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Lifecycle Costing of Low Energy Housing Refurbishment: A case study of a 7 year retrofit in Chester Road, London

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Abstract

The low energy retrofit of the UK existing building stock is an urgent matter after the government's commitment to reduce carbon emissions by 80% until 2050. This research addressed the question of whether it is preferable to refurbish in an extensive way or to choose a retrofit strategy with lower capital cost, embodied energy and CO₂, tackling issues of cost – effectiveness, embodied and operational energy throughout the lifecycle of an existing Victorian house in London.

The indicator Cost per Ton carbon Saved (CTS) was used, which resulted in higher values for the EnerPHit retrofit model, rendering it a less viable alternative. It was also concluded that retrofitting, in general and especially the application of EnerPHit, are an appealing option only with rising gas prices, low discount rates and long lifespans. Those results were even more amplified when climate change was taken into account, a conclusion very important for the application of future legislation and the possible transfer of this study to other climates.

It was deduced that a house's remaining lifetime is a very significant factor to be taken into account, as investments of higher capital cost give higher benefit in long term.

Keywords: Retrofit, Cost per Ton carbon Saved (CTS), EnerPHit, Lifecycle Analysis

1. Introduction

Dwellings account for 60 % of EU building energy use, 40 - 60 % of which is energy used for heating with 80% of the existing building stock proven to exist in 2050 (Thorpe, 2010). With the Climate Change Act (HMSO, 2008) low carbon retrofitting of this stock becomes a necessity for the UK, as it sets targets of 80% reduction in net carbon account emissions by 2050 and 34% by 2020 with a baseline of 1990. This policy is mainly driven by two key driving forces: climate change and energy security.

1.1 Energy consumption in UK domestic buildings

The majority of energy consumed in the domestic sector is for space heating, producing in 2009 25 % of the total CO₂ emissions (HMSO, 2011). Water heating and lighting and appliances accounted for a further 18 and 19 % respectively with cooking accounting for a further 3 % (DECC, 2012).

As resulting from the above, in the context of climate change, fossil fuel insecurity and the attribution of the second biggest percentage of energy consumption to domestic buildings it is essential to prioritize the minimization of energy in the domestic stock in the way towards an 80% reduction in CO2 emissions by 2050. With heating making up the biggest part of the consumption, increasing the insulation levels and the heating systems' efficiency in the existing building stock is expected to cause a big improvement.

1.2 Aims and hypothesis

Aim of this study is to address the topic of sustainable refurbishment of the existing building stock, by tackling the issues of cost – effectiveness, embodied and operational energy throughout the lifecycle of a residential building. This is researched by the comparison of a case study refurbishment complying with Part L1 B and a hypothetical refurbishment complying with PH standards, under the prism of Cost per Ton carbon Saved. The effect of individual measures and the optimization of insulation levels throughout the buildings' lifetime will be assessed under the same perspective.

Thus, this study will address the debate of whether it is preferable to refurbish in an extensive way (insulating as much as possible), in order to achieve the minimum operational energy or to choose a retrofit strategy with lower capital cost, embodied energy and CO2, which hypothetically will be paid back earlier.

2. Literature review

2.1 Life Cycle Costing and Low Energy Retrofit

In order to assess the optimum retrofit strategy for existing buildings, LCC was used in numerous studies, underlying the importance of considering the building as an energy system throughout its lifetime.

LCC is the total cost of a building or its parts throughout its life, including the costs of Acquisition (including pre-construction and construction), Operation, Maintenance, Replacement (or refurbishment) and Disposal (sale or demolition) (ISO, 2003). It is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value (ISO, 2003).

Retrofitting aims to the minimization of operational energy, however, focusing solely on the operation phase may bring less overall benefits due to potential trade-offs in other life cycle phases. According to a study (Feist, 1997) comparing the cumulative primary energy input over a lifetime of 80 years of six construction standards, the total production energy input for the passive house is 1391 kWh/m², with thermal insulation measures accounting for 14 % (194 kWh/m²). The study claims that thermal insulation and ventilation saved 123 kWh/(m²a) on primary energy, having, thus, less than two years payback time. In the Life-Cycle primary energy balance for the 'reference', LE, PH and self sufficient house, it is obvious that the latter is always above the passive one, while the starting points for the five first types are very close, contradicting the argument that PH has a significantly bigger initial energy input compared to standard buildings.

The 'Arbeitskreis Kostengünstige Passivhäuser, 1997' (Research Group on Cost Efficient Passive Houses) (Passipedia) concluded that the condition of the building prior refurbishment strongly determines whether an energy saving measure can be considered economical or not. It was also claimed that the implied extra investment of a PH retrofit leads to an overall gain during the lifetime of the components, with careful planning and implementation processes. Most importantly, it was inferred that the highest levels of thermal protection measures available are also the optimum ones, in terms of cost-effectiveness, based on the 'do it as good as possible' principle.

A study comparing the retrofit of a 1950 Belgian dwelling to common practice, LE and PH standard (not EnerPHit standard) concluded that, although the PH retrofit saves on 87 % on heating demand, in contrast to 63 % of the LE one, its initial cost's payback period is highly dependent on fuel price increase. With 2 % increase the PH is not paid back not even in 40 years, making LE more cost effective, while with the improbable 10 % fuel price increase, the payback time is 18.4 years (Versele A., 2008).

On the other hand, Hermelink (2009) compared an existing PH development to a fictitious LE alternative based on environmental life cycle assessment, assuming constant gas prices. He found that construction and maintenance/repair have a relatively high environmental impact, exceeding the impact of space heating. Moreover, it was

concluded that the slightly higher environmental impact of PH building stemming from construction and maintenance/repair is clearly over-compensated by its significantly lower operational energy consumption. While assessing the CO₂ emissions of the two LE building types, it was found that the LE would fail the 2050 target and the PH hardly reaches it, mainly due to the carbon intensity of electricity generation. From the cost point of view, as well, PH appears to be the most attractive solution, especially with increased gas and electricity prices.

Dodoo et al. (2010) and Gustafsson and Karlsson (1988) highlight the importance of the type of energy supply system which is substituted by the retrofit, concluding that the un insulated building with district heating has lower life cycle primary energy use than if the same building was retrofitted to the PH standard and heated electrically. Similarly to Feist (1997), a 4 year payback period of the primary energy for building construction through the operational energy savings was assessed.

