Sustainable Building Conference 2013

Exploring the whole life carbon benefits of insulation materials in housing refurbishment

S. Tucker* and B. Spittle†

*Cardiff University, Welsh School of Architecture,
Bute Building, King Edward VII Avenue, Cardiff, United Kingdom, CF10 3NB
e-mail: tuckerS3@cardiff.ac.uk
Web page: http://www.cardiff.ac.uk/archi/index.php

†Centre for Alternative Technology, Graduate School of the Environment
Machynlleth. Powys, United Kingdom, SY20 9AZ
e-mail: benegf@yahoo.co.uk
Web page: http://gse.cat.org.uk/

Abstract. *Embodied carbon can be an important part of a building's whole life carbon cost and as such offers potential possibilities to reduce carbon emissions. To date the majority of research in this area has focused on new buildings and overlooked the existing housing stock much of which is in urgent need of upgrading if emissions reduction targets set out by the Government are to be achieved. This paper briefly explores the whole life benefits of including embodied carbon in the specification of insulation materials in UK retrofits. Insulation has the potential to both reduce in-use CO2 emissions of a building as well as lead to further emissions during its manufacture and transport, and in the case of bio-insulations to even sequester CO2.*

Dynamic thermal simulation was used to predict CO2 savings over 25 to 50 year periods resulting from heating reductions of retrofitting, and the embodied carbon values of the materials used was calculated using two freely available databases. Three insulation materials were used for comparison; Polyurethane foam, Mineral wool and Wood fibre. The results suggest that the reduction of embodied carbon in retrofitting has the potential to reduce a buildings whole life carbon, with the extent of this reduction dependent on whether sequestered carbon is included in the figures for bio based insulation. Although the accepted orthodoxy recommends the use of the most efficient insulation available, this study shows that the inclusion of embodied carbon values into the equation brings this approach into question.

Low carbon refurbishment, embodied carbon, whole life carbon

1 INTRODUCTION

Rising fuel prices and the spectre of climate change are driving moves to improve the thermal efficiency of our homes. The UK's existing housing stock is in particular need of attention with many requiring extensive retrofits to achieve emission reductions on the scale needed. Household energy use is responsible for 27% of the total UK Carbon dioxide emissions (Boardman 2007). Of this, space heating accounts for some 53% (SDC 2006). Increasingly stringent building regulations are resulting in new homes with much improved operational emissions but the majority of the UK population live in older, less efficient homes. Estimates suggest around 86% of the UK's houses will be made up of existing stock by 2050 (SDC 2006). Almost 40% of these were built before 1945 (EHCS 2009) to standards far below those needed to reach emission reduction targets set by government.

Applying insulation to the building envelope is core to any retrofit project and typically employs petrochemical based foams or mineral wools. Although these materials can substantially reduce the carbon emission resulting from space heating, their manufacture and disposal has an embodied carbon (EC) cost. The current doctrine suggests that the resulting energy savings more than compensate for this initial carbon debt.

In contrast, a number of insulation materials such as Wood fibre and cellulose offer a low embodied carbon alternative. Such materials can possess negative EC values, due to carbon sequestered as the plants grow. Accepting the urgent need to reduce CO2 emissions, this paper explores the potential net carbon savings offered by the use of these materials in a low EC approach to retrofitting. A number of refurbishment scenarios are modelled in order to determine the scale of potential carbon savings over time.

2 CONTEXT

As greater quantities of natural materials appear on the market, consumers can now choose between the typically cheap, highly efficient man-made materials with a high embodied carbon, and the less efficient, more expensive plant derived materials with a low or even negative embodied carbon. Negative values result from the sequestration of carbon through photosynthesis, as the plant grows. Although dependent on a number of variables, these negative values have the potential to exaggerate differences in EC costs.

This paper examines through a number of simulations the initial EC difference and the trade-off between embodied energy and energy saving potential, and therefore the potential of sustainable material specification to maximise the whole life carbon savings resulting from thermal improvements to typical UK housing stock. High EC approaches to refurbishment using conventional man made building materials are compared to Low EC approaches using natural materials and the resulting net carbon savings calculated. The high EC approach reflects very closely standard practice today.

