (m^2)***	
N wall	1.3	25	single	5.1	wood	1	3.2			y
S wall	1.3	25	single	5.1	wood	1	9.6	3	2.16	y
E wall*	1.3	33	single	5.1	wood	1	3.2			y
W wall	1.3	33	single	5.1	wood	1	0.0			y
TOTAL WALLS	1.3	116		5.1			16.0	3	2.16	
Roof	2.3	69	single	5.1	wood	1	0.0			y
Floor	1.2	69								y

As shown in Table 15, the calculated wall U-value is slightly improved when compared to variant 1 due to the external render. However, the existence of this render, along with the other building details on the dwelling façade, is likely to make external insulation measures less practical, or at least dissuade the occupants from installing such a measure (see section 4.3). The roof is again a slate, pitched roof, assumed to have no insulation initially. The floor is solid concrete, making refurbishments such as floor insulation and underfloor heating difficult or, in the latter case, impossible.

Figure 10 – window and sandstone wall of detached house (variant 3)

Figure 10 shows that the building is broadly similar to the first variant, in that it is a solid-walled building with single-glazed, timber-framed windows.

With variant 3 having the largest number of people occupying the building, it is unsurprising that the electrical demand is relatively high (Table 16), particularly with the presence of two teenage children. With the lighting energy consumption added to this (Table 17), the total electrical demand of 6,140kWh is slightly higher than the UK average (of approximately 4,400kWh).

Table 16 – Appliance list (and refrigeration) for variant 3

	Number	Total electical consumption (kWh)
Clock radio	2	40
laptop	1	33
broadband	1	31
VCR	1	84
Digibox	1	95
DVD non record	2	30
Video game	1	105
Hairdryer	1	60
Hair straightners	1	60
fridge freezer	1	328
Sec Lighting	4	188
TV - CRT	2	256
TV – Plasma	1	693
CD Player	2	398
WSH/Mch	1	417
Kettle	1	272
Microwave	1	141
Oven	1	217
Hob	1	236
Phone	1	35
Smoke Alarms	1	13
boiler electricity consumption	1	400
external power supplies	2	306
irons	1	75
toaster	1	12
vacuum cleaner	1	83
food processor	1	1
extractor fan kitchen	1	20
extractor fan bathroom	1	20
burglar alarm	1	9
lawnmower	1	16
electric shower	1	300
TOTAL		4976

Table 17 – Lighting usage in variant 3

Dwelling area	Design illuminance (lux)	Light required (lumens)	Use per day (hrs)	Bulb-type	Utilisation factor	Ballast factor	Daily energy consumption (Wh)	Annual energy consumption (kWh)
Hall	150	705	4	gls	0.7	0.9	217	118
Living area	150	2720	3.9	gls	0.7	0.9	816	444
Dining room	150	2099	3.9	gls	0.7	0.9	630	343
Landing	100	219	4	cfl	0.7	0.9	16	9
Kitchen	300	2610	1.5	T8	0.7	0.9	56	30
Bedrooms	50	1185	0.9	cfl	0.7	0.9	19	11
Bathrooms	150	435	0.5	gls	0.7	0.9	17	9
Total Dwelling Energy Consumption per Annum								**964**

The resulting baseline energy consumption of the dwelling (Table 18) is relatively high, with appliances being a greater factor than for the other two variants.

Table 18 – Total energy consumption and CO_2 emissions of variant 3 (pre-refurbishment)

	Energy consumption ($kWh/m^2/yr$)	**CO_2 emissions $kgCO_2/m^2/yr$**
Appliances	48	24
Refrigeration	3	2
Lighting	12	6
Space heating	233	44
Hot water	31	6
TOTAL	327	82

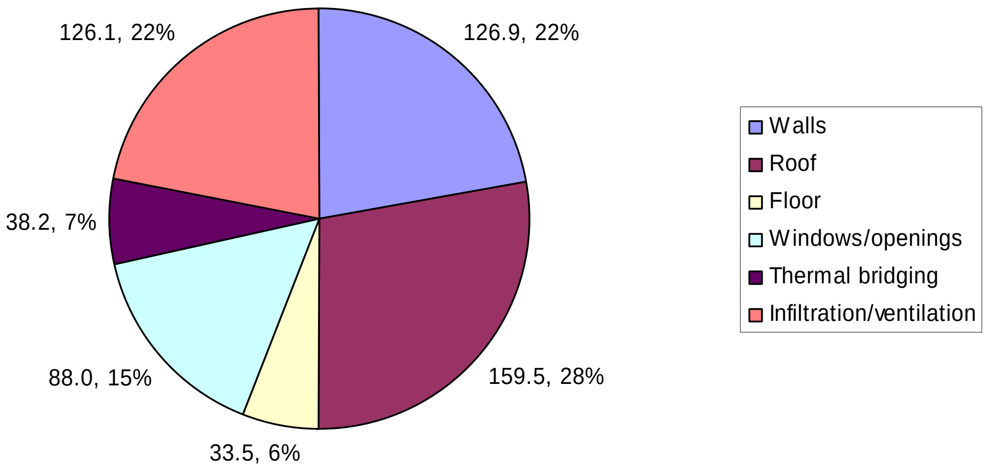

Figure 11 – Heat loss (W/K) and percentage contribution to space heating load of different building elements and processes for variant 3

Figure 11 demonstrates the effect of having an insulated roof, with roof heat loss being the main contributor to space heating, closely followed by heat loss through the walls. When converted into carbon emissions, and compared with other dwelling energy uses (Figure 12), the problem of consumer electronics in a modern household becomes clear. This is now, for the chosen categories, the main contributor towards the building carbon emissions – although the *total* space heating is still significantly more than this, the proportion of space heating carbon emissions assigned to the individual building elements does not exceed the appliance carbon emissions. For this dwelling the priorities would therefore be the promotion of energy efficient appliances, followed by a reduction in the heat loss through the roof and walls.

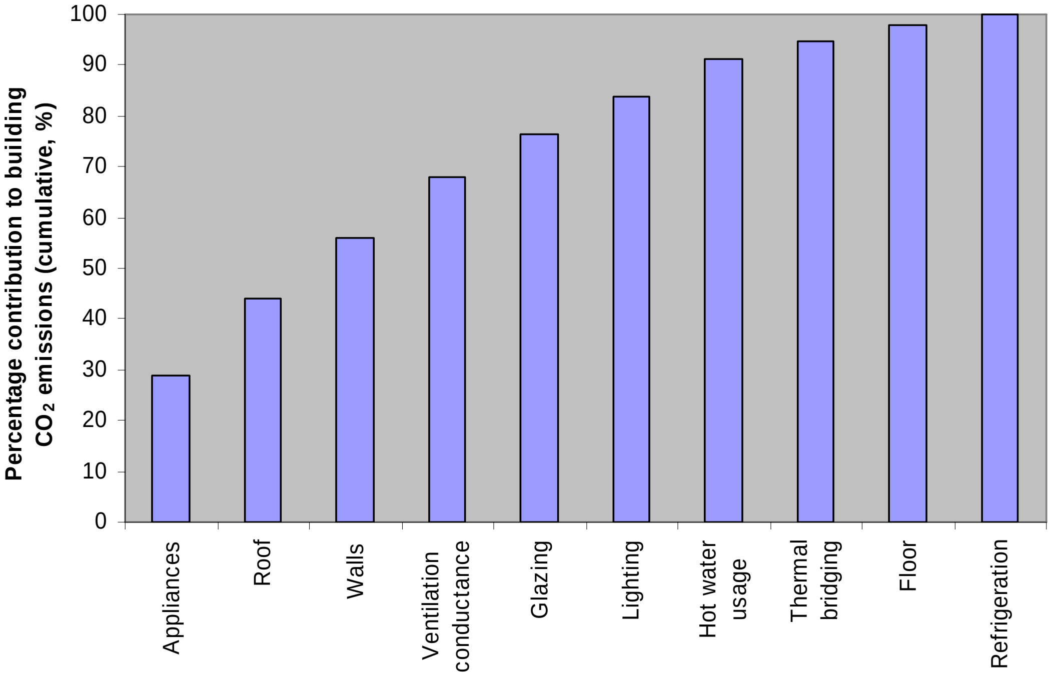

Figure 12 – Causes of building CO_2 emissions as percentage of total building emissions for variant 3 prior to refurbishments (shown cumulatively)

4. Results of modelling carbon-saving refurbishments

Detailed intervention packages will now be specified for the three buildings. While commonalities exist across the buildings, there are also building-specific refurbishments investigated that are not necessarily applicable to other buildings within the traditional Scottish housing stock. This will be discussed in the conclusion of the report.