The payback period of an energy retrofit is highly dependent on fuel prices and weather data and, as resulted from the WLCC study of Mohammadpourkarbasi (2013) of a refurbished Victorian house under three gas prices and three weather scenarios, such an investment is only economically attractive with the rising gas prices scenario, although the additional costs of maintenance and replacement of the base case house were not taken into account, which is expected to alter the results. Interestingly, the cumulative cash flow of the refurbished near to PH standard building shows that the payback time from heating saved will be 27 years with upward prices and may never realistically pay back if prices fall or remain constant.

It is important to stress, however, the importance of the boundary condition of each study in the validity of the results. Fuel prices, construction costs, risk rates and climatic conditions affect significantly the outcome of the cost assessment.

3. Methodology

3.1 Case Study Selection

An existing house has been selected as the case study for the investigation of the optimum retrofit of Victorian end terrace buildings. It is located at 73 Chester Road, Dartmouth Park, London.



3.1.1 The house

The case study house is a Victorian semi – detached end terrace house built before 1919. It is formed by two volumes, a three - storey one in the front, facing North West, and a two - storey extension in the rear and is currently used by its two owners (Figure 1).

The total usable floor area is approximately 167 m². The ground floor consists of the hall, two living room areas connected with each other and the kitchen in the rear extension (Figure 2). The staircase in the hall leads to the first floor's hall which distributes to a front bedroom, used as an office, a rear bedroom, an office and to the bathroom and utility space. The staircase continues to the attic floor, consisting of a guest room and a WC.

Figure 1 Front Elevation



Figure 2 Ground Floor Plan, not in scale

3.2 The retrofit

3.2.1 Building Envelope

Table 1 Refurbishment of building envelope

Element	Refurbishment description
Walls	Double brickwork 220mm Internal insulation with 100mm Diffutherm woodfibre boards ($U=0.043\text{W/m}^2\text{K}$)
	50mm insulation installed in the kitchen, the bathroom and around the fireplace
Party wall	Kitchen: partly insulated (130 cm from the junction with the external wall) Bathroom: insulated for the whole length Hall: above the height of 7m
Side wall	Re-pointed with a cement mortar with moisture resistance
Roof	100mm rockwool installed between the rafters, two layers of Diffutherm (40mm) and 22mm of Isolair ($U=0.047\text{W/m}^2\text{K}$) above)
Floors	Living room: Suspended floor retained, floor boards replaced and the old ones used in the attic. Intermediate space between the joists filled with rockwool (150 mm) and 20mm of Diffutherm added below them. Junctions with walls foamed
	Hall: tiled Victorian floor not altered
	Kitchen: solid floor insulated with 50mm XPS
	Attic floor: insulated mainly for noise proof issues with 100mm rockwool between the joists, Regupol acoustic isolating strips on joists and chipboard on top
Windows and doors	Original sash windows at the front: now argon-filled double glazing manufactured by Vogrum
	Rear living room French door: triple glazed Ecocontract ($U=0.9\text{W/m}^2\text{K}$).
	Kitchen, bathroom and attic: Rationel double ($U=2.1\text{W/m}^2\text{K}$)
	First floor windows: double glazed
	Skylights: Velux Conservation ($U=1.7\text{W/m}^2\text{K}$)
	Windows and doors: draught – sealed
	Second door added to the entrance space, creating a draught lobby

3.3 Whole Life Cycle Costing

One of the most important questions in the process of achieving 80 % reduction of CO₂ is economic feasibility. As cost is a determining factor both for individual and governmental initiatives, the importance of finding the most economical choice among alternative refurbishment levels and measures in long term is vital. In this study a LCC

technique has been used for comparative cost assessments initially over a 30 year lifespan, taking into account the present value of initial capital costs, future operational costs and savings from the two different retrofit approaches.

3.3.1 Embodied Energy Inputs

The Inventory of Carbon and Energy (Hammond and Jones, 2008) was used for the calculation of the EE and ECO₂ of the materials used for the refurbishment of the building envelope. For the calculation of the window's frames', the data were obtained from the Ökobilanzdaten im Baubereich database of the Swiss Coordination of Construction and Property Institutions (KBOB). Since those databases include only data from resource extraction to factory gate (cradle to gate) and due to the fickle nature of transport's and processes' EE it was considered that their calculation based on distances and number of vehicles used from factory to site would include many uncertainties and those were placed out of the system's boundaries. It is acknowledged, however, that this would underestimate the energy and carbon payback, although it would not induce significant differences between the two cases in comparison.

3.3.2 Operational Energy, CO₂ and Cost Inputs

Operating cost is defined as the sum of energy consumption, maintenance and repair costs (Fuller, 2010). The estimation of these costs is a significant factor, as the greatest part of the building's impact occurs after construction (University of Reading, 1985) and accounts for 78% - 96% of the total consumed energy (Gignac and Jensen, 2007). Required inputs for calculating operating costs are: energy consumption, energy cost savings, gas prices (the refurbished house is heated by gas); predicted gas price trends in the future and assumed discount rate.

Energy consumption for heating was calculated using a multi – zone thermal model produced with EDSL TAS software, having three comparison cases: pre-refurbishment, current refurbished house and EnerPHit refurbished (Table 2). The infiltration rate for the pre – refurbished state (0.53 ach @ STP) was assumed based on Johnston et al. (2011), the current state based on the blower door test results of 5.6 ach/h @ n₅₀ (0.3 ach @ STP) and reduced by one third (0.2 ach @ STP) for the EnerPHit, as the target of 1 (0.05 ach @ STP) was considered unachievable. For the simulations the London Heathrow CIBSE TRY weather file was used, causing probably some deflection from the actual weather conditions (centre of London).

Table 2 Summary of the three iterations' U values (W/m²K)

	Pre refurbishment	Current state	EnerPHit
External Wall – Front Facade	1.24	0.32	0.13
External Walls	1.24	0.5/ 0.32	0.13
Party Wall	0.73	0.73	0.21
Attic Wall	2.17	0.24	0.14
Roof	3.11	0.20	0.13

Attic Floor	2.27	0.35	0.35
Intermediate Floor	2.06	2.06	2.06
Kitchen Floor	0.96	0.32	0.15
Hall Floor	0.96	0.96	0.15
Living room Floor	0.78	0.18	0.134
Windows	4.80	0.8/ 1.7/ 2.1	0.8

The actual house consumption metering files were used for the calculation of hot water heating and electricity consumption, omitting the reduction due to solar thermal and PV panels, as this study focuses only on the evaluation of the thermal envelope measures.

Both calculated and actual energy consumptions were divided by efficiency factors¹ and multiplied by carbon factors. Cost factors were calculated according to Quarterly Energy Prices Indices 2013 (National Statistics, 2013).