2.1 Embodied carbon

Embodied Carbon (EC) extends the concept of Embodied Energy (EE) which itself can be described as the "*the sum of the energy requirements associated, directly or indirectly, with the delivery of a good or service*" (Cleveland & Morris 2009). Calculation of EC follows energy flows back to the carbon emissions resulting from their generation and supply. Although carbon emissions are responsible for the majority of global warming other atmospheric gases also contribute. The embodied carbon equivalent (ECe) is a more comprehensive quantification of a material's emissions expressed in Kg CO2 but including other greenhouse gases (if emitted). Table 1 shows embodied energy, embodied carbon and embodied carbon equivalent values for a selection of materials from the ICE database (Hammond & Jones 2011) that were used in this study. Although ECe values are not always very different from EC values, certain materials of which the plastic foams listed are a good example show marked increases. The ICE database uses a 'cradle to gate' measurement due to it being the most commonly seen in the data sources reviewed (ibid).

Material	Embodied Energy (MJ/kg)	Embodied Carbon (KgCO2/Kg)	Embodied Carbon eq. (KgCO2e/kg)
Mineral wool	16.6	1.2	1.28
Expanded polystyrene	88.6	2.55	3.29

Polyurethane	101.5	3.48	4.26

Table 1. Embodied energy and carbon of insulation materials (source: ICE database)

2.2 Sequestered carbon

The embodied carbon in a material remains stored for an assumed life period. While carbon can be sequestered for any amount of time, the longer it is removed from the atmosphere the more pronounced its effect on reducing global warming. However, while carbon stored in wood is unlikely to be stored indefinitely, if it is held for a period comparable with those used to assess GWP it is considered sequestered. Indeed, attributing a negative EC value must assume a reasonable time frame. The IBO (Waltjen, 2009) database ascribes GWP over a 100 year period and assumes ideal future scenarios. The uncertainty surrounding the realisation of such assumptions is a reason sequestered carbon is omitted from the ICE database. The large number of unknowns in timber products (e.g. how much of the cut timber is used, transport, machining) mean that EC figures could become meaningless or even misleading. However, the manufacturers of the Wood fibre insulation modelled in this study claim that 99% of the wood it uses are off cuts from local saw mills. The use of what would otherwise be a waste product from monitored, managed forests gives a level of confidence to attributing a figure for sequestered carbon. Of course, suitable operational and end of life scenarios must be assured. Recycling, wastage during building and transport of materials can all alter the EC value.

2.3 EC in buildings

To date, consideration of the embodied carbon has focussed on embodied carbon in new buildings. EC values vary with building size, construction type, building use and the study parameters, but approximate figures can be drawn. Monahan and Powell (2011) calculate emissions at 34.6 tonnes CO_2 for a 3 bedroom semi-detached house constructed with modularised timber panels, and 52 tonnes when constructed with traditional masonry cavity walls. In another study, three new builds showed comparable values of 50 TCO2 each (EHA 2008).

EC values are often described as a proportion of the total carbon cost. Ramesh et al. (2010) in an overview of LCA of buildings concludes that EE accounts for around 10-20% of the lifetime energy. These values depend largely on the operational energy of building which can vary greatly. Sturgis & Roberts (2010) estimate EC to account for 30% in houses, 45% in offices and 60% for warehouses. A report (Wray & Atkinson, 2011) on the cradle to grave footprint of offices showed EC to make up approximately one third the total life carbon.

As new buildings become ever more energy efficient the EC proportion, of the whole life carbon cost, will increase. Hammond & Jones (2009) estimated EC of domestic new builds (built to 2006 regulations) to be between 12-19 years of their operational energy related emissions and it can be assumed that this value will increase in a building constructed to 2010 regulations. A report by Jones (2011) proposes that EC has been further underestimated due to an overestimation of operational electricity emissions of the future. They argue that previous studies have not considered the future decarbonisation of electricity generation and as a result overestimate operational energy by 50% for a typical domestic new build.