4.1 Terraced Flat

A summary of interventions is given in Table 19. Details of the appliances options are documented in detail elsewhere[2]. However, the main changes are: more efficient ovens (through improved insulation and operation); washing machines using less water (through optimised drum size) and at a lower temperature (where a maximum wash temperature of 40°C has been applied); energy efficient LCD screens (rather than CRT) and more efficient external power supplies (e.g. for phone charging). Despite a limitation to currently available technologies, the savings are significant, with a 30% reduction in appliance energy consumption.

Table 19 – Summary of carbon-saving interventions for variant 1

Area of improvement	Description of refurbishment	Effect of changes
Appliances	Series of Tarbase informed improvements to appliances throughout building	Reduces appliance consumption by 30% (internal heat gains similarly reduced)
Refrigeration	Refrigeration with improved insulation (using vacuum insulated panels) and free piston stirling cooler	Reduces refrigeration energy consumption by 40%
Lighting	All lighting changed to CFL (assumed efficacy 55lm/W)	Total lighting energy consumption reduced by 45%
Glazing	Seconday glazing installed to existing windows	U-value improved from 5.1 to 2.3W/m^{2}K and 16% reduction in infiltration rate
Roof insulation	Increase in mineral wool from 200mm to 250mm thickness	U-value improved from 0.18 to 0.15W/m^{2}K
Boiler	Replace boiler with gas condensing model (also accounts for change in thermal demand due to above measures)	Average efficiency improved from 78% to 88%
Solar thermal	Installation of 2.4m^2 system sized to meet 50% of hot water demand	Annual delivery of 975kWh
Solar photovoltaic	Installation of 1kW (8m^2) system, 14% rated efficiency, 30deg inclination (south facing)	Annual output of 830kWh
Micro-wind	Installation of 1.5kW system with 2.2m/s average wind resource at 15m altitude	Annual output of 387kWh*

*for a higher, rural wind resource (of 5.5m/s average) at 15m altitude, output would reach 3038kWh based on collected wind speed data at Heriot-Watt University campus, but this is not likely to be indicative of the site in question

Refrigeration use is reduced on the basis of choosing an appliance with improved insulation (assumed here to be vacuum insulation panels). This can reduce refrigeration consumption by an estimated 40%[11].

While the baseline building has substantial compact fluorescent lighting, some of the larger areas (see Table 5) were recorded as using incandescent (i.e. GLS) bulbs. Therefore, replacing all bulbs with CFL lighting has a significant effect, reducing total lighting energy consumption by an estimated 45%.

Glazing changes are somewhat limited for historic buildings, in that the appearance of the façade will generally need to be conserved. Secondary glazing, accepted for similar projects[12], is chosen to reduce building heat loss while also reducing the infiltration rate of external air into the building (by a calculated 16%). The improvement in U-value is significant, while maintaining a suitable façade to the dwelling.

Roof insulation, of 200mm, already exists in the building but could be topped up to 250mm. With an improved U-value of 0.15W/m^{2}K, this would bring the loft up to best practice targets for similar buildings[13]. The loft itself was not explored during the site visit so the exact configuration of space was unknown. There can sometimes be issues with having to compress roof insulation to make it fit into such spaces – this is bad practice and can reduce the effectiveness of the insulation considerably. Also, very high levels of insulation in the roof can cause condensation and damp problems, with warm air rising from inside the building (see also discussion in section 4.2 for the cottage). However, it is believed that, for the building specified, this should not be an issue with only 250mm of mineral wool. With reference to this material, the example of mineral wool has been used for ease of modelling (and consistency with previous work). However, there is an issue with moisture retention for such material[14] (an issue likely to be particularly problematic for a retrofitted solid wall building) and sheep's wool, often used in historic building refurbishments[15], can achieve similar results in terms of U-value performance. For roof insulation in particular, it might be advisable to use sheep's wool rather than mineral wool (so in the case of variant 1, the existing mineral wool would be removed and sheep's wool added at a thickness of 250mm). Sheep's wool will also have a lower embodied carbon level associated with it and therefore have enhanced environmental credentials.

After the insulation refurbishments, it might be desirable to reduce the infiltration rate further (in addition to the reduction that would occur when installing secondary glazing). However, research[16,17] has suggested that there is a danger in making buildings more air tight without accounting for the effect on internal comfort conditions. If a dwelling becomes too humid, or if the general air quality becomes unpleasant (due to high internal carbon dioxide concentrations or dust mite levels), then an occupant might choose to open windows even when the heating is on and so increase their heating consumption (as their stimulus for doing this is not that they are too warm – so turning the heating down will not improve their comfort). Therefore, no further infiltration measures are suggested for this building, particularly as the "passive house" ideal, where airtight houses use mechanical ventilation (with heat recovery) to maintain internal comfort, is unlikely to be suitable as a retrofit approach for this building.

After reducing the thermal demand through the above measures, the gas boiler can be upgraded to a modern condensing boiler at an efficiency of 88%[18] – higher efficiencies are sometimes quoted (from the same reference) but are at odds with empirical evidence[19].

With all demand-side measures applied, the remaining measures are optional supply-side measures – they are specified with the knowledge that some installations in buildings of this type will have difficulty getting planning permission. However, for such technologies, it is interesting to investigate whether pushing for planning permission is actually worth it for buildings of this type. Solar thermal panels are sized on 50% of the hot water requirement (total domestic hot water requirement, prior to solar thermal, is assumed to be 1951kWh/yr[6] with a baseline energy usage of 2501kWh/yr to satisfy this). This would equate to a 2.4m^2 system producing 830kWh per year. It is suggested that aiming to meet more than 50% of the load will simply result in a system that has a surplus of hot water in the summer and will still not be contributing significantly during the winter (due to poor solar resource). The output of solar thermal panels can vary considerably (with occupancy and domestic hot water schedule as well solar resource) but would typically be in the region of 300-400kWh per m^2 of panel. The remaining hot water requirement will be supplied by the gas boiler.

For onsite electrical generation, a 1kW solar PV system (which, at 8m^2, would be a very large system for this particular building) and a 1.5kW micro-wind turbine are specified (again, with an uncertainty that all these systems would be given planning approval). Based on independent Tarbase models, the solar PV panels could produce 830kWh (for an Edinburgh climate) whereas the wind turbine could be as low as 390kWh. This is based on 10-minutely wind-speed datasets, for an entire year, recorded at Heriot-Watt University and then extrapolated for the estimated hub height if installed on top of the flat in question. The quoted figure is for wind-speeds deigned to be similar to urban conditions (with an average of 2.2m/s), where sheltering from neighbouring buildings would be common. Applying a different wind speed dataset, representing a more rural, unsheltered location with an average speed of 5.5m/s. produces an output of over 3000kWh. This highlights the large variations in building-integrated wind turbines, discussed in more detail elsewhere[20].

