ECO-RETROFITTING VERY OLD DWELLINGS:
CURRENT AND FUTURE ENERGY AND CARBON PERFORMANCE FOR TWO UK CITIES

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ABSTRACT: Concerns about climate change impacts have led the UK government to commit to reducing CO_2 levels to at least 80% of their 1990 levels by 2050. The built environment is one of the major contributors to CO_2 emissions in developed countries and thus is a key sector for reaching emission targets. Moreover, 70% of the existing UK housing will still be in use in 2050. Consequently, the wide scale eco-refurbishment of poorly performing, mainly old, buildings is critical if reduction goals are to be met. This paper uses computer modelling to evaluate the benefits of the sustainable refurbishment (to near Passivhaus standards) on the energy performance and internal thermal conditions of a 19th century end-terraced house under current and future climates for two UK cities. Modelling outputs tended to suggest very little reduction in heating demand in the future for the house with no refurbishment, while the eco-refurbished home showed a sharp reduction in energy demands and CO_2 emissions. Also, for both cities, summer overheating was very likely to be experienced in the dwelling, based on predicted 2030 and 2050 weather data. A second objective was to see how savings in CO_2 emissions (which are increased by reusing and refurbishing an existing building) might relate to the operational carbon costs during the building's life cycle. Results indicate that by year six after refurbishment the carbon costs of this type of refurbishment will be recovered.

Keywords: climate change; low carbon housing refurbishment; Victorian house; embodied carbon costs

INTRODUCTION

Climate Change and Buildings

The effects of climate change on the environment, human health and the economy has made climate change one of the 21th century's major challenges. The main driver of climate change is the concentration of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere. The built environment itself is responsible for a significant amount of this emission - typically around 20-40% for developed countries [1, 2]. On the other hand, building performance is also affected by these environmental changes, which can cause problems for buildings and their occupants. There is therefore a need for adaptation of the built environment to reduce the effects of changing climate and improve occupants' comfort.

Climate Change and the UK Housing Stock

According to the UK's Department of Energy and Climate Change (DECC), in 2009, the residential sector accounted for 27% of final-user emissions. The UK housing stock is very old and the replacement rate is less than 1% per year. As a result, it is estimated that over 70% of the dwellings that will be in use in 2050 have already been built. There is therefore a need for eco-refurbishment of existing dwellings to extensively improve their energy efficiency and provide them with a comfortable environment in a changing climate [3].

RESEARCH OBJECTIVES

Benefits of Eco-Refurbishment

Essentially, a typical eco-refurbished house is air-tight and super-insulated, with mechanical ventilation with heat recovery (MVHR) and multi-glazed windows. The overall aim of eco-refurbishment is to find methods by which the UK government's commitment to an 80% reduction in CO_2 emissions by 2050 (compared to 1990 levels) might be met within the existing housing stock [4]. The research presented in this paper investigates on the benefits of eco-refurbishment on a refurbished 19th century solid wall end-terraced house. The energy performance and CO_2 emissions of this case study have been evaluated under current and future climates. Geographical diversity is also an important factor in decision makings and results in different energy demands in different parts of the UK. This effect was investigated by modelling and comparing the dwelling's performance for Liverpool, in the north west of England, with London in the south of England.

Embodied carbon of Eco-Refurbishment

In the UK, most of the legislation on reducing carbon emissions from buildings has concentrated on the operational stage of a building, including the CO_2 emissions from energy consumption of lighting, heating and ventilation. However, using new and improved technologies in more buildings has increasingly improved buildings energy efficiency and reduced the carbon emissions created from operational stage. This improvement often achieved by more energy demand in material production stage, which explains the growing importance of the energy consumed during other life cycle stages of projects, such as the carbon emissions created in the manufacture of the materials used, their transportation, the construction activities themselves and the eventual demolition and disposal[5, 6].

Therefore, a second objective of this paper was to estimate the carbon payback times of the retrofit to realise how savings in CO_2 emissions might relate to the operational carbon emissions during the building's life cycle.