These operational and embodied values cannot always be considered distinctly separately and can be interrelated. Hacker et al (2008) studied the relationship between thermal mass and

EC over the next hundred years in southern England and concluded that, although the buildings with higher thermal mass had higher EC values (due to the large amount of cement etc.) the resulting energy savings from avoiding cooling loads offset the higher EC values relatively quickly. By contrast, the Bed-zed development (Lazarus, 2002) focused on the potential to reduce EC. The use of recycled materials and local procurement was prioritised. Recycled materials made up 15 % of the total materials used and reduced the embodied impact by some 20-30 % whilst maintaining building performance. As regards sequestration, a modelling study (McInerney and Tucker, 2012) on small houses built to the Passivhaus standard found that constructing them of low EC materials could result in sequestration of 26 $TC0_2e$ whereas a non-renewable fabric led to emissions of +31 $TC0_2e$.

2.4 EC in Retrofit

Little research has focused on the EC of refurbishment. One report (EHA, 2008) showed that renovations produced some 15 tonnes of CO2 compared to new build values of around 50 tonnes and the renovated houses reached a thermal efficiency comparable to that of the new builds. The conclusion highlighted the increased period needed by the new builds to offset their larger EC cost. Although using it as a comparative measure to show the benefit of refurbishment, the report did not examine reductions of EC.

Many of the materials commonly employed when retrofitting, such as foam insulation, plasterboard and mineral wool insulation have high embodied carbon values but are commonly specified for a number of reasons. Firstly the current orthodoxy focuses heavily on the reduction of operational emissions through the specification of high performance insulating materials; typically these possess higher EC values. This initial outlay of carbon is justified by the insulations potential to save many times the value of its EC over its lifetime through heating energy savings. One report (XCO2, 2009) concludes that *"the choice of insulation material is not important"*.

Secondly the insulation market is dominated by a small number of large companies who produce very cheap, very efficient insulation. The large scale manufacture and relatively cheap raw materials enable these companies to produce their products very competitively. Comparison of two fibrous insulations, mineral wool and sheep's wool, showed sheep's wool to be over four times the price (Spittle, 2012). Both materials have similar conductivity values and possible applications but the price difference is substantial. With cost always an important driver the cheaper and more efficient a product is, the shorter its pay-back period. From a consumers perspective a financial view may take priority over levels of EC.

3 METHODOLOGY AND RESULTS

Dynamic thermal simulation (IES, 2012) was used to predict saving in space heating energy use over a base line model. This figure was then converted to ECe for the fuel type used (gas). The volumes of materials used for each study were calculated and corresponding ECe figures were obtained using the ICE (2011) and IBO (Waltjen, 2009) databases. The thermal properties of the insulation materials were based on specific commonly available brands of insulation (table 2).

Insulation	Element	Conductivity (W/mK)	Density (Kg/m3)	ECe (Kg CO2/Kg)
Polyurethane (PU)	All elements	0.022	32	4.26

Mineral wool (MW)	External Wall / floor	0.04	140	
	Cavity	0.04	30	
	Roof	0.038	36:0-120mm, 45: >120	1.33 (mean)
Wood fibre (WF)	Internal/external wall	0.044	190	-0.18
	Cavity	0.038	24	-0.907
	Floor and roof	0.038	140	-0.18

Table 2. Properties of insulation materials modeled

3.1 Retrofitting three house types to three levels of insulation

A semi-detached house, a bungalow and a terraced house were modeled (table 3 and figure 1) and their heating energy use assessed. The buildings were all uninsulated. Low (L1), medium (L2) and high (L3) levels of retrofitted insulation were applied to each base model (table 4). The wall insulation was applied in line with a realistic practice, by filling cavity first then adding internal insulation followed finally by external insulation. The ECe and emissions from space heating energy were added to give the whole life net savings.