Taking these measures and applying them cumulatively to the building produces Figure 13. A total CO_2 saving of 24% (or 1.5tCO_2/yr) is estimated prior to any onsite generation measures. Adding the effect of solar thermal, PV and wind (combined) increases the savings to nearly 40% (or 2.4tCO_2/yr), albeit with optimistic assumptions as to the available roof space on the building. It is suggested that, in reality, the solar thermal installation would be the final measure applied (producing a 28% saving, or 1.7tCO_2/yr). More detail is given in the Appendix, summarising the effect of each refurbishment step on the energy categories.

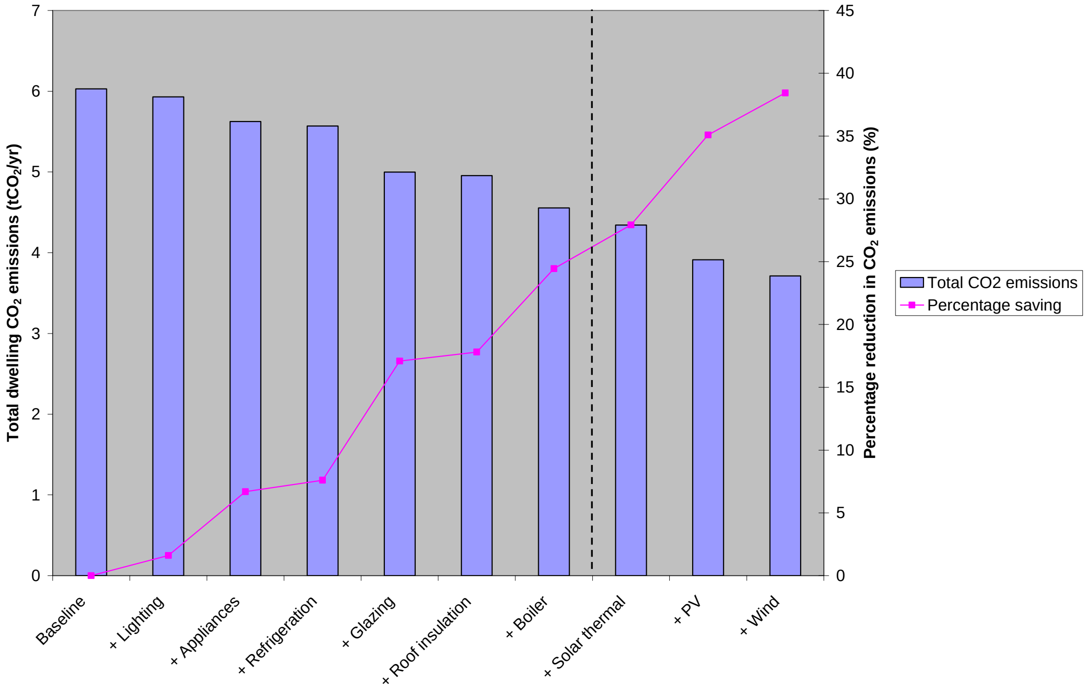

Figure 13 – Carbon dioxide savings of chosen interventions in variant 1 (applied cumulatively)

4.2 Cottage

Table 20 gives a summary of the chosen carbon-saving refurbishments for the cottage. The modelling approach, and the sources of information used, is similar to that of variant 1. For appliances, there is slightly less scope for savings as the level of consumer electronics is already relatively low. However, an appliance electrical consumption saving of 19% is achieved through these measures, with refrigeration also reduced by 40%.

Due to the poor efficiency of the existing incandescent lighting, introducing low energy bulbs has more of an impact than for variant 1. Total lighting energy consumption is reduced by 76%.

The building has a number of single-glazed windows, particularly on the eastern façade. This can be improved with secondary glazing, and draughtproofing can be provided to all window frames. As with variant 1, this reduces the infiltration rate by a similar level.

Table 20 – Summary of carbon-saving interventions for variant 2

Area of improvement	Description of refurbishment	Effect of changes
Appliances	Series of Tarbase informed improvements to appliances throughout building	Reduces appliance consumption by 19% (internal heat gains similarly reduced)
Refrigeration	Refrigeration with improved insulation (using vacuum insulated panels) and free piston stirling cooler	Reduces refrigeration energy consumption by 40%
Lighting	All lighting changed to CFL (assumed efficacy 55lm/W)	Total lighting energy consumption reduced by 76%
Glazing	Seconday glazing installed to existing single-glazed windows and draughtproofing measures for all windows	U-value improved from 5.1 to 2.3W/m^{2}K where relevant and 16% reduction in infiltration rate
Roof insulation	Insulation added to surfaces of "room-in-roof" - 12mm to pitched sections, 200mm to other sections. 40mm added to flat roof extension	Average U-value (across all roof areas) improved from 2.1 to 0.76W/m^{2}K
External wall insulation	External insulation of expanded polystyrene with render (40mm with R value of 1.5m^{2}K/W)	Average wall U-value improved to 0.45W/m^{2}K
Boiler	Improved oil boiler efficiency	Average efficiency improved from 78% to 88%
Other heating options	Ground source heat-pump (with underfloor heating) sized to meet 60% of peak space heating requirement (typically meeting 90% of the annual space heating energy consumption). Electical back-up auxiliary system meets remaining requirement.	For meeting space heating, assumed average system COP of 4.4 (with output temperature of 35°C). For hot water, auxiliary system meets 50% of energy consumption (required to reach suitable output temperature of 60°C)
	Biomass boiler using local wood log/wood chip fuel at average efficiency of 88%	Fuel carbon intensity of 0.025kgCO$_2$/kWh (see comments)

Again, care should be taken with infiltration levels, particularly with solid wall dwellings. For this reason, a slightly conservative approach is taken for the roof insulation measures, though large savings can still be made. The room in the loft consists of interior walls, an interior ceiling and sloped sections that correspond to the pitched roof (all these surfaces are assumed to be part of the roof for purposes of the heat loss calculations). While some guides would suggest aiming for a U-value target of 0.16W/m^{2}K for a pitched roof[13], this would require a substantial thickness of insulation material. Installed internally (i.e. within the room), this would have implications for the available space in the loft room. Alternatively, insulation could be installed within the remaining loft space for some areas (i.e. between the room and the pitched roof). Mineral wool or sheep's wool, at 200mm, is therefore suggested for the vertical and horizontal surfaces of the room (with a new U-value of 0.2W/m^{2}K but an *effective* U-value of 0.18W/m^{2}K when accounting for the unheated space between the insulation and the external roof), where it has been assumed there will be enough room for doing so in these areas. For the pitched area/sloped ceiling section there might be two options, depending on the available space in the rafters. For buildings of this construction, it is sometimes possible to insulate between the rafters. If this isn't possible, insulation can be applied to the inside of the existing ceiling. The former option would have the advantage of not reducing the actual living space in an attic room, though it would be necessary to maintain ventilation through the eaves to prevent condensation and damp problems. Therefore, only 12mm of insulation has been suggested (see Figure 14), which is reasoned to be a suitable compromise between space restrictions, ventilation allowance and thermal performance (whether this would be applied in the rafters or internally to the ceiling will not affect this modelling exercise but might be an important installation issue in practice). This improves the U-value of the pitched surfaces to 1.5W/m^{2}K, not including the small rooflight. With regards to the rooflight it is suggested that, other than simple draughtproofing, it could be left unchanged as it currently illuminates the stairwell region adequately during the day and, due to its relatively small size, it is probably not worth replacing with a double-glazed system. The flat roof on the extension part of the building will also have some restrictions in terms of available space. It is estimated that 40mm of insulation would be appropriate, improving the U-value to 0.7W/m^{2}K.

