



Retrofit versus new-build house using life-cycle assessment

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Abstract

This paper reports the findings of research on the environmental performance of two case study houses, a retrofit and new build. The retrofit was completed to a *PassivHaus* standard whilst the new build was completed to current Irish building regulations. Environmental performance of the retrofit and new build was measured using life cycle assessments, examining the assembly, operational and end of life stage over life spans of 50 and 80 years. Using primary information, LCA software and LCA databases the environmental impacts of each stage were modelled. The operational stage of both case studies was found to be the source of the most significant environmental damage, followed by the assembly and the end of life stage respectively. The relative importance of the assembly and end of life stage decreased as the life span increased. It was found that the retrofit house studied outperformed the new build in the assembly and operational stage whilst the new build performed better in the end of life stage however this is highly sensitive, depending on the standards to which both are completed. Operational energy savings pre and post-retrofit were significant indicating the future potential for adoption of high quality retrofitting practices.

Keywords: Energy conservation; Rehabilitation, reclamation & renovation; Sustainability.

1 INTRODUCTION

In recent years there has been an increased focus on sustainable development, with world leaders endeavouring to reduce anthropogenic environmental impacts such as climate change. The Climate Change Act (2008) saw the UK Government committing to a legally binding target of a 34% reduction of greenhouse gas emissions/ CO_{2eq} by 2020 on 1990 levels and an 80% reduction of greenhouse gas emissions / CO_{2eq} by 2050 on 1990 levels. In order to achieve these ambitious targets, CO₂ emissions from sectors such as industry, transport and construction have been quantified with the required reductions presented in numerous Government strategies. The energy use of the housing sector is the source of over a quarter of total annual UK CO₂ emissions (Energy Saving Trust, 2010). The Energy Performance of Buildings Directive (2010) aims to improve the energy efficiency of buildings, requiring public buildings and new buildings to be nearly zero energy from 2018 and 2020 respectively, with certification based on life cycle analyses. The UK intends that all new homes will be zero-carbon by 2016 (Department of Energy & Climate Change, 2011), with the recently updated definition requiring the mitigation of emissions from regulated energy use such as space heating, water heating and lighting as included in Part L1A of the Building Regulations whilst unregulated energy use such as plug-in appliances are excluded (Zero Carbon Hub, 2011). Smart meters allowing householders to monitor energy consumption, are to be installed in all homes by 2020. However, these initiatives alone will not meet the required 80% reduction in CO₂ with between 66 - 80% of homes in 2050 having been built before the implementation of these new strategies (Energy Saving Trust, 2010; Department of Energy & Climate Change 2011). Existing stock is aged and underperforming, with the most recent House Condition Survey using standard assessment procedure (SAP) showing an average energy efficiency in Northern Ireland and England of 52.4 and 51.4 respectively, achieving an energy efficiency rating of 'E' (Department of Communities & Local

Government, 2010; Northern Ireland Housing Executive, 2008). In order to achieve the 80% reduction by 2050 the majority of housing will have to achieve above a 'B' energy efficiency rating, which means achieving a minimum SAP rating of 81.

Studies have been conducted with varying underlying assumptions such as population growth and housing stock turnover by BRE and the Environment Agency, amongst others to compare methods of improving the housing stock as per recommendations by the Sustainable Development Commission. These methods may broadly be categorised as supporting solutions with increased rates of demolition and new build or high quality retrofitting of existing homes. These studies have been summarised by Environmental Change Institute (2006) and Power (2008), which also debate their merits and highlight weaknesses for those interested in further reading. However, the main limitation of these studies is that a systematic assessment of the environmental performance and potential energy savings of the two solutions has not been carried out. In a research project at Queen's University Belfast, this was given emphasis, the results of which are summarised in this paper, so that a well informed and an appropriate strategy to achieve the goal of an 80% reduction in CO₂ by 2050 could be developed.