Wall	Brick – cavity - Brick
Floor	Suspended Timber floor, un-insulated
Roof	Felt – batten – Slate
Glazing	4 mm single glazing
Ventilation	1 air change/hour
Weather file	Kew
Heating profile	Oct 1 – May 31 (0600 – 1000 & 1600 – 2200)
Glazed area	10% External Wall

Table 3. Base model parameters.

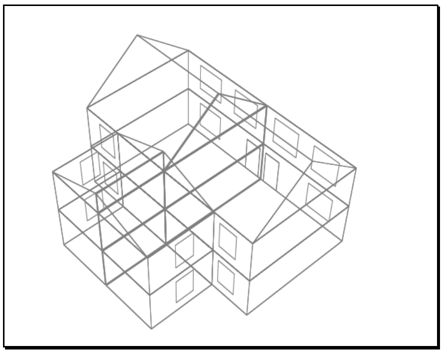

Figure 1. Semi-detached model

	Insulation added					(Kg CO2/Kg)		
Retrofit measures	External Wall (mm)	Internal Wall (mm)	Cavity Wall (mm)	Floor (mm)	Roof (mm)	PU	MW	WF
Control	0	0	0	0	0	0	0	0
Low (L1)	0	0	50	50	50	1735	548	-309
Medium (L2)	0	50	50	100	100	3471	2216	-705
High (L3)	100	0	50	150	150	5206	3884	-1101

Table 4. Insulation levels applied

Figures 2-4 show the results for the semi-detached house which follow a similar pattern to the other two house types. For the L1 level of retrofit (figure 2) the net saving for the Polyurethane is the greatest of all three insulations at over 20 tonnes ECe, due to its effective thermal performance giving greater energy savings than Mineral Wool or Wood fibre. However, for L2 and L3 levels of retrofit the Wood fibre shows the largest net saving due to the combined factors of increased levels of sequestered carbon and the diminishing returns of heat energy saved with greater depths of insulation. At high levels of insulation there is not so great a difference in heat losses between the Polyurethane and the Wood fibre despite the difference in values of conductivity.

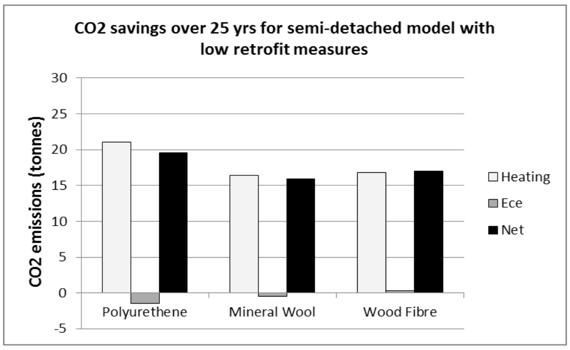

Figure 2. Semi-detached model (L1)

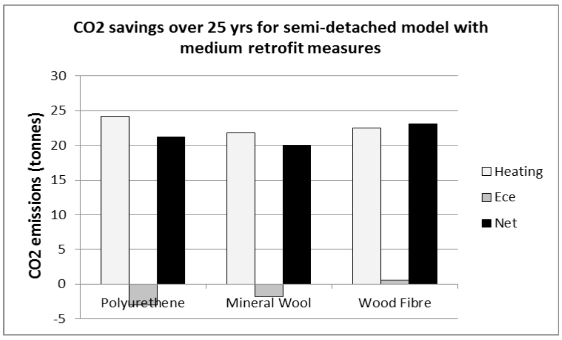

Figure 3. Semi-detached model (L2)

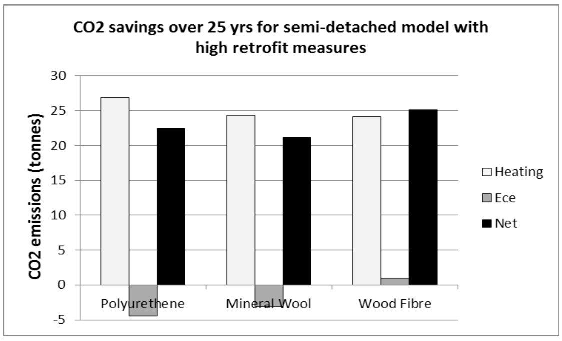

Figure 4. Semi-detached model (L3)