3.3.3 Indicators Used

The main indicator used for the comparison between the two cases is CTS, which is derived from the following formula:

$$CTS (\text{£/tCO}_2) = \frac{\text{Lifetime Cost}}{\text{Carbon Saved}} \text{ where}$$

$$\text{Carbon Saved (tCO}_2) = \frac{(\text{OCO}_2 \text{ pre refurbishment} - \text{OCO}_2 \text{ after refurbishment}) \times \text{Lifespan} - \text{ECO}_2}{1000}$$

$$\text{Lifetime Cost (£)} = (\text{OC pre refurbishment} - \text{OC after refurbishment}) \times \text{Lifespan} - \text{IC}$$

Table 3 Indicators and Units

Indicator Abbreviation	Indicator	Unit
CTS	Cost per Ton carbon Saved	£/tCO ₂
OCO ₂	Operational CO ₂	Kg/m ² annum
ECO ₂	Embodied CO ₂	Kg/m ²
OC	Operational Cost	£/m ² annum
IC	Initial Cost	£/m ²
OE	Operational Energy	MJ/m ² annum
EE	Embodied Energy	MJ/m ²

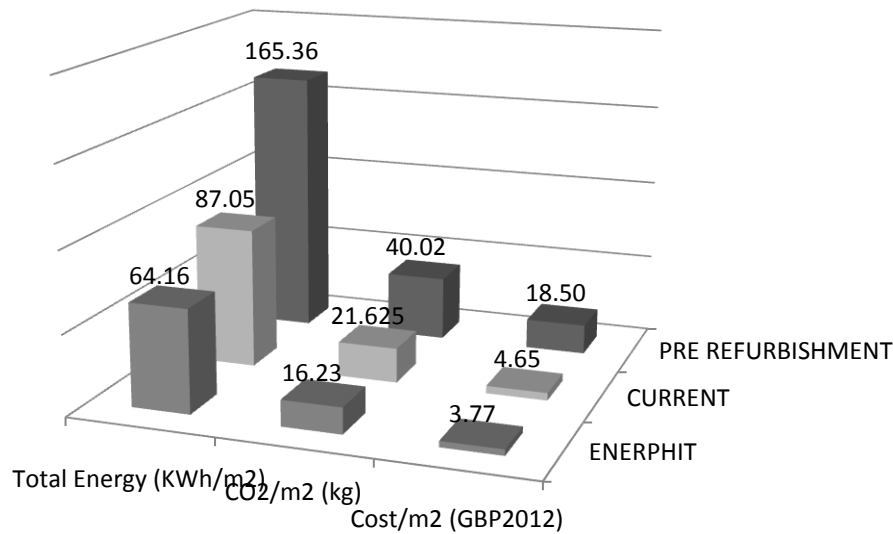
¹ Boiler efficiency for the pre-refurbishment condition was not altered, as this study is focused on the evaluation of the impact of measures concerning the thermal envelope of the building.

4. Life Cycle Analysis

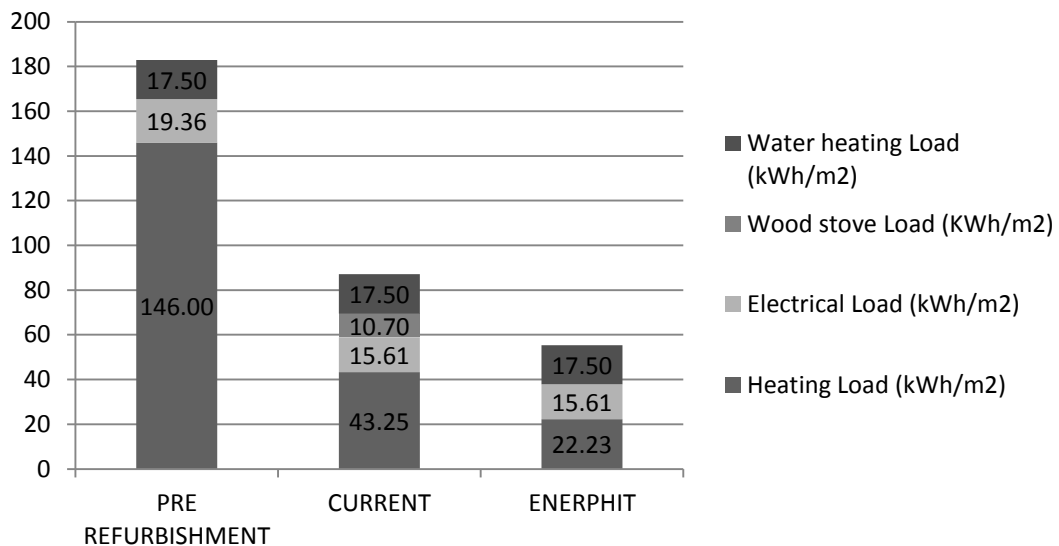
4.1 Operational Energy Use, Cost and CO2 Emissions

The operational energy use was compared between the pre-refurbishment condition, the current and the retrofitted according to EnerPHit standard. Modelling results both with and without the effect of active energy systems (PV and solar thermal) are presented, although only the latter will be analyzed (Graph 1).

Graph 1 Passive measures (thermal envelope only)



Graph 2 Energy Use Breakdown (KWh/m2a)



The current house performs significantly better than prior refurbishment, with a 47 % reduction in total energy consumption and 70 % in heating load, while the EnerPHit house would perform even better, with 61 and 85 % reduction respectively (Graph 2). By comparison, the average heating consumption for the existing UK building stock is 180 kWh/m²a, 100 kWh/m²a when renovated and 50-60 kWh/m²a

for new build (Dowson, 2012), which indicates that the current house performs significantly well. The EnerPHit house performs even better, as expected, with a heating demand below 25 kWh/m²a.

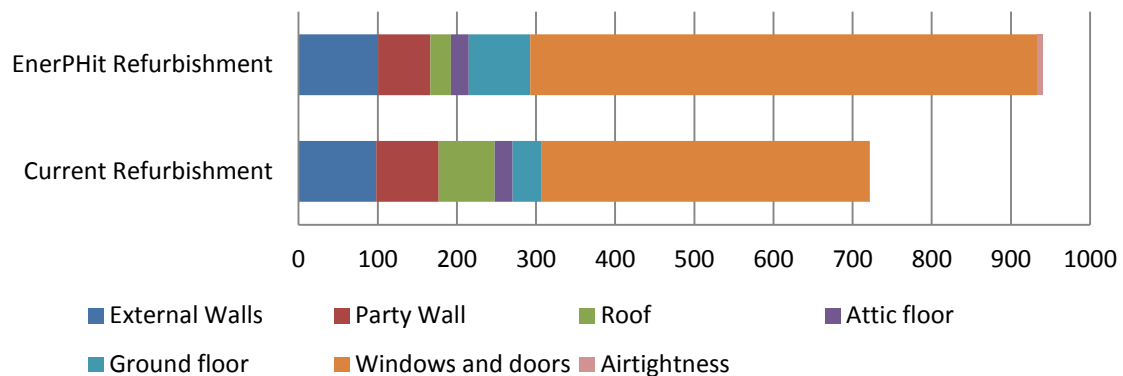
In the energy use breakdown it becomes apparent that the primary source of energy consumption is space heating in all cases. The initial un-insulated house had a very high heat space demand, due to high heat losses through the opaque and glazed areas and infiltration as well, which made the improvement of the thermal envelope imperative.