METHODOLOGY

Case Study

The dwelling used for this study was a solid wall, 19th century Victorian terraced house in Liverpool, UK. The house was a part of the '*Retrofit for the Future'* programme, a Government-funded competition launched by the Technology Strategy Board (TSB) in 2009. The competition aimed to encourage and support building and renovation companies to retrofit and refurbish existing housing to make 80% cuts in carbon emissions [7]. The *Retrofit for the Future* targets were linked to the Government's Climate Change Act and for the purpose of the competition the following targets were set per m^2 of floor area:

1. Maximum CO_2 emissions—17 kg/m^2yr
2. Maximum primary energy use—115 kWh/m^2yr

The primary energy consumption figure includes all the energy used in the house, including that for appliances (white goods) and consumer electronics [7].

Figure 1 shows the selected case study, which was refurbished by the Plus Dane Group. The aim was to go beyond current UK thermal building regulations criteria and to try and achieve the more demanding German Passivhaus standard on a 130-year old home. The retrofit of the building included: very high levels of insulation and very high levels of airtightness (1.0 ACH@50Pa), triple glazed windows, mechanical ventilation with heat recovery, solar gain via a new conservatory, LED lighting in the kitchen and bathroom, and A-rated low energy appliances [8].

Figure 1: Terraced house after refurbishment.

Modelling

First, the Victorian type end-terrace house, was modelled (before and after refurbishment) using the advanced thermal simulation package 'DesignBuilder'. There was not enough information about the previous condition of the house. Therefore, characteristics of typical terrace houses and also neighbourhoods were studied to create a pre-refurbished model of the existing house in DesignBuilder and then simulated with current weather data for Liverpool to evaluate the effect of eco-refurbishment on energy consumption and CO_2 emissions (see Tables 1 and 2).

Table 1: Pre-refurbishment thermal features of the 19th century terraced house [9]

Element	Fabric U-value (W/m^2K)
Insulated roof-100mm mineral wool	0.40
Solid Walls-215mm thick brick work	2.10
Uninsulated suspended timber floor	0.50
Windows-single glazed timber frames	4.80
Doors-unglazed solid timber	3.00

Table 2: Post-refurbishment thermal features of the terraced house [10]

Element	Fabric U-value (W/m^2K)
Insulated roof-400mm Rockwool	0.15
Solid wall-internal insulation-Supa Wall	0.11
Concrete floor slab, Supa floor panels	0.12
Windows-triple glazed	0.78
FD20 rated fire doors	1.00

In addition, the energy and CO_2 performances of the same pre and post refurbishment dwellings were examined for current and future climates in the warmer city of London, UK.

Weather Data for the Simulation

A building's long life time and substantial changes in climate suggest that buildings should work successfully in both current and future climates. To make well-founded decisions for this adaptation process detailed data concerning future climate are necessary. For the UK's specific climate projections the UK Climate Impacts Programme (UKCIP), a UK based agency, in conjunction with the UK's Meteorological Office's Hadley Centre, published its first climate change projections in 1998. These were substantially updated in 2002 and again in 2009 [11]. In previous research publications the UKCIP 2002 data were used to generate future weather files, but recently the PROMETHEUS project in Exeter University has produced a number of EPW future weather files using the UKCP09 weather generator [12]. These predictions represent a random sampling of a probability distribution function and hence the probabilities of a particular level of climate change as well. In this paper the results from current and 2030 and 2050 medium emission scenarios at the 50% probability level for Liverpool and London will be presented. Table 2 compares the current, 2030 and 2050 external air temperature in °C for Liverpool.