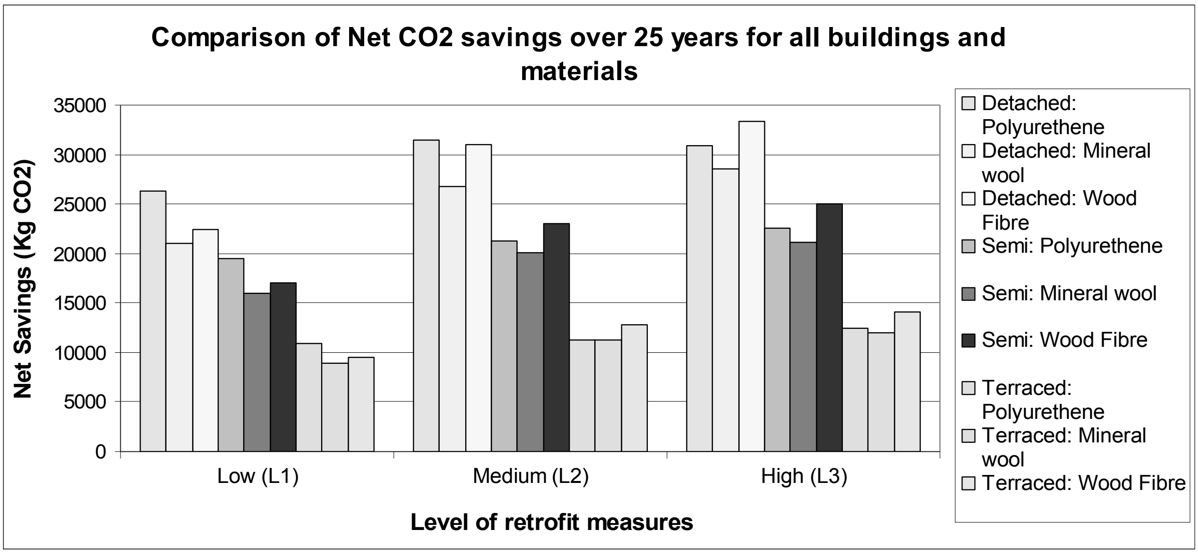

Figure 5. Net CO2 savings for terraced, detached and semi-detached under three levels of retrofit

For all buildings (terraced, detached and semi-detached) for the L1 level of refurbishment scenario, Polyurethane achieves the largest net savings (figure 5). Although it has a high ECe value per Kg, its superior thermal efficiency out performs the other materials. On the other hand, L2 and L3 level refurbishment results in Wood fibre insulation giving the higher net savings in the majority of cases. This is due to the larger quantities of sequestered carbon in the Wood fibre outweighing the better thermal performance over time of the Polyurethane.

Mineral wool performs poorest throughout yet does show a closer equivalence with Polyurethane as insulation levels increase.

The figures are significant when compared with the 25 year totals of annual heating emissions which for the semi-detached house after insulating were between 42 and 52 tonnes depending on the refurbishment scenario and the insulation type. For the L3 retrofit the difference in ECe of Polyurethane and Wood fibre is about 5 tonnes which is equivalent to around 2-3 years of heating energy emissions.

3.2 Retrofitting bungalow with wall insulation only

A bungalow with a floor area of 96m^2 was modelled (based on an existing building) and external wall insulation added in increments. Internal and external finishes such as render and plaster were included in the ECe calculations (full details not given here due to space restrictions). The construction was of brick/block cavity with an initial 50mm of cavity insulation, and a concrete floor with 25mm Polystyrene insulation. The results show that as external wall insulation is added, up to a thickness of approximately 60mm Polyurethane gives the highest net CO2 savings over 25 years due to a better thermal performance (figure 6). At 60mm both Polyurethane and Wood fibre save equivalents amounts of CO2, and above 60mm the Wood fibre saves the most. The curves of both lines reflect the diminishing returns of adding further insulation, and the more pronounced curve for Polyurethane is a result of its increase in positive ECe value with increased thickness.