All the roof insulation measures would need to be clarified with an installer whom is familiar with solid wall dwelling refurbishments. Over-insulating (or the use of incorrect materials) and high air-tightness levels can have serious long-term implications for solid wall buildings. While choosing materials, such as sheep's wool, that do not retain moisture to the same degree and correct use of vapour control layers can be effective[21], aiming to meet best practice benchmarks for retrofit U-values might not be advisable, hence the more conservative targets suggested here.

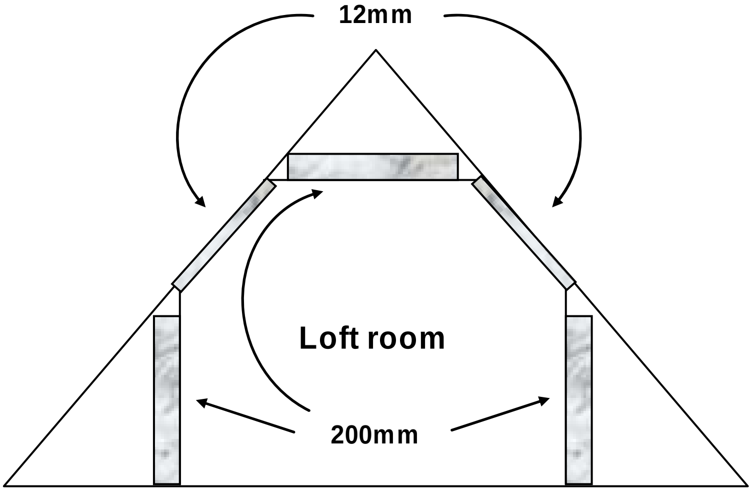

Figure 14 – Proposed insulation for loft of variant 2

Similar issues exist when estimating retrofit wall options. While the cottage building does not have listed status (and so has been selected as a possible candidate for external wall insulation), there is a physical restriction in that the overhang of the pitched roof (evident from Figure 5) will act as an effective limit for any insulation and render solution applied to the external façade. The external insulation refurbishment, consisting of wall lining, stud and polystyrene/concrete render, is chosen with this issue in mind. Even this relatively thin external wall insulation measure might be difficult to install in this property, particularly when also accounting for moisture retention and aesthetic barriers to this measure. For some buildings, if cornices and other internal features are not evident, it might be appropriate to install internal wall insulation. This will still carry with it user-acceptance concerns, although for this measure the problem might be restriction of internal space along with invasiveness of installation. However, if carbon savings are a priority and the building is not subject to A or B-listed restrictions, external wall insulation can be a highly effective strategy for reducing space heating. With the chosen material improving the average wall U-value to 0.45W/m^{2}K, this measure, along with roof insulation, is likely to have a high impact on energy savings.

Subsequent to these demand-saving measures, three options are suggested for satisfying the thermal demand of the dwelling. The most conservative, but perhaps with the highest chance of success, is to replace the oil boiler with a modern, condensing alternative (with an average efficiency of 88%).

The first alternative to this would be to install a ground-source heat pump (GSHP). There is considerable land available around the cottage (suitable for installation of a horizontal or “slinky” ground loop system) but also the floor of the dwelling is partly raised, allowing for the consideration of underfloor heating. With such a distribution system, the output temperature of the heat pump, for space heating, need only be 35°C as opposed to 55°C for more conventional radiator systems. This improves the Coefficient of Performance (COP) of the GSHP quite considerably, as modelled by previous Tarbase work. The aforementioned model suggests average system COPs of up to 4.4, providing the GSHP is sized correctly and uses underfloor heating with a required output temperature of 35°C. It should typically be sized to meet 60% of the peak heating requirement, which will usually cover in the region of 90% of the total space heating energy requirement. An electrical back-up auxiliary system should be used to meet any shortfall (and this is accounted for in the calculations of this study). The GSHP can also contribute towards domestic hot water, but will typically not be designed to meet the output temperature of 60°C required to prevent Legionella. Therefore, it is assumed that only 50% of the domestic hot water demand is met by the GSHP, with the other 50% met by the electrical auxiliary heater (which will guarantee suitable output temperatures). From conclusions of the Tarbase study, it is recommended that GSHPs should not be retrofitted without underfloor heating if the existing building already uses a gas or oil boiler. The drop in COP for a GSHP using conventional radiator distribution systems can result in any carbon saving (when compared to modern gas or oil boilers) being quite small or even non-existent (although there is still an argument for installing such systems if they are replacing existing electrical space heating).

The other alternative heating option is to use a biomass boiler for space heating and hot water. Despite this technology often being suggested as an “easy win” approach to reducing the carbon emissions of dwellings, there are several caveats that should be considered. Firstly, and looking at the wider problem, there is an issue with specifying biomass and bioenergy solutions across all sectors (i.e. for domestic, commercial, industrial and transport applications). There are vast energy demands in these sectors that cannot all be satisfied with home-grown biomass (even with an optimistic assumption for available land for bio-crops[22]) – continually promoting the use of biomass for all these sectors will increase the size of this market and therefore increase the risk of imported biomass being used in the UK, which will have a much higher embodied carbon associated with it. A more sensible approach would be to define a type of building, or area of the country, where a supply of biomass could be feasible in a low-carbon and sustainable way. A cottage in a rural location, with substantial forestry surrounding it, might be a scenario where biomass is indeed feasible. While the position of the cottage, within a clearing in a wooded area, would be difficult to reach for a wood pellet provider, the reduced thermal demand of the building could be met by wood chips or logs in the vicinity of the building. The standard biomass carbon intensity of 0.025kgCO_2/kWh[4] has been used to calculate the carbon emissions of such a boiler. This carbon intensity is only appropriate if the supply of wood is indeed from a local and sustainable source.

Finally, no solar or wind-related onsite generation technologies were deemed feasible. The cottage is sheltered by surrounding trees, making the wind resource potentially quite poor, despite it being a rural location. Also, in addition to the shading from the trees, the pitched roof slopes to the East and West, making solar thermal and solar photovoltaic less appropriate.

Processing all these interventions produces Figure 15 for all the identified carbon savings measures. With the measures again applied cumulatively, a 46% CO_2 saving is estimated for the first boiler measure (i.e. using a new oil boiler). The main contributions to this figure come from roof insulation and external wall insulation. This emphasises the importance of installing these insulation measures correctly. The alternative heating options, with their associated caveats, are included separately and should only be installed if certain conditions are met (in particular the appropriateness of underfloor heating, for the GSHP, and definition of biomass resource for the biomass boiler). The GSHP option, including all other measures prior to its installation, is predicted to save 66% of the baseline CO_2 emissions, whereas the biomass option reaches an 81% saving. The latter is simply a consequence of the fuel type having, officially, a very low carbon intensity. It would be incorrect to assume that the latter two heating options could apply to the majority of the housing stock, and the modelling results presented here should not be used to advance this idea. However, for a specific scenario, these indicative carbon savings might be reached if a suitable feasibility study is first carried out for that building.