4.2 Embodied Cost, Energy and CO2 Emissions

4.2.1 Cost

As far as costs are concerned², the PH retrofit cost accounts for 130% more than the current one. Graph 3 shows that in both cases the most expensive intervention is the replacement of windows. Interestingly, the current roof refurbishment cost is 2.7 times higher than the EnerPHit, which is attributed to the big price difference between Diffutherm 80mm (£31.3/m²) and Mineral Wool 80 mm (£3/m²). The same applies in the case of external walls, where the same thickness of Woodfibre board costs more than 2.5 times higher than XPS. Thus, the extra costs for increased rafter depth and scaffolding imposed by external wall insulation is almost equalized to the current retrofit's costs. As expected, the 100 % triple glazed windows of the EnerPHit house increase the budget by 156 % compared to the current case. Finally, with regards to air - tightness, for the current refurbishment there is no extra cost recorded, whereas for the decrease from 0.3 to 0.2 ach in the EnerPHit case an extra cost of £1200 was assumed (Johnston et al., 2011).

Graph 3 Total Costs (£/m²)



4.2.2 Embodied Energy

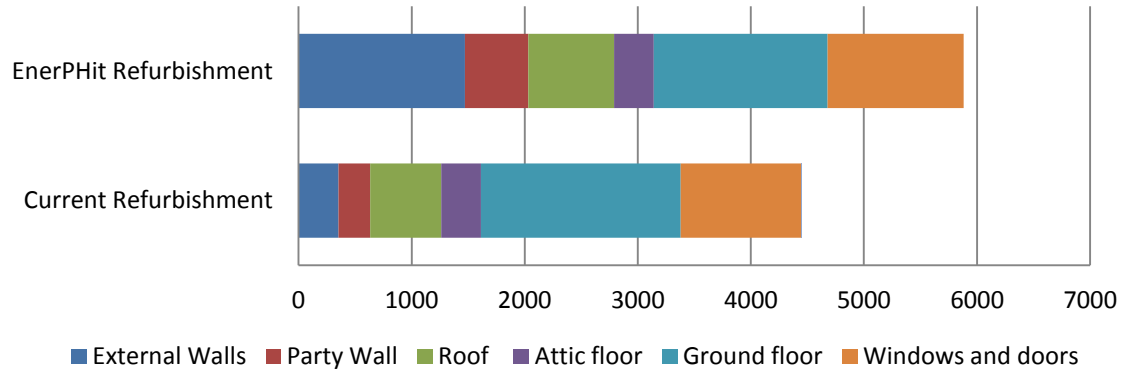
From Graph 4 it becomes apparent that the EnerPHit refurbishment EE one is extremely higher (2.4 times more), with walls showing the greatest difference. This is mainly attributed to the use of XPS³ with 88.6 MJ/kg EE, instead of woodfibre board insulation with 20 MJ/kg and the increased thickness needed to achieve the lower U

² All costs were calculated based on 2013 prices.

³ As imposed by the Passive House Certified Components (http://passiv.de/en/03_certification/01_certification_components/01_component_database.htm)

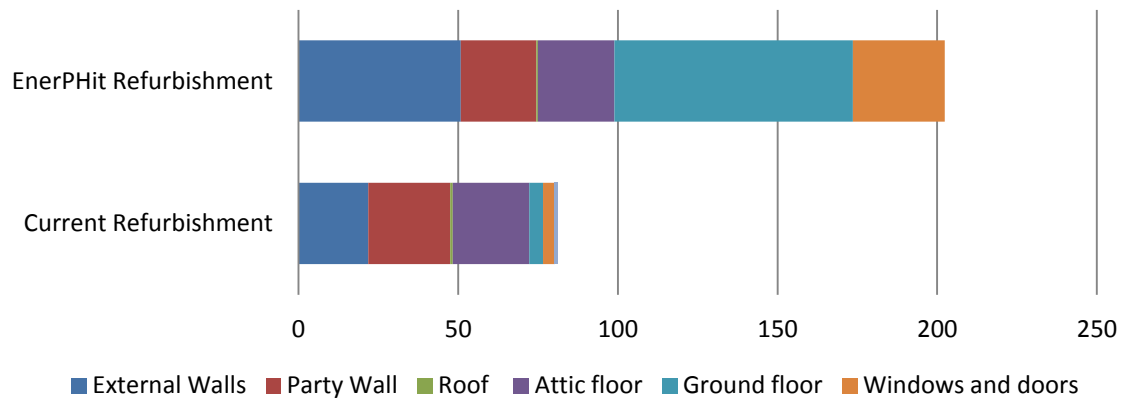
values for the thermal elements. In addition, the triple glazed units and the insulated wooden frames and wooden door with polyurethane foam add 13 % more to the EE.

Graph 4 Embodied Energy (MJ/m2)



4.2.3 Embodied CO2

Graph 5 Embodied CO2 (kg/m2)



Embodied carbon shows a huge difference between the current refurbishment and EnerPHit in the range of 357%. This is also due to the use of different insulation materials and thicknesses and concrete products for the floor insulation.

4.3 Cost per Ton carbon Saved

The lifecycle analysis over a thirty years lifetime⁴ combines the pre refurbishment operational data with those for post intervention operation and embodied ones as well. The CTS arises as a quotient of the LC divided by the LCS. The savings arising from the EnerPHit refurbishment are constantly higher, although, due to the high amount of EE associated with it, the LCS is higher in the case of the current refurbishment.