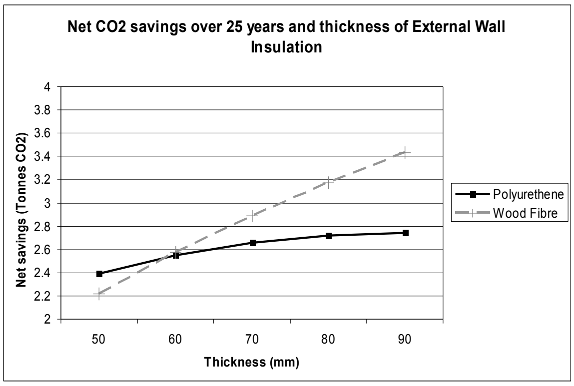

Figure 6. Insulation thickness and CO2 savings

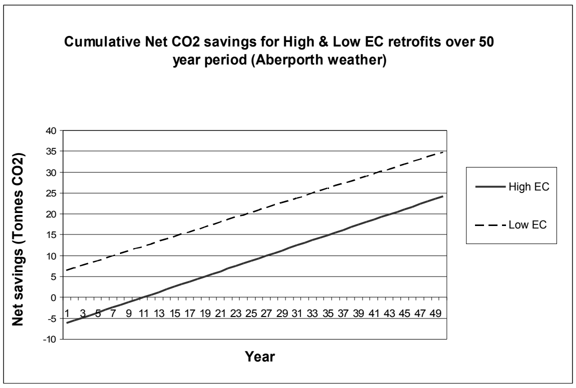

Figure 7. ECe type and CO2 savings

The high and low ECe approach was further developed to include the materials and methods of adding insulation. The insulation was increased in thickness to give a U-value in each envelope element of 0.2 W/m2K, and double glazing was added. The high ECe materials used such as plasterboard and screed are not exceptional but are commonly employed. The low ECe approach saves more CO2 until the 302nd year (figure 7).

The quantities of wall and roof insulation in the low ECe model were then reduced to determine how much Wood fibre would be required such that the point at which both high and low ECe models saved equal amounts of CO2 at the 50 year point. Only 35mm of Wood fibre on the walls was needed which is only a quarter of its initial thickness of 140mm, and half the thickness of the required Polyurethane. At the same time roof insulation was reduced to 100 mm compared to the 200mm of Polyurethane needed. This level of Wood fibre insulation resulted in U-values below those required by Building Regulations. The results indicate that if a specific length of building life was to be assumed, then buildings would need less insulation if sequestering insulations were used, and such saving in volume of insulation could reduce the cost differential between the manmade and natural insulations.

3.3 Sensitivity tests

Finally, some sensitivity tests were done to quantify the effects on net ECe savings that other building parameters would have. Figure 8 shows the effect on 25 net year saving of improving airtightness (or reducing ventilation) of the building from 1ac/hour to 0.5 ac/hour. The figures indicate that the effect of this parameter change is of the same order as that obtained by switching from a high to a low ECe approach. Figure 9 shows the effect of climate on net savings, and the order of difference in net saving between the high to a low ECe approach is similar to that resulting from the difference between London and Aberdeen climates. These two results provide further evidence that levels of ECe should be taken seriously and that potential effects on net savings are significant.