Table 3: 2009 and predicted 2030 and 2050 external average monthly air temperatures (°C) for Liverpool, UK

	2009	2030	2050
Jan	4.1	5.3	6.1
Feb	4.2	5.5	6.1
Mar	5.7	7.4	8.1
Apr	8.2	9.2	9.8
May	11.6	12.7	13.5
Jun	14.2	16.1	16.8
Jul	15.9	17.9	18.6
Aug	15.9	17.4	18.4
Sep	13.6	15.3	16.1
Oct	10.6	12.6	13.3
Nov	6.5	9.4	10.1
Dec	5.0	6.7	6.8

Model Validation

To study the impact of climate change on building energy performance, simulation software is a useful tool. However, there are always some discrepancies between the real performance of buildings and predicted results of the model created in the software. Ideally, the software should be validated against measured data from the building that is being simulated. Fortunately, the selected case study was monitored over a two year period after refurbishment from October 2009. Large amounts of data, such as internal and external air temperatures, indoor CO_2 levels, the power consumption of the MVHR system, and total consumptions of gas and electricity and water, were captured and analysed. These monitored data were then compared with simulations made by DesignBuilder as a part of a validation procedure.

This paper focused specifically on gas consumption for heating. A comparison of monitored annual gas usage can be seen in Table 4. There are small differences between the results, which could be attributed to the small differences in the weather data as DesignBuilder simulation results were based on 2009 CIBSE weather data whilst the monitoring was carried out between November 2010 and October 2012.

Table 4: Measured and predicted annual gas usage for heating, Liverpool, UK

	Monitoring	DesignBuilder
Gas Usage for Heating (kWh/m^{2}yr)	49.21	47.38

Embodied carbon

The second stage of this study sought to determine the carbon costs of the improving construction in this eco-refurbished house and it concerns the embodied CO_2 emissions arising from Materials used in the renovation and transportation of materials to the construction site. The Inventory of Carbon & Energy (ICE) database from Hammond and Jones at the University of Bath was selected as database to calculate the embodied carbon of each stage [13]. Then, the contribution of each of these stages was added together to calculate the embodied carbon.

FINDINGS AND DISCUSSION

Eco-Refurbishment- Current Weather Conditions

Simulation results illustrated in Figure 2 compares the annual heating demand for the pre-refurbished and post-refurbished house in both London and Liverpool for current weather data. Significant heating demand reductions of around 76% can be seen after refurbishment in both cities.

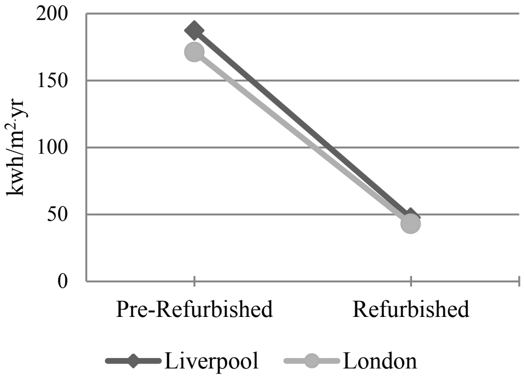

Figure 2: Annual heating demand for the pre and post-refurbished terrace house in Liverpool and London for current weather data.

Also, as a part of validation procedure the measured monthly gas consumption for heating the refurbished house (kWh) under 2011 weather conditions of Liverpool was compared with predicted monthly gas consumption for heating the refurbished house by DesignBuilder using 2009 Liverpool hourly weather data. This comparison can be seen in Figure 3. Having validated the model made it possible to investigate how the same refurbished terraced house and also pre-refurbished house might perform in different current and future climate scenarios.

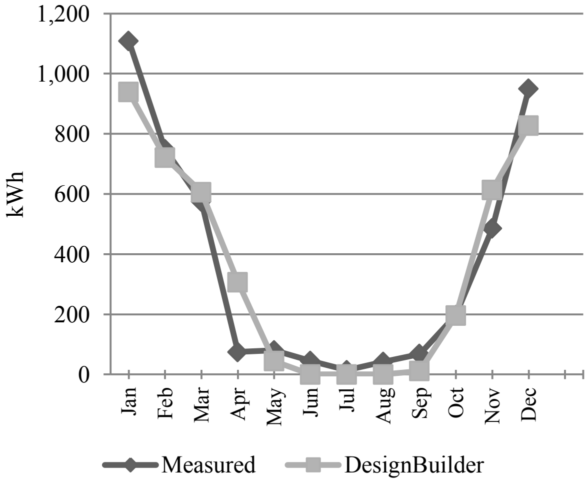

Figure 3: Measured and predicted Monthly gas usage (kWh) for heating the refurbished house for current weather condition (Liverpool).