The resulting CTS can be evaluated through a comparison to the Social Cost of Carbon for 2012 of £27.17⁵ /tCO2 (Department of Environment Food and Rural

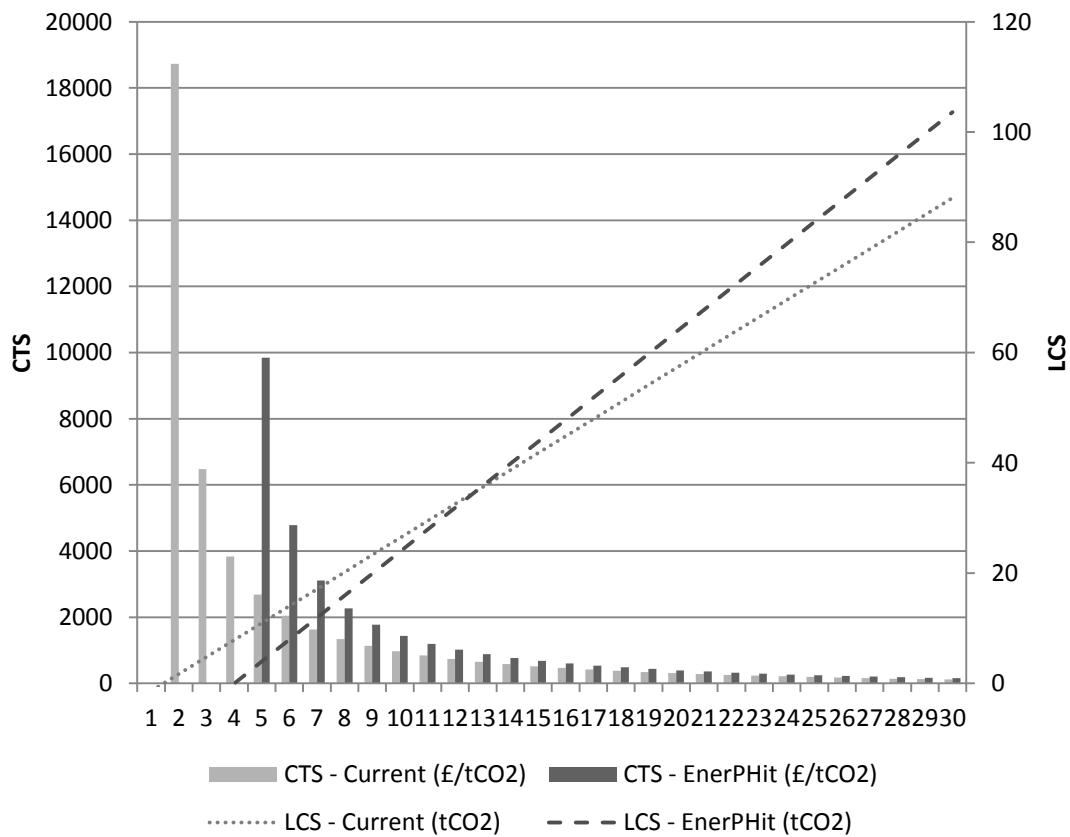
⁴ This was chosen as a likely lifespan of the refurbishment measures.

⁵ £19/tCO2 with 2000 prices, inflated to 2012 prices

Affairs, 2007b), which represents the global cost of the damage a ton of carbon causes over its lifetime in the atmosphere and the price that society should be paying to prevent or mitigate the damage caused.

In both cases the CTS is way above the SCC, with the EnerPHit retrofit being 1.3 times higher than the current refurbishment, indicating that the extra initial cost and EE involved are not offset by the higher savings during the operational phase of the building. In addition, the carbon savings for the EnerPHit are quite delayed compared to the current retrofit, where savings begin just before the second year, resulting always⁶ in higher CTS (Graph 6). In addition, after the 13th year the carbon savings from EnerPHit outreach the current refurbishment.

Graph 6 CTS and LCS Comparison



⁶ Values checked for 250 years.

4.4 Simple payback

Simple payback compares the capital investment for a project with the annual benefit, which is assumed to be the same every year, giving the payback period. This method ignores time preference, discounting and the benefits after the payback period and thus should be only used for initial calculations (Ellingham and Fawcett, 2006).

$$\text{Payback Period} = \frac{\text{Capital Cost}}{\text{Annual Income}}$$

In both cases the capital costs are not expected to be repaid after the end of life of the project (30 years), rendering both interventions not cost - effective. With regards to Carbon and Energy, the current refurbishment shows, as expected, shorter payback periods.

Table 4 Simple payback

		Current Refurbishment	EnerPHit Refurbishment
Simple Payback	years	43.18	47.38
Carbon Payback	years	1.45	4.01
Energy Payback	years	5.21	7.75

4.5 Payback period for discounted cash flow

The cash flow of a project associated with future expenditures and incomes is greatly influenced by time preference, which derives from the natural desire to enjoy benefits as soon as possible and to defer payments as long as possible (Ellingham and Fawcett, 2006).

The most critical assumption of LCC is the discount rate, as a high one gives great emphasis on the early years of the project, favouring short – term approaches, while low r favours higher capital investment and a long – term approach. As this project involves low risk, a discount factor of 3.5% was assumed, reflecting the time preference of the UK society (Ellingham and Fawcett, 2006).

The results of NPV for the two alternatives showed that none of the two would give payback in a reasonable amount of time, if discounting is taken into account and steady gas prices are assumed, with EnerPHit having a higher deficit.

5. Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs (Saltelli A. et al., 2008). In the model developed in this study in order to assess the LCC of the two retrofit cases many assumptions were made and the sensitivity analysis will address the most important of them.

5.1 Gas price volatility

The model used in Chapter 4 considered steady fuel prices, which is highly unlikely to happen in real life. Fuel price volatility can be measured from historic data and can be used to predict the range of possible future outcomes. A quite widespread tool to do that is the binomial tree.

Energy prices show in general upward trends, thus a falling fuel price trend is highly unlikely in NPV costing. The results of the binomial tree for rising and steady fuel prices⁷ are summarized in Table 5, where it becomes apparent that only with rising fuel prices the initial investments would be repaid before the project's end of life, with EnerPHit demanding in all cases longer payback periods. Its NPV is exceeding the NPV of the current refurbishment after the 33rd year.

As far as CTS is concerned, when discounting and rising fuel prices are applied to the calculations, both cases show negative CTS values, indicating profitable investments. Yet again, the current refurbishment shows a higher benefit, which stays above the EnerPHit one for 50 years. On the other hand, when steady prices and discounting are assumed, only the current refurbishment shows negative CTS in 50 years.

Table 5 Payback time comparison

		Current Refurbishment		EnerPHit Refurbishment	
		Steady fuel price	Rising fuel price	Steady fuel price	Rising fuel price
Simple Payback	years	43.18	19	47.38	22
Discounted Payback	years	-	24	-	25
30 Year NPV	£	-20790.33	13754.19	-28465.6	13145.84
30 Year CTS Discounted	£/tCO2	-614.27	-698.7	254.66	-614.49

⁷ With falling gas prices the initial investment is not repaid, so they were not included in the table. In addition, the binomial tree showed for both cases that only one gas price reduction could be accepted in 30 years.