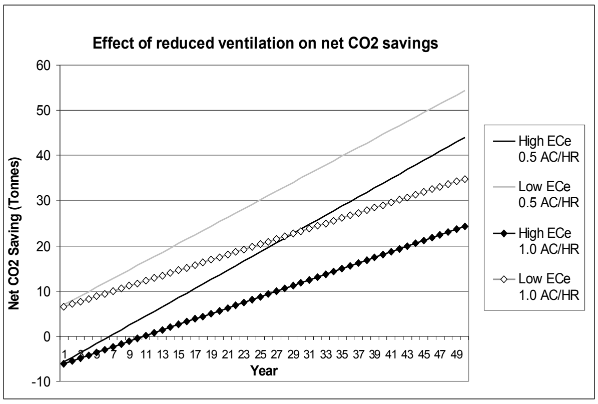

Figure 8. Ventilation rate and CO2 savings

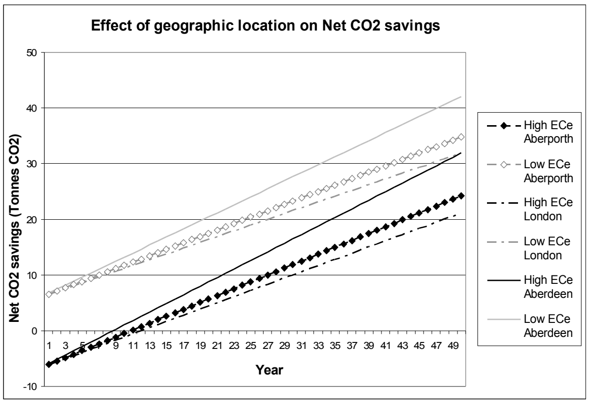

Figure 9. Climate and CO2 savings

4 DISCUSSION

The Embodied Carbon of the materials used to thermally retrofit existing buildings has been shown to have a noticeable effect on the building whole life carbon cost. While the specification of low ECe materials over high ECe materials will directly reduce the carbon debt of a building, a further less obvious relationship is seen with insulation. Here the net carbon savings are a function of the ECe value of the material, its achieved U-value and the law of diminishing returns obtained from incremental increases of insulation thickness. Over a 25 year period Polyurethane shows superior net savings when small amounts of insulation are used, but for higher levels of insulation Wood fibre insulation saves greater quantities of CO2 over time. Including secondary materials and methods of application further exaggerates the relationship.

Any alteration of time parameters would affect the specific results shown here. Increasing the time period over which net savings are considered would benefit the higher ECe approaches, giving them a longer saving period over which to repay their ECe debt. However, an argument also exists for the increased value of carbon saved today over that saved ten years from now [Harvey & Aggerwal, 2011]. The Low ECe approaches in this study save carbon sooner rather than later. Although Polyurethane insulations outperform Wood fibre at lower thicknesses, the move toward more advanced insulation standards such as Passivhaus and the higher levels of Code for Sustainable Homes and AECB standards, mean that bio-based insulations may have a more important role to play than has been previously thought.

Government schemes intended to promote energy saving such as ‘Warm Front’ have tended to insist that the cheapest materials are used for insulation, and bio based insulations such as Wood fibre, Hemp and Sheep’s Wool have been excluded from such schemes. It is interesting that the net CO2 emissions over periods of time that relate to building life cycles can be reduced by using bio based insulations suggesting that a different metric could be chosen for assessing effectiveness of insulation other than cost or conductivity.

If the potential benefits of embodied carbon to reduce whole life carbon are to be capitalised upon, it must become included in government policy. Although this study and others would support such a move, analysis of the implications of embodied carbon is still a relatively new field and the weight of evidence supporting its inclusion is relatively small. Any further research in this field would serve to strengthen its case. Crucially, any development in the area of embodied carbon would benefit from larger, more accurate, primary databases. The accurate consideration of carbon requires the ability to accurately measure it.

5 CONCLUSIONS

Modeling has indicated that the net emissions of a bungalow refurbished with high ECe materials are about 11 tonnes greater than the same building refurbished with Low ECe materials over a 35 year period, when the elements of both buildings were given similar U-values. Ignoring the sequestration of carbon in the Wood fibre would reduce but not remove this difference. The important effect of minimising ECe in the retrofitting approach was highlighted when High ECe refurbishment with advanced U-values was compared against the Low ECe refurbishment with reduced thicknesses of insulation resulting in U-values below current building regulations. Contrary to what might be expected the Low ECe approach had a higher net saving until the 50th year. A further finding was that the relative importance of ECe can be influenced by geographic location and indirect benefits of retrofitting such as improved air tightness.