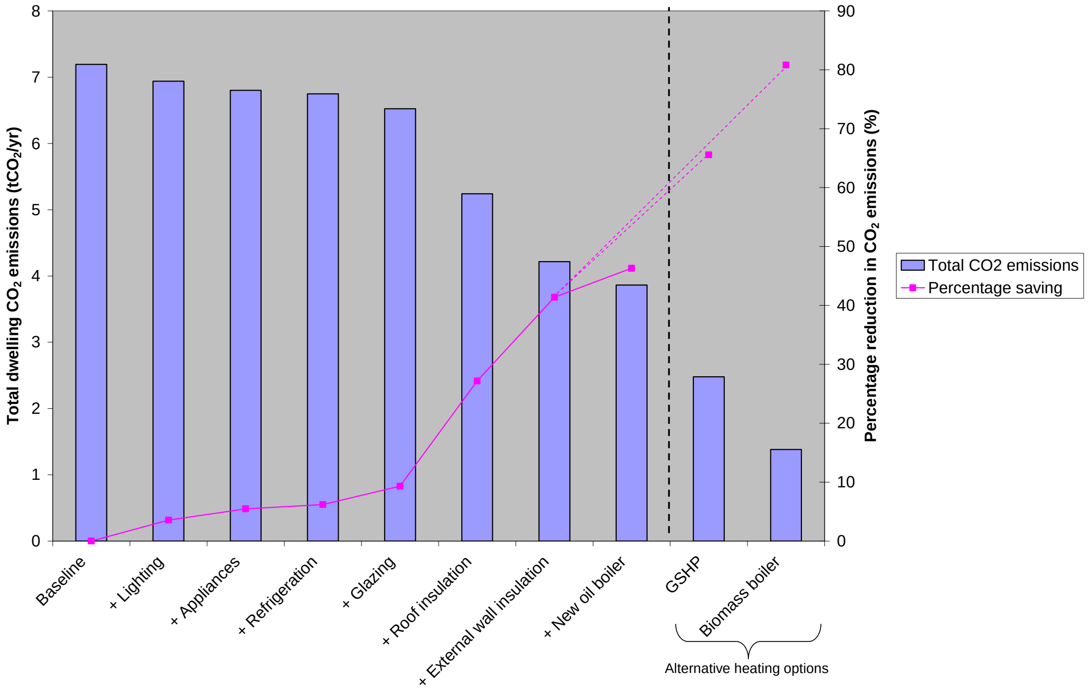

Figure 15 – Carbon dioxide savings of chosen interventions in variant 2 (applied cumulatively)

4.3 Detached house

The chosen refurbishment strategies, as processed by the Tarbase model, are listed in Table 21. The savings through energy efficient appliances and refrigeration are significant, especially as the baseline appliance energy consumption is so large. Likewise, with a poor lighting baseline (with significant use of incandescent lighting), large savings can be made from improving the lighting technology in the dwelling.

It has been assumed that double-glazing would be achievable for this building, in the same way that many C-listed Edinburgh tenement flats have had this measure installed. A glazing unit has been selected that, for air-filled glazing, would correspond to the most energy efficient products on the market (the U-value of $2.0W/m^2K$ includes the frame). This is achieved through a low emissivity coating. This will also have the slightly detrimental effect of reducing solar gain (some of which will contribute to the heating requirement), with the glazing solar transmission reduced by a calculated 15%. This does reduce the chances of overheating, but such a building in this part of the UK will have a relatively low overheating risk, especially after reducing the internal heat gain from appliances and lighting.

Roof insulation dramatically improves the roof U-value to 0.15W/m^{2}K, with the loft being large enough that installation and ventilation problems should be less of a factor than with, for example, variant 2 [NB – the loft was not accessible during the site visit so if existing roof insulation was present then this measure would clearly have less of a saving]. This reduced heating load is then met by a condensing boiler, as with variant 1.

External insulation was initially considered for the house, with such a C-listed building not having the restrictions of an A or B listed dwelling. However, there is already an existing render on the building as well as several architectural features (such as the soffit, window frames, drainpipes etc) that would make further rendering, with external insulation, quite difficult to achieve. There is also the issue of user-acceptance of such a measure on a building of this type and size. Therefore the results do not include this measure, although an indicative saving can be estimated from the same measure with variant 2.

Additional draughtproofing, other than around the window, has again been ignored due to the other changes being made to the fabric, and concerns over whether such changes would be detrimental to the internal environment of the house and the construction itself. This is discussed further in the conclusions.

Table 21 – Summary of carbon-saving interventions for variant 3

Area of improvement	Description of refurbishment	Effect of changes
Appliances	Series of Tarbase informed improvements to appliances throughout building	Reduces appliance consumption by 25% (internal heat gains similarly reduced)
Refrigeration	Refrigeration with improved insulation (using vacuum insulated panels) and free piston stirling cooler	Reduces refrigeration energy consumption by 40%
Lighting	All lighting, other than kitchen, changed to CFL (assumed efficacy 55lm/W)	Total lighting energy consumption reduced by 71%
Glazing	Double glazing (low emissivity, $\varepsilon = 0.05$) replacing single glazing	U-value improved from 5.1 to 2.0W/m^{2}K and 16% reduction in infiltration rate
Roof insulation	Mineral wool added at 250mm thickness	U-value improved from 2.3 to 0.15W/m^{2}K
Boiler	Replace boiler with gas condensing model (also accounts for change in thermal demand due to above measures)	Average efficiency improved from 78% to 88%
Solar thermal	Installation of 3m^2 system sized to meet 50% of hot water demand	Annual delivery of 1190kWh
Solar photovoltaic	Installation of 1kW (8m^2) system, 14% rated efficiency, 30deg inclination (south facing)	Annual output of 830kWh
Micro-wind	Installation of 1.5kW system with 2.0m/s average wind resource at 10m altitude	Annual output of 277kWh*

*for a higher, rural wind resource (of 4.9m/s average) at 10m altitude, output would reach 2541kWh based on collected wind speed data at Heriot-Watt University campus.

The detached house, of the three variants, was probably the most viable candidate for onsite renewable technologies. It was a stand-alone building and so did not have excessive solar shading (though trees were present on the East side) and the pitch of the roof was sloped towards the south, hence maximising the solar resource. The house was near the coast and the village itself on a hill. This would suggest that the wind resource might be significant. However, there were surrounding structures that, although not affecting the solar resource, would act as a wind break to the wind coming from the coast. It is therefore, as with all dwellings, difficult to estimate the potential success of a roof-top wind turbine. A reasonably conservative estimate has been given in Table 21, with a note suggesting a much more optimistic value for an ideal site.

Quantifying all these measures produces Figure 16. All the measures, prior to onsite generation, produce a total carbon dioxide saving of 40%, or 3.2 tonnes of CO_2. This comparatively large saving is mostly due to the effect of insulating a roof that was previously without any insulation. The introduction of high-performance double glazing is also significant, with these two measures producing a 26% saving on their own (although this is only an approximation as, when performing cumulative measures, the order that the measures are carried out can affect their carbon saving potential).

When onsite generation measures are added, namely solar thermal, a 1kW PV system and a 1.5kW wind turbine, the total carbon dioxide savings are increased to 50%, or 4.0 tonnes of CO_2. This has been achieved without any dramatic change to the building façade, other than the visibly different glazing (and the onsite generation technologies).