Thermal Comfort- Current Weather Conditions

For current weather conditions Figure 4 illustrates the comparison of monthly mean operative temperature (°C) from pre and post-refurbished houses under current weather conditions in Liverpool.

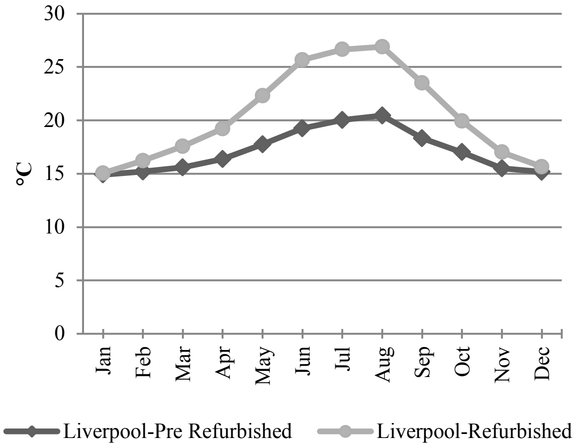

Figure 4: Monthly mean operative temperature (°C) from pre and post-refurbished house under current weather conditions (Liverpool).

This comparison shows that no cooling was required before refurbishment, while during the summer months the mean peak operative temperature may exceed 25 °C after refurbishment and so there could be a risk of thermal discomfort if no adaptive measures were taken. However, for most of the year the refurbishment is greatly enhancing thermal comfort in the house (no external shading was added to the building after refurbishment).

Eco-Refurbishment- Climate Change

Then, both pre-refurbished and refurbished houses in different cities under current and future weather condition and different scenarios were simulated to see if the UK‘s carbon reduction targets (through heating demand reductions) should rely more on eco-refurbishment or climate change. Changes in heating demand for London and Liverpool can be seen in Figure 5. It confirms that despite the fact that heating energy consumption and consequently CO_2 emissions are affected by climate change, future heating demand simulations indicate very little reduction in demand for the house with no refurbishment, while the eco-refurbished dwelling shows a sharp reduction of more than 76% in energy demands in both cities.

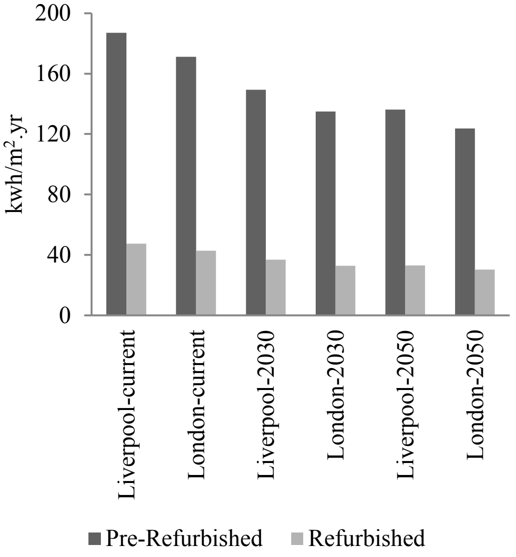

Figure 5: Annual heating demand for the pre and post-refurbished terrace house in different cities for current and weather data of Liverpool and London.

As was discussed before, geographical diversity in the UK has an effect on energy consumption in different cities. Figure 5 shows that heating demand is typically higher in Liverpool than in London.