The benefits of Low ECe insulation become apparent when considering whole life carbon emissions of a building. Focussing only on operational emissions and or cost (of insulation or heating bills) favours High ECe insulation. While the cost of the various approaches was considered here only briefly, it is clear that in today’s market the Polyurethane is both cheaper and more thermally efficient per unit volume. Considered from a home owner’s point of view the Polyurethane will typically provide lower fuel bills each year while Wood fibre will paradoxically result in higher fuel bills but yet have the potential to save more carbon over a given period.

The accuracy of ECe data, along with the assumptions inherent in attributing sequestered carbon, has the potential to significantly change the results given here.

ACKNOWLEDGMENTS

This paper is based on the MSc thesis of the second author (supervised by first author).

REFERENCES

Boardman, B. (2007) *Home Truths: A low carbon strategy to reduce UK housing emissions by 80% by 2050*, University of Oxford Environmental Change Institute, A report for the Co-operative bank and Friends of the Earth.

Cleveland, C.J. & Morris, C.G. (2009) *Dictionary of Energy: Expanded Edition*, Elsevier Science.

EHA (2009) *New Tricks with Old Bricks,* The Empty Homes Agency Ltd, London.

EHCS (2009) *Decent homes and Decent places,* English House Condition Survey 2007, Department for Communities and Local Government.

Hacker, J., De Saulles, T ., Minson, A., & Holmes, M. (2008) Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change, *Energy and Buildings*, Elsevier, Vol. 40, pp375–384.

Hammond, G. & Jones, C. (2011) *Inventory of Carbon and Energy* (*ICE),* BSRIA.

Hammond, G. & Jones, C. (2009) *Embodied Carbon: The Concealed Impact of Residential Construction*, *in* Global Warming. Engineering Solutions, Chapter 23, Springer.

Harvey, H. & Aggarwal, S. (2011) *The Costs of Delay.* ClimateWorks Foundation [Available online] http://www.climateworks.org/ accessed 2/11/11.

Jones, C. (2011) 'Embodied Carbon: A look forward'*, Sustain insight article: Volume 1,* Sustain 2011 [Available online] http://www.sustain.co.uk/articles-presentations/3/embodied-carbon-report/

I.E.S. (2012) Integrated Environmental Solutions [Available online] www.iesve.com

Lazarus, N. (2002) *BedZED: Toolkit part 1.A guide to construction materials for carbon neutral development.* Bioregional 2002 (reprinted 2009).

McInerney, M. and Tucker, S. (2012) 'Renewable versus Non-Renewable Building Fabric: A comparative study of the effect of material choice on the embodied energy and global warming potential of low energy dwellings', *Proceedings of Advances in Computing and Technology: 7th Annual Conference*, London: University of East London

Monahan, J. & Powell, J.C. (2011) 'An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework', Energy and Buildings, Vol 43, Issue 1, pp. 179–188.

Ramesh, T., Prakash, R., & Shukla, K.K. (2010) Life Cycle Energy Analysis of Buildings: An Overview*,* Energy and Buildings, Vol 42, Issue 10, pp. 1592-1600.

Spittle, B., (2012) *Minimising the Embodied Carbon of Retro-fitting Materials for Existing Homes: What is the whole life carbon benefit*? Unpublished MSc thesis, University of East London.

Sturgis, S. & Roberts, G. (2010) *Redefining Zero: Carbon profiling as a solution to the whole life carbon emission measurement in buildings.* RICS Research, 2010.

SDC (2006) *Stock Take: Delivering improvements in existing housing stock*. Sustainable Development Commission.

Waltjen, T. 2009. *Details for Passiv houses: A catalogue of ecologically rated constructions.* IBO Austrian Institute for Healthy and Ecological building 3rd edition. Springerwein New York.

Wray, M. & Atkinson, J. (2011) *Whole life cost and carbon: Sustainable offices,* South west regional development agency.

XCO2 Conisbee Ltd (2009) *Insulation for Sustainability: A Guide.* A study undertaken by XCO2 for BING Federation of European Rigid Polyurethane Foam Associations.