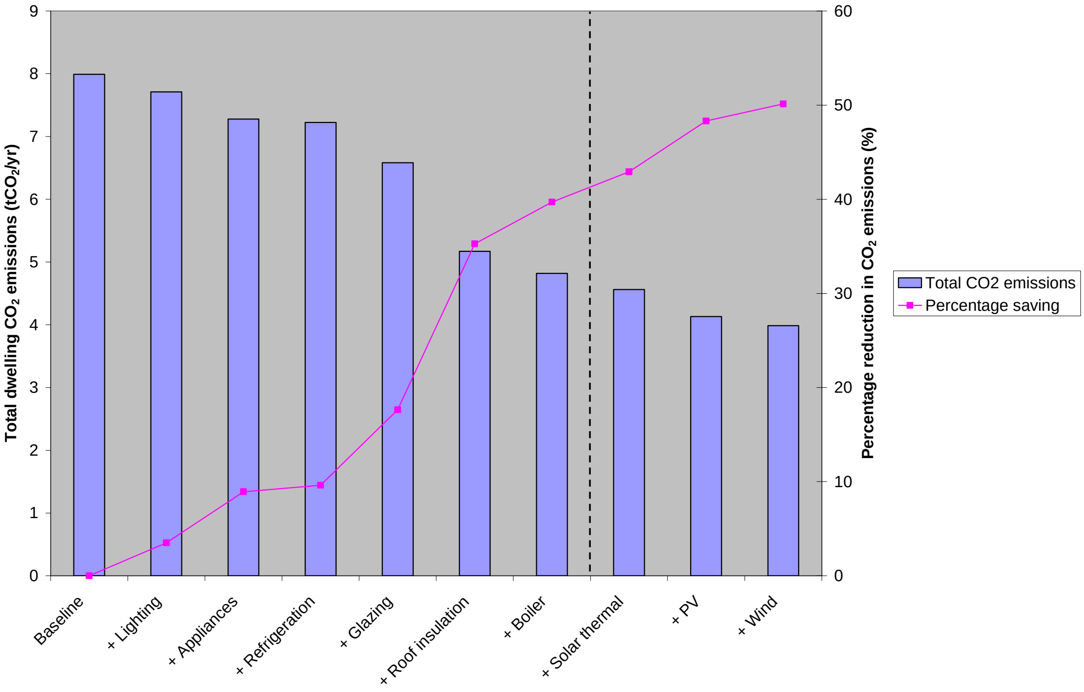

Figure 16 – Carbon dioxide savings of chosen interventions in variant 3 (applied cumulatively)

5. Conclusions

The energy use of three dwellings, believed to be indicative of the traditional Scottish housing stock, were analysed using a series of models developed by the Tarbase project at Heriot-Watt University. The results suggest that, though such buildings are sometimes defined as “hard-to-treat”, they are by no means impossible to treat. Through the identification of baseline energy use of the buildings, appropriate carbon-saving refurbishments were identified for each building variant. Table 22 summarises the savings across the three buildings.

Table 22 – Summary of CO_2 savings for the three building variants

		Total CO_2 emissions (tCO_2/yr)			
	Description	Baseline	With demand reduction measures	Demand reduction and solar thermal	With all onsite generation measures
Variant 1	Terraced flat	6.0	4.6	4.3	3.6
Variant 2	Rural cottage	7.2	$3.9^1/2.5^2/1.4^3$	n/a	n/a
Variant 3	Detached villa	8	4.8	4.6	4

[1] Using an oil condensing boiler
[2] Using a ground-source heat pump
[3] Using a biomass boiler

The results indicate that a “broad brush” approach is not completely appropriate for dealing with these buildings, or indeed the housing stock at large. However, there are general points of importance that are likely to be relevant to large proportions of the traditional Scottish housing stock. Firstly, heat loss through walls and roofs will commonly be the main contributors to the carbon emissions of the building. Reducing this heat loss must be dealt with in a sensitive way, accounting for aesthetics (particularly if the building is of listed status) but also long-term effects of changing insulation and infiltration levels. The moisture content, and how this moisture is retained by the building fabric, can be quite different in a solid wall dwelling than for a more modern building. The results of this study would suggest that, even if using more conservative refurbishment U-value targets, substantial carbon savings are still possible.

Other issues such as lighting and appliances are likely to be as varied with the traditional building stock as they are with the stock at large. Lighting improvements should be straightforward for most buildings. In addition, the reduction in heat generation (by exchanging incandescent and halogen lights for compact fluorescent technologies) could be advantageous for traditional buildings, where the production of heat and moisture at ceiling level could cause problems in the loft area. Appliances and equipment changes would be more difficult to apply as this involves a diverse range of technologies (e.g. cooking appliances, refrigeration and consumer electronics), most of which would be outside the remit of building regulations to enforce. This emphasises the need for consensus of legislation across a range of areas.

In terms of building-specific conclusions, the terraced flat variant showed the smallest savings with the existing building already having roof insulation and also other building fabric improvements being slightly restricted (due to the building being listed but also having adjoining surfaces to other properties). Despite these restrictions, substantial savings were still predicted ranging from 23% (with demand-side measures only) to 40% (with all supply-side measures installed). There is a modelling issue that should be addressed for such buildings – for a terraced building, how should the heat loss to neighbouring areas (both occupied and unoccupied) be accounted for? It is suggested that a modelling exercise using a dynamic simulation model could perform a role in this regard (where varying heat loss parameters over time can be accounted for – this is also the case for modelling heat transfer in loft spaces). Steady-state models, by definition, will generally struggle to quantify such effects accurately. Furthermore, when carrying out refurbishments to such a dwelling, the effect on neighbouring properties will clearly be of concern. This is true for any change to the building fabric but also for onsite generation solutions. The property in question was actually part of a housing co-operative and so less prone to such problems, but more generally, barriers might be imagined that would restrict the type of refurbishments available.

The cottage variant had a relatively poor carbon emission baseline due, in part, to being off the gas grid and using an oil boiler (which is a more carbon intensive heating fuel than gas) but also due the building construction. Therefore, demand-side measures had a large impact on the carbon emissions of the building, with a saving of 46% initially predicted (which included upgrading the boiler to an oil condensing model). Although the building was deemed unsuitable for onsite generation (i.e. solar thermal, solar PV and wind), the use of ground-source heat pumps or a biomass boiler could, in theory, push the savings to 66% and 81% respectively. As discussed, these latter figures should be approached with some caution and are subject to a number of externalities. Other than this, the main area of concern was over whether such a dramatic change in the building fabric would have detrimental side effects to the internal environment and the building itself. Quality of installation, using appropriately trained installers, would be a prime factor in realising the proposed carbon savings. So, while the building might have limitations relating to maintaining the aesthetic appeal of a rural cottage, its location actually provides opportunities for carbon saving that would not be applicable to a building in an urban, densely populated region.

Finally, the detached house had the highest electrical demand of the three variants. This presents a hurdle to reducing carbon emissions in that a diverse range of electrical appliances/equipment would need to be improved or replaced. Unless a dramatic change in lifestyle and/or technology is implemented, it is difficult to achieve very large reductions in electrical demand. However, the baseline lighting technology was sub-optimal and the roof was assumed to be without insulation so the potential for carbon savings in these areas was large. As a result, demand-side measures are predicted to achieve total carbon dioxide savings of 40%, which is increased to 50% with onsite generation measures. Like the cottage variant, the fact that the building is not situated in a densely populated area would suggest that fewer barriers would exist to the implementation of the described measures, although attaining planning permission for onsite generation is always likely to be time-consuming.