An introduction to the life cycle assessment (LCA) framework, a methodology whose application is becoming prevalent for the evaluation of environmental impacts and sustainability, particularly within the EU (http://lct.jrc.ec.europa.eu/index_jrc), is outlined. This is followed by the description of the two case studies that formed the basis of the analysis with the life cycle stages of assembly, operation and end of life disposal discussed and analysed. The results are then compared to draw conclusions on the environmental impact and potential energy savings by 2050.

2 LIFE CYCLE ASSESSMENT

2.1 Life cycle assessment background

The life cycle assessment (LCA) methodology allows for the quantification of consumed resources, emissions and environmental impacts of a product. LCA considers the entire life cycle of a product, examining the extraction of resources, manufacturing process, use and eventual disposal. LCA is internationally standardised through the ISO 14040 series, however these were lacking in technical detail and gave LCA practitioners a wide range of choices. The ISO were supplemented by best practice developed by the Society of Environmental Toxicology and Chemistry and currently the International Reference Life Cycle Data System is being developed to create a robust, consistent and prescriptive framework with greater quality assurance (EC JRC, 2010).

2.2 Life cycle assessment methodology

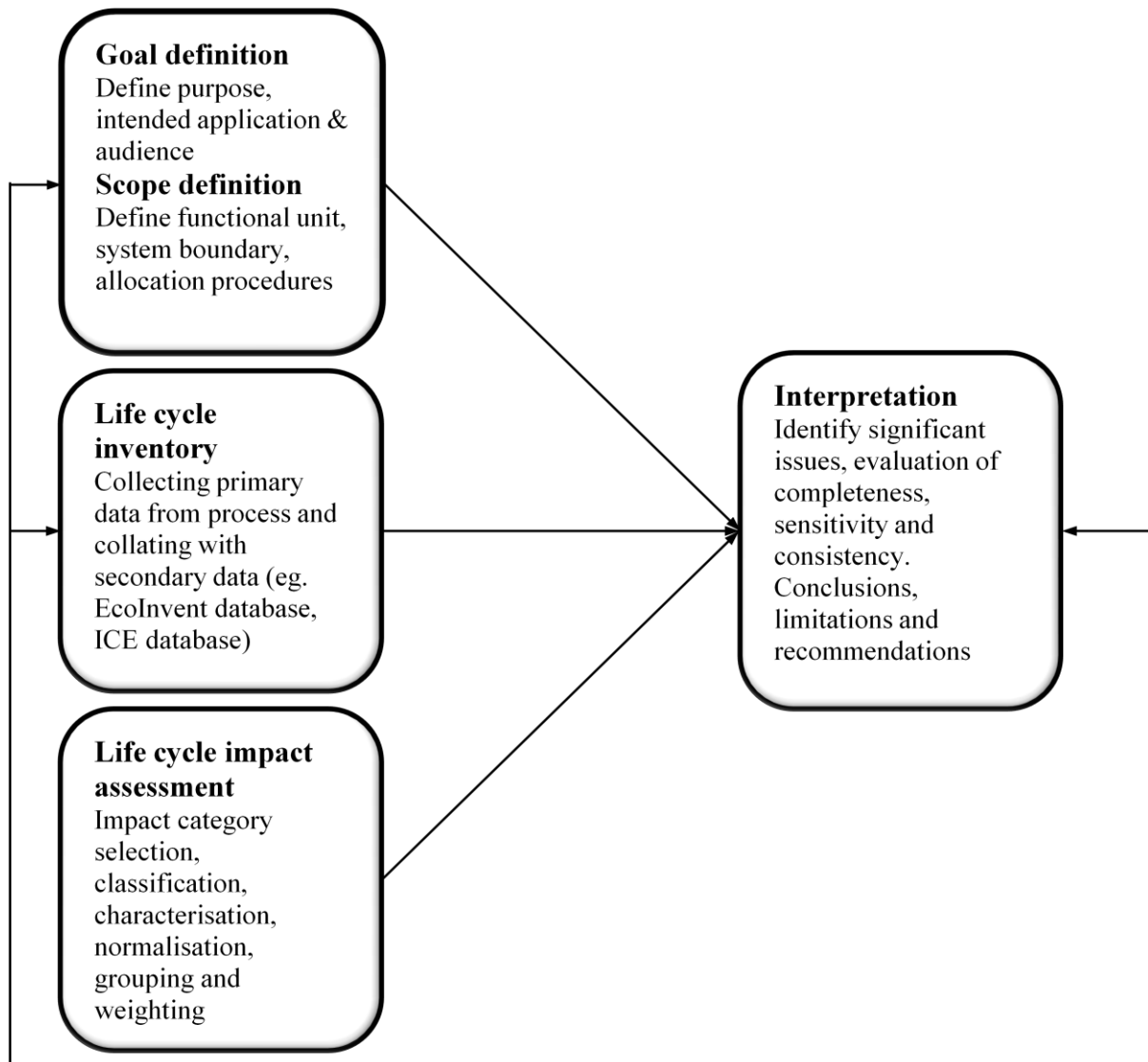
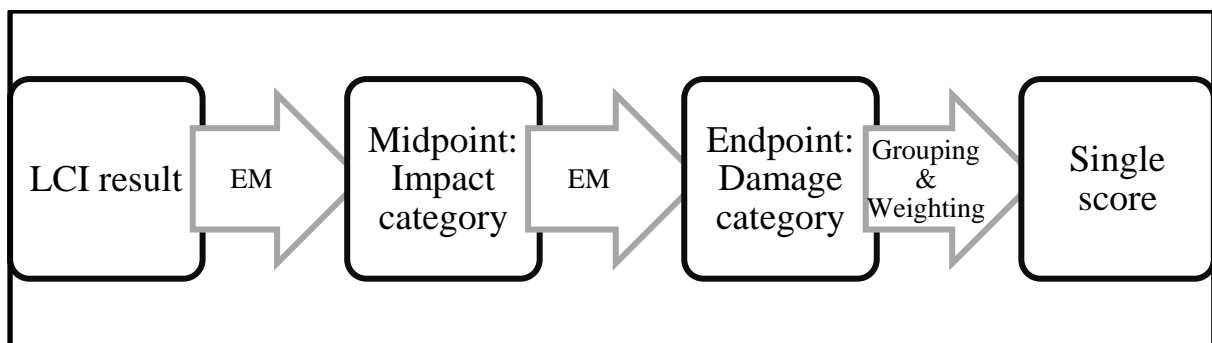
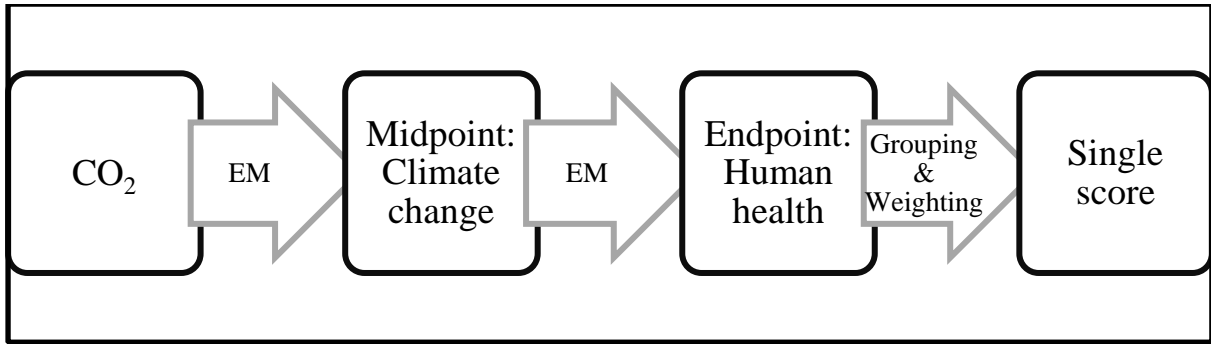


Figure 1 - Life cycle assessment process, adapted from ISO14044

Life cycle assessment consists of four steps which are described in ISO 14044; goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation which are shown in Figure 1