In addition, Figure 6 demonstrates that although the mean indoor operative temperature will increase for both cities under 2050 weather conditions, and summer overheating are very likely to occur in the second half of this century, it is also apparent that cooling demand is typically higher in London than in Liverpool.

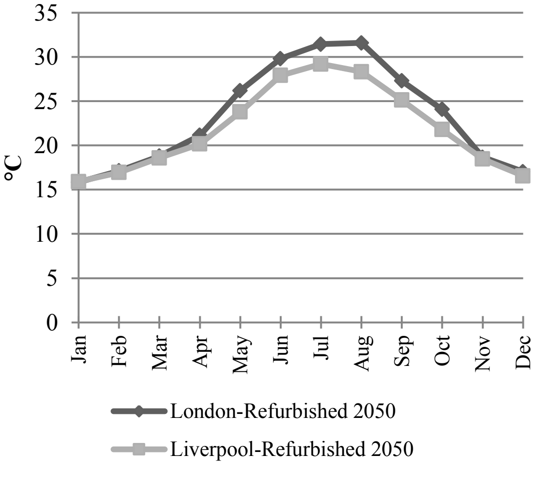

Figure 6: Monthly mean operative temperature (°C) from refurbished house under 2050 weather conditions (Liverpool and London).

Embodied Carbon - Contribution of Materials, Transport and waste

The second stage of this study aimed to calculate the payback time of improving construction to reach eco-refurbishment targets. To do so, the effects and savings on CO_2 emissions from improving construction have been evaluated. These changes are presented in Table 5.

Table 5: Annual Carbon savings from lower gas consumption for heating via construction improvements - current weather data

CO_2 Emissions (tonnes CO_2/yr)	
Pre-Refurbished	Refurbished
3.036	0.777

Also, the embodied carbon of wall, floors and roof insulation and replacing windows and doors has been assessed. The aforementioned Inventory of Carbon & Energy (ICE) database from Hammond and Jones at the University of Bath was selected as database to calculate the embodied carbon of each stage [13]. Figure 7 shows the breakdown of embodied carbon for improving construction.

In this case the majority of the embodied costs arise from the materials, which account for about 95% of the total compare to embodied carbon of waste and transportation. It can be also seen that the ground floor refurbishment contributes the highest embodied loads with approximately 5.5 tonnes of embodied carbon whereas roof insulation shows the lowest embodied burdens with around 0.35 tonnes CO_2.

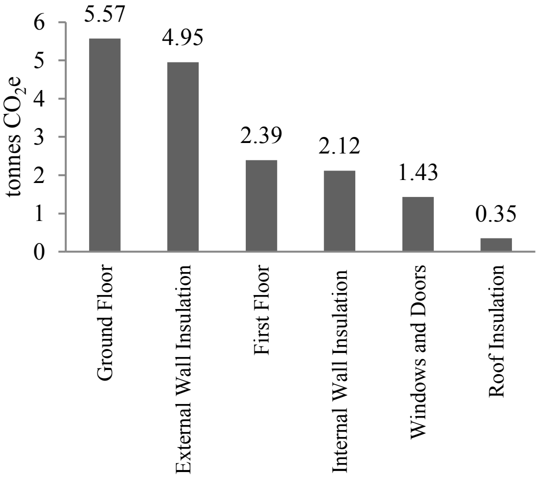

Figure 7: Embodied carbon of various low carbon technologies for the terraced house

The graph in Figure 8 shows that between the sixth and seventh year the carbon costs of improving construction and replacing all windows and doors have been recovered. Thereby, embodied carbon can be considered a good carbon investment.

Year 0 represents the year of the refurbishment and the point on the y-axis shows the amount of embodied CO_2. The angle at which the lines incline depends on the amount of annual operational carbon and the point at which they intersect represents the payback period, that is, the point in time when the additional carbon costs that arose from the retrofit have been recovered.