An issue was raised regarding the appropriate level of draughtproofing that is suitable when conducting large-scale building refurbishments. While all buildings underwent draughtproofing around the window frames, the model suggested that further draughtproofing would results in an internal air change that was too low, as suggested by aforementioned studies[16,17]. This is not the same as recommending that draughtproofing should not be applied to traditional buildings, merely that when carrying out several different fabric refurbishments, including glazing upgrades, the *combined* effect of this with additional draughtproofing could make the internal environment of a solid wall dwelling unhealthy to live in. A further caveat to this statement would be that none of the three building variants underwent air-tightness testing, with domestic air-change rates being extremely variable. If a building has a very high air change rate, due to infiltration, then it is more likely to be a suitable candidate for large-scale infiltration measures. Taking the “PassivHaus” route, a building can be made extremely air-tight providing it has mechanical ventilation (ideally with heat recovery) to maintain suitable air quality. This is, however, difficult to achieve retrospectively, both in terms of the air-tightness level and retrofitting a mechanical ventilation system.

In summary, while it is difficult to identify a generic hierarchy of interventions for all traditional dwellings in Scotland, a few general rules-of-thumb have been identified that should allow for an informed selection of technologies and measures to reduce the carbon dioxide emissions of such dwellings. The measures with high probability of user-acceptance, such as improving lighting and some appliance measures, should usually be carried out first, followed by basic insulation measures such as roof insulation. Subsequent technology-replacing measures, such as more advanced appliance options (e.g. improving refrigeration) and boiler upgrades, will have an increased capital cost but can still be effective carbon-saving options. Larger-scale changes to the building fabric, such as external rendering and new glazing, become conditional to the house in question (e.g. listed status of building and user acceptance of occupants) and expensive but can produce very significant carbon savings. Onsite generation technologies provide supplementary, though modest, carbon savings but are unlikely to be cost-effective. It is suggested that time and resources would be better spent towards ensuring that regulations for traditional buildings allow for the installation of other carbon saving technologies, such as those relating to building fabric and internal appliances.

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Appendix – Summary of building refurbishments

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Building variant 1—Terraced flat

Internal dimensions

Width: 9.5m

Length: 14m

Height: 5.5m

Total floor area: 110m^2

Age: 1820s construction

Description

Single storey, top floor flat with two working adults, one child occupying.

Construction

Wall (craigleith sandstone) and roof (recently insulated loft) U-values of 1.5W/m^{2}K and 0.18W/m^{2}K respectively. Single-glazed sash windows with U-value of 5.1W/m^{2}K. Infiltration rate of 0.575ach

Heating/hot water

16kW gas combi boiler, assumed efficiency of 78%

Carbon-saving interventions

- **Appliances/equipment**

⇒ General improvement in equipment energy efficiency (as suggested by the Tarbase project)

- **Fabric**

⇒ Secondary glazing added to existing sash windows (new U-value of 2.3W/m^{2}K) and fitted with draughtproofing measures

⇒ Existing mineral wool in loft increased from 200mm to 250mm and rooflight removed (U-value improved to 0.15W/m^{2}K)

- **Heating/hot water**

⇒ Condensing boiler replaces non-condensing boiler

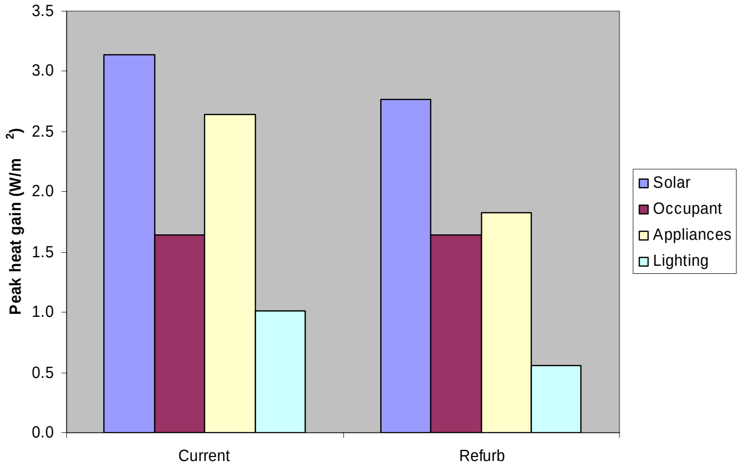
⇒ Solar thermal panel meeting 50% of annual hot water requirement

- **Onsite electricity**

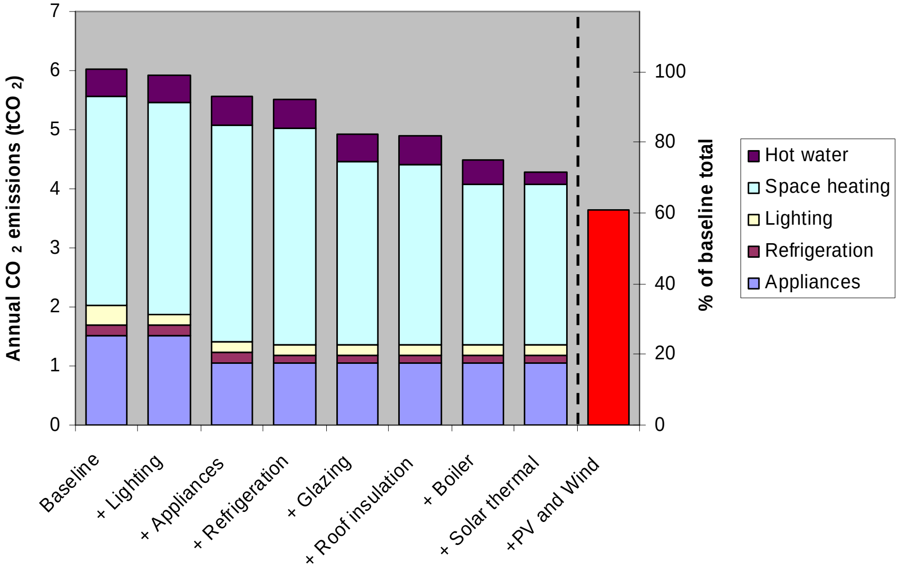
⇒ 1kW mono-crystalline solar photovoltaic system

⇒ 1.5kW rated micro-wind turbine (with assumed urban wind resource)

Change in heat gains due to all measures (for heating season)



Effect of CO$_2$ saving measures



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Building variant 2—Cottage

Internal dimensions

Width: 4.5m

Length: 9.7m

Height: 5m (inc. loft room)/2.5m (extension)

Total floor area: 75m^2

Age: 1870 construction with c1950 extension

Description

Two storey cottage (with loft conversion and kitchen extension), with two retired adults occupying.

Construction

Average wall (sandstone), floor (suspended) and roof (pitched loft conversion) U-values of 1.4W/m^{2}K, 1.2W/m^{2}K and 2.1W/m^{2}K respectively. Single-glazed sash windows with U-value of 5.1W/m^{2}K with some recently converted to double-glazed uPVC (2.75W/m^{2}K. Infiltration rate of 1.18ach.