5.2 Impact of climate change

In order to test the validity of the results in case of higher temperatures in the future, a new model was developed using London Design Summer Year weather file. As expected, the total energy consumption was reduced in all cases, with heating loads falling and electricity loads increasing due to additional cooling needed. The overall energy savings are minimized in both cases, especially in the current refurbishment and, consequently, CTS and payback times increase. The current retrofit's CTS is increased by 50% and the EnerPHit's by 47%, while carbon and energy payback times all rose in the range of 20%, rendering both interventions less sustainable. Therefore, it is evident that climate change will influence the benefits of retrofit measures as heating loads and, thus, operational energy savings will decrease, a conclusion applicable in the case of retrofit in warmer climates as well.

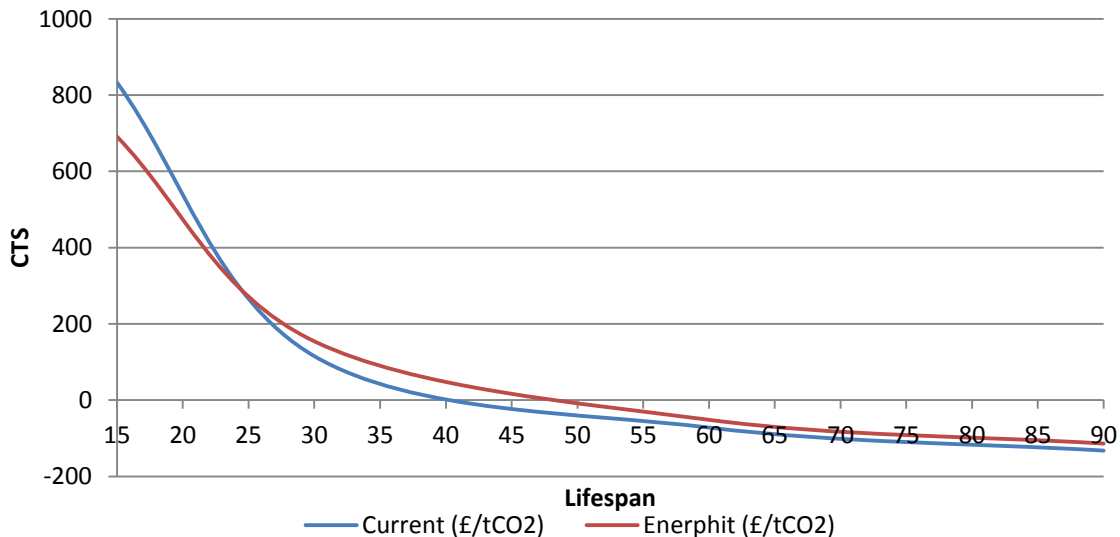
5.3 Lifetime effect on CTS and NPV

5.3.1 No replacement

One of the most substantial assumptions taken during the calculations was the project's lifetime of 30 years. The CTS is sensitive to the lifetime cost savings and the lifetime carbon savings and therefore the assumed lifetime. In all cases, carbon payback must be achieved before the CTS can be calculated. In this section the effect of varying lifespans will be addressed, assuming that no additional cost, EE and EC is needed.

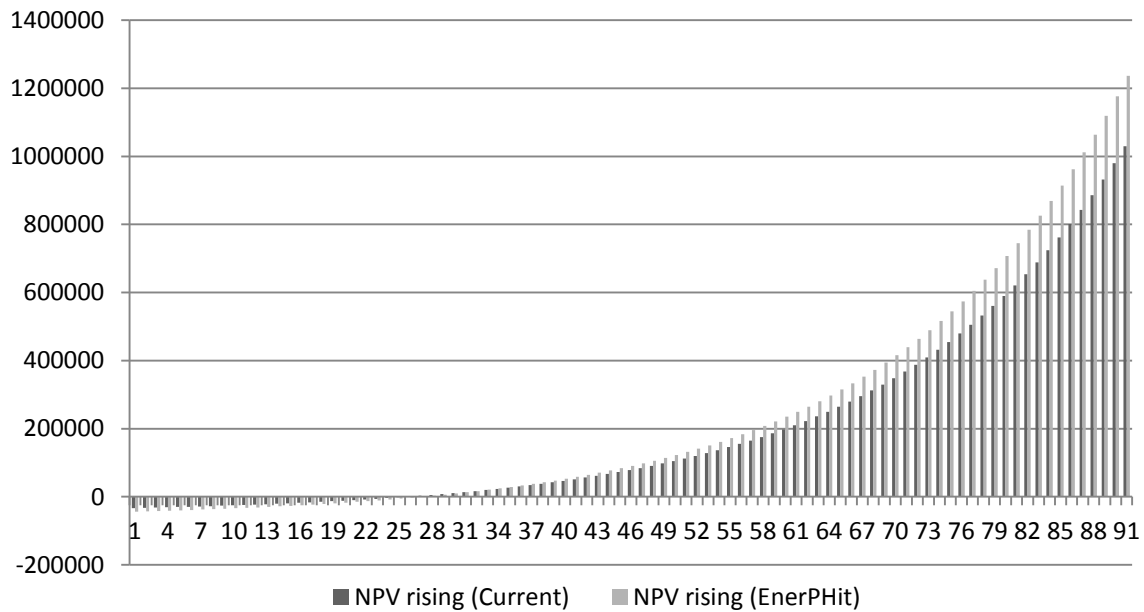
As expected, the CTS for a lifespan smaller than the assumed one leads to rocketing of the CTS for both retrofit cases, as the operational energy savings are not enough to offset the initial investments. From Graph 7 it becomes clear that for up to 24 years of lifetime the EnerPHit's CTS is lower than the current one, while from the point they equalize until 90 years lifetime it never exceeds the current one. Interestingly, the current refurbishment starts to generate profit from the 43th year and the EnerPHit from the 47th reaching £-71.76/tCO₂ and £-51.9/tCO₂ by the 60th year respectively.

Graph 7 Effect of lifespan on CTS



Likewise, the NPV shows different results over different lifetimes. The EnerPHit option becomes more viable than the current one after the 29th year with the difference increasing logarithmically within time, generating very high benefits compared to the initial investment (Graph 8). With steady fuel prices none of the two options is repaid within 90 years.