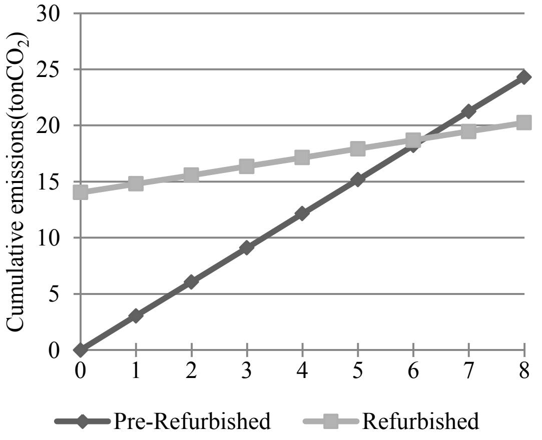

Figure 8: Payback time of the retrofit in terms of CO_2 emissions

CONCLUSION

This analysis of a 19th century terraced house that was refurbished to near Passivhaus standards has been divided into two stages: first, the energy consumption and CO_2 emissions were determined and, second, a life cycle carbon analysis of the construction type (improving the glazing type, wall and loft insulation) was undertaken. In the first step, applying all strategies was studied to determine the possibility of reaching an 80% emissions reduction by eco-refurbishment. Results indicate that energy demands and CO_2 emissions experience a sharp decline following eco-refurbishment. However, it can be concluded from the results that during the summer months the mean peak operative temperature may exceed 25 °C after refurbishment and as a result there could be a risk of thermal discomfort if no adaptive measures were taken. Comparing the carbon cost of this type of refurbishment shows the carbon payback time of this type of refurbishment is less than 7 years, which can be considered a good carbon investment.

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REFERENCES

1. Dimoudi A, Tompa C. Energy and environmental indicators related to construction of office buildings. Resources, Conservation and Recycling. 2008; (53):86–95.
2. Gustavsson L, Joelsson A, Sathre R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy and Buildings. 2010; (42):230–420.
3. Department of Energy and Climate Change [Internet]. 2010. [cited 2013 May 7]. Available from: http://www.decc.gov.uk/assets/decc/What%20we%20do/A%20low%20carbon%20UK/1358-the-carbon-plan.pdf
4. Trafford Eco House [Internet]. 2009. [cited 2013 May 7]. Available from: http://traffordecohouse.wordpress.com/2009/01/03/a-passivhaus-passive-house-renovation/
5. Gustavsson L, Joelsson A, Sathre R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy and Buildings. 2010; (42):210–220.
6. Sahagun D, Moncaster A. How much do we spend to save? Calculating the embodied carbon cost of retrofit. In: Proceedings of Retrofit 2012 Conference. 24-26 January 2012, University of Salford, UK
7. Technology Strategy Board. [Internet]. 2009. [cited 2013 May 7]. Available from: http://www.innovateuk.org/ourstrategy/innovationplatforms/lowimpactbuilding/retrofit-.ashx
8. Plus Dane Group. [Internet]. 2010. [cited 2013 May 7]. Available from: http://www.plusgroupltd.org.uk/article.asp?id=389 (accessed on 25 September 201 2).
9. Appendix S: Reduced Data SAP for existing dwellings. [Internet]. 2009. [cited 2013 May 7]. Available from: http://www.bre.co.uk/filelibrary/accreditation/scheme_standards/SAP_2009_9-91_Appendix_S_January_2012.pdf
10. Low Energy Building Database. [Internet]. 2009. [cited 2013 May 7]. Available from: http://retrofitforthefuture.org/projectPDF.php?id=77
11. Eames, M, Kershaw, T, Coley, D. On the creation of future probabilistic design weather years from UKCP09. Building and Services. 2010; (32): 127–142
12. Mohammadpourkarbasi H, Sharples S. The Eco-Refurbishment of a 19th Century Terraced House: Energy and Cost Performance for Current and Future UK Climates. Buildings. 2013; 3(1):220-244
13. Hammond, G. Jones, C. Inventory of Carbon & Energy (ICE). (2011). Version 2.0.