Heating/hot water

16kW oil combi boiler, assumed efficiency of 78%

Carbon-saving interventions

- **Appliances/equipment**

⇒ General improvement in equipment energy efficiency (as suggested by the Tarbase project)

- **Fabric**

⇒ Secondary glazing added to existing sash windows (new U-value of 2.3W/m^{2}K) and all windows fitted with draughtproofing measures

⇒ Various insulation measures to loft conversion and flat roof producing average U-value of 0.76W/m^{2}K

⇒ External wall cladding of 40mm polystyrene with render (R-value of 1.5m^{2}K/W) producing average U-value of 0.45W/m^{2}K

- **Heating/hot water (three options)**

⇒ Condensing boiler replaces non-condensing boiler (oil)

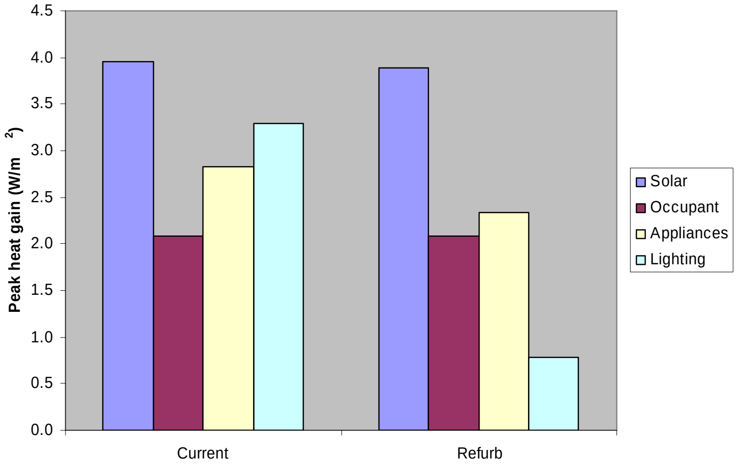
⇒ Ground-source heat pump sized to meet 60% of peak space heating demand with electric auxiliary

⇒ Biomass boiler with locally-sourced fuel

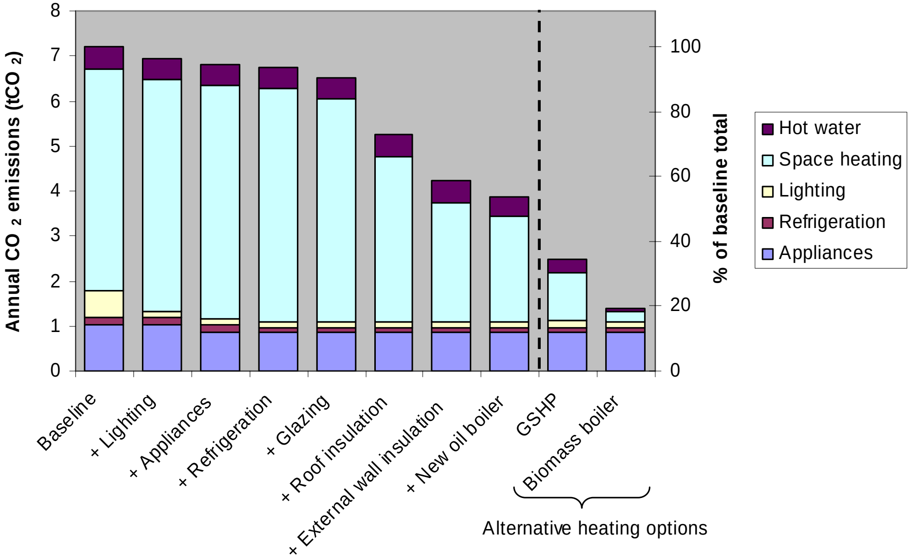
- **Onsite generation**

⇒ Wind/solar resource deemed insufficient to justify solar thermal/PV or onsite wind.

Change in heat gains due to all measures (for heating season)



Effect of CO$_2$ saving measures



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Building variant 3—Detached House

Internal dimensions

Width: 10.1m

Length: 6.9m

Height: 5m (to soffit)

Total floor area: 98m^2

Age: late 19th century with modern render applied

Description

Detached two-storey house in coastal village occupied by two adults and two children

Construction

Average wall (sandstone), floor (solid) and roof (pitched slate roof) U-values of 1.3W/m^{2}K, 1.2W/m^{2}K and 2.3W/m^{2}K respectively. Single-glazed sash windows with U-value of 5.1W/m^{2}K. Infiltration rate of 1.08ach.

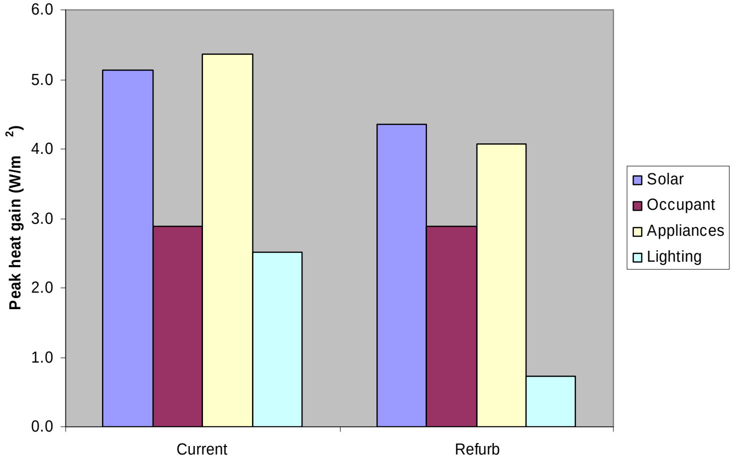
Heating/hot water

23kW gas combi boiler, assumed efficiency of 78%

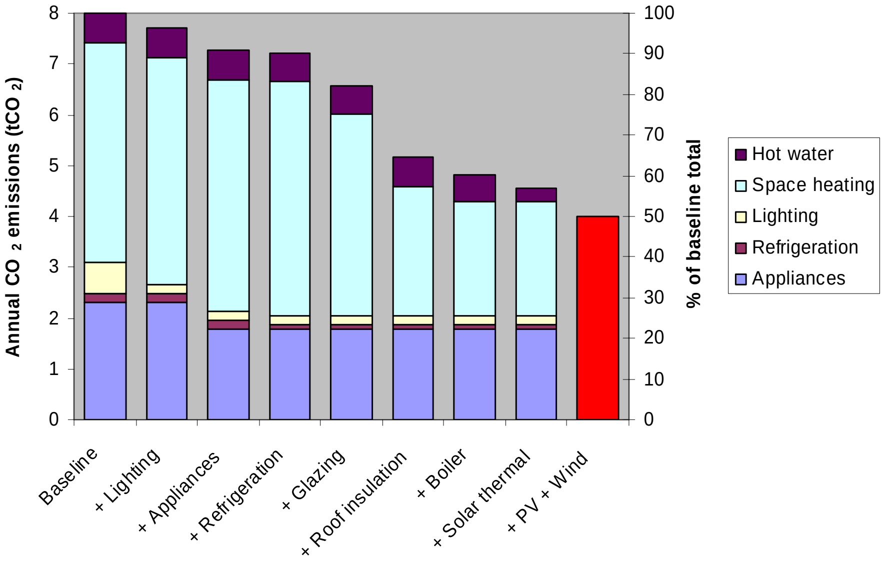
Carbon-saving interventions

- **Appliances/equipment**
  - ⇒ General improvement in equipment energy efficiency (as suggested by the Tarbase project)
- **Fabric**
  - ⇒ High-specification double- glazing with low emissivity coating (ε = 0.05) (new U-value of 2.0W/m^{2}K) replacing all existing windows and fitted with draughtproofing measures
  - ⇒ 250mm of mineral wool/sheep's wool added to loft (reaching U-value of 0.15W/m^{2}K)
- **Heating/hot water**
  - ⇒ Condensing boiler replaces non-condensing boiler
  - ⇒ Solar thermal panel meeting 50% of annual hot water requirement
- **Onsite electricity**
  - ⇒ 1kW mono-crystalline solar photovoltaic system
  - ⇒ 1.5kW rated micro-wind turbine

Change in heat gains due to all measures (for heating season)



Effect of CO$_2$ saving measures



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