Graph 8 NPV with rising fuel prices over 90 years

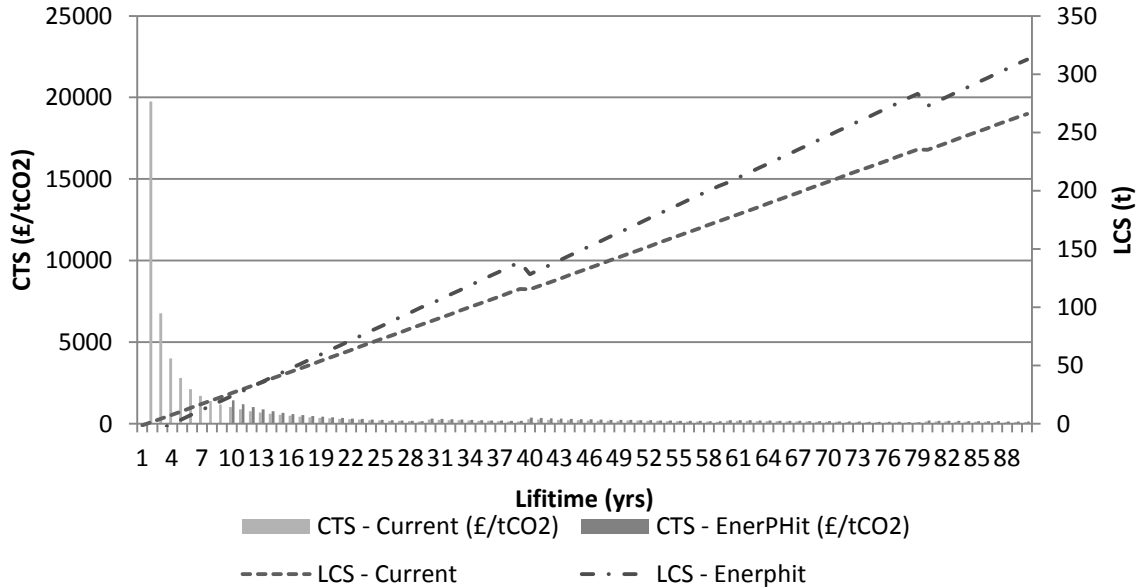


5.3.2 Replacement

In the previous section the effect on various lifespans on the CTS of the two retrofits was addressed, assuming that no additional replacements are needed, which could be considered utopian for a 90 years lifespan. Based on Jakob (2006) five replacement cycles were incorporated in the CTS analysis.

When these replacements are included, no benefit arises within 90 years. Quite interestingly, the carbon saved in EnerPHit manages to outreach the current after the 13th year, even though it is more decreased by replacement cycles (Graph 9). However, the EnerPHit CTS remains constantly above the current one, leading yet again to the conclusion that it is less sustainable.

Graph 9 CTS and LCS including replacements over 90 years

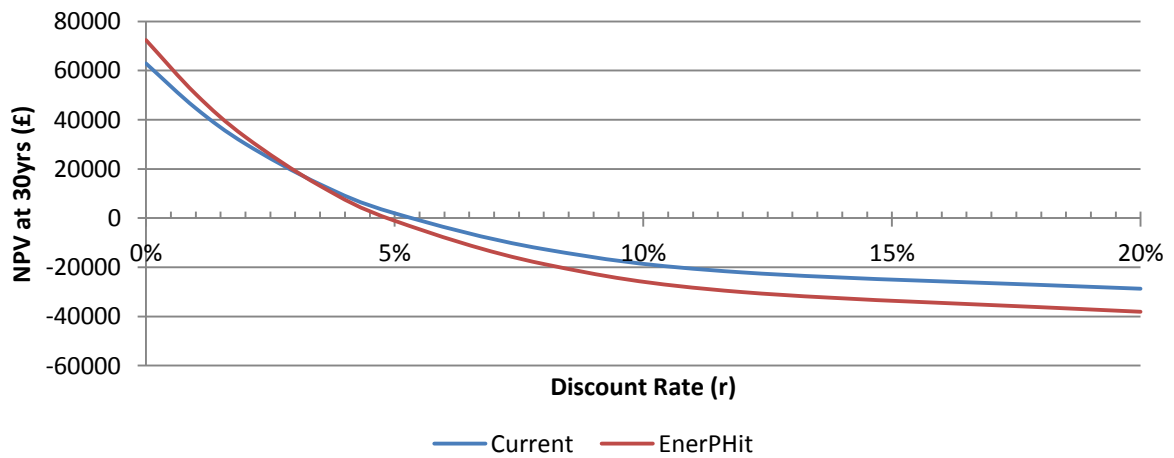


5.4 Discount rate

As described above (4.5), the discount rate is a quantification of uncertainty associated with benefits arising from investments, with high discount rates favouring short-term approaches and vice versa with low. It reflects three factors: inflation, time preference and risk. For the purpose of this study a conservative $r = 3.5\%$ was assumed, based on UK society overall time preference (Ellingham and Fawcett, 2006).

This assumption was tested against the effect it has on the two strategy's NPV with rising gas prices, resulting in favour of the EnerPHit for $r < 3.25\%$ confirming the sensitivity of the results to this input and the fact that low discount rates are advantageous for long term approaches and higher initial investments (Graph 10).

Graph 10 Effect of r to NPV

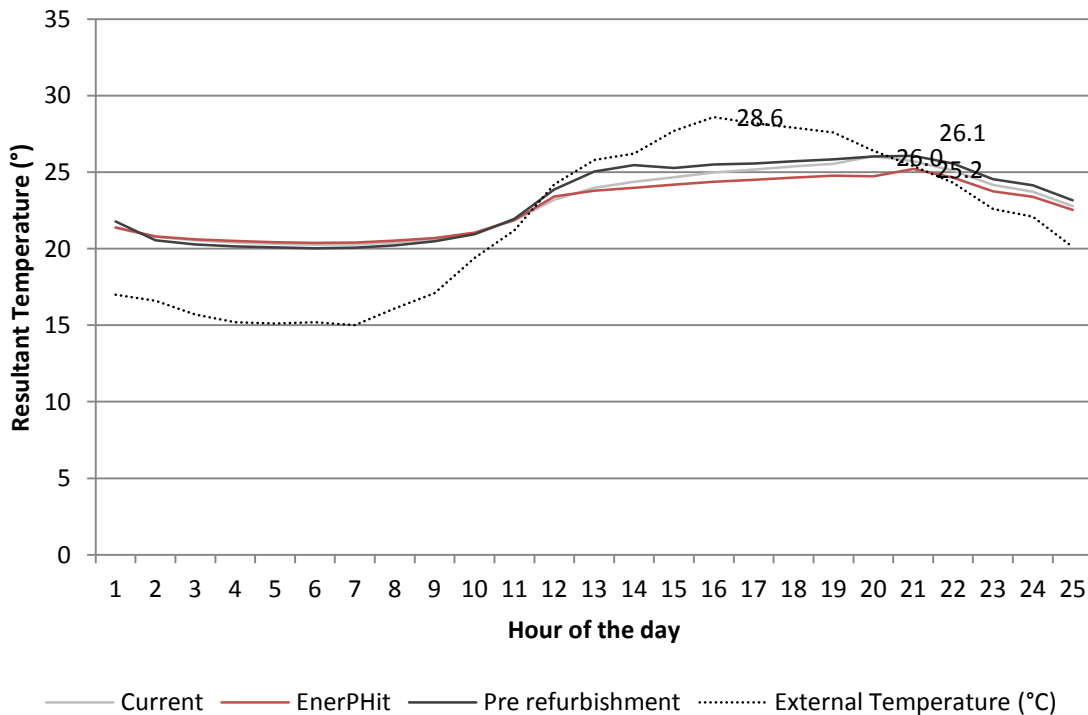


6. Overheating Occurrence

In the previous sections the study was focused on energy consumption; however, one of the main aspects of retrofit is the improvement of the house's thermal conditions, as these have implications on occupants' health. In addition, one of the EnerPHit refurbishment's criteria is the restraint of the overheating percentages ($t > 25\text{ }^{\circ}\text{C}$) below 10%. The pre - retrofit, the current and the EnerPHit cases were tested against this constraint over a 24 hour basis, except for the guest room which is tested only when occupied. Both refurbished cases show significantly low overheating percentages, quite below the strict limit of 10 % over $25\text{ }^{\circ}\text{C}$.

In order to identify the different responses of the house during hot periods, the hottest day of the weather file was chosen and the temperatures in the main living space were modelled (Graph 11). The EnerPHit house performed better, having a $3.4\text{ }^{\circ}\text{C}$ difference of maximum temperature with the outside, followed by the current refurbishment, which responded a little worse. On the other hand, by using the DSY the frequency of overheating appears to be higher for the EnerPHit case (4%), when no additional cooling is implemented.

Graph 11 Living room resultant temperature



7. Discussion

Aim of this study was to evaluate the most sustainable way to refurbish the thermal envelope of an end - terraced house in London, by comparing issues of cost, EE and ECO₂ between the applied retrofit and EnerPHit standard. At first glance one would assume that since EnerPHit is based on stricter U-Values and therefore higher insulation levels, it would be the optimum alternative by achieving higher operational energy savings, which is translated in cost savings. However, this study proved this hypothesis wrong, as the EnerPHit's price to be paid in order to achieve those higher energy savings in terms of IC, EE and ECO₂ renders it a less appealing retrofit model than the applied one.

The main variable used in order to perform this comparison was Cost per Ton carbon Saved, a quite representative value for the aim of this study as it incorporates all the variables under assessment (IC, OE, OCO₂, ECO₂). The lower CTS the more advantageous the option, with negative values signifying profitable investments. It was concluded that retrofitting in general and especially the application of EnerPHit is a viable option only with rising gas prices, low discount rates and long lifespans. Those results were even more amplified when climate change was taken into account, a conclusion very important for the application of future legislation and the possible transfer of this study to other climates.

When making an investment, the most important concern of the people involved is usually the cost payback time. This study used this parameter as a means to compare the two models, with quite interesting results. First and foremost, it was concluded that with steady (and falling) fuel prices none of the two is ever repaid when discounting is taken into account. In addition, if the imminent climate change is taken into account, both retrofit models appear to be unworthy with extremely long payback times, as energy savings from heating decrease with higher external temperatures. However, with rising fuel prices, which are highly probable according to trends, the two models are repaid within 19 years for the current one and 22 for EnerPHit, with the financial benefits coming from the EnerPHit exceeding the current one after the 33rd year, ending in 20% more NPV in the 90th year (without taking replacements into account). This inference led to another important one: the definition of the lifetime's length is very important in WLC, as significant benefits may arise after the end of the assumed lifespan, leading to incorrect conclusions.

The analysis on lifespans resulted in the same conclusion whether replacement works are included in the analysis or not. The current refurbishment still performed better in terms of CTS in 15, 30, 60 or 90 years. However EnerPHit's NPV is more appealing with rising gas prices and lifespans more than 33 years. One can conclude that the longer the lifespan the more worthy it is to invest more capital initially, thus the EnerPHit model is only viable in houses that do not incur major stresses on their structural framework and are predicted to stand for a long time period, as stated by the Research Group on Cost Efficient Passive Houses as well (Passipedia).

8. Conclusion and Further Research

This study evaluated the existing retrofit applied to an end terraced house in London against a retrofit according to EnerPHit standard, resulting in better results in most cases for the former. However, throughout the study it became evident that retrofitting is only sustainable if energy prices will rise in the future and for climates with high heating degree days, so that the initial investment could be repaid through operational savings. The lifetime is a very significant factor to be taken into account as well, as investments with higher capital cost give higher benefit in long term. Thus, when a building is structurally intact and expected to exist for a long time, it is worth to invest in an extensive retrofit.

On the other hand, one should not overlook that retrofitting has to play an important role on the reduction of CO₂ emissions, as the existing UK housing stock is among the least energy efficient in Europe and is therefore a great contributor to climate change. In addition, energy refurbishment increases the property value and thus rent premiums, improves health and comfort conditions in the house and also acts against fuel poverty. In 2011 4.5 million UK households were spending more than 10 % of their income in order to maintain adequate warmth (Department of Energy and Climate Change, 2013), making the great importance of building fabric to occupant's health apparent, especially to those with lower income. Moreover, retrofit is one of the tools for a gradual release from fossil fuel energy consumption, as the minimization of operational energy makes it feasible to supply a big part of this energy through renewables. Finally, it contributes positively to the creation of work places, especially in densely built cities with low construction rates, a financial benefit that should not be disregarded.

It is suggested that this study is applied on a larger scale as well, so that it could be generalized and applied to governmental strategies towards carbon emissions' reduction. It is important to state here, that minimization of costs would be achieved if retrofits are done massively and with governmental guidance, through bulk discount and expertise effect. The CTS in this case would be minimized and might be comparable to the social cost of carbon.

Finally, further research could be done regarding insulation materials which could be applied in standards. The embodied energy in the materials used in a retrofit is a determining factor of its environmental friendliness and it's always a matter of **how much do we really spend in order to save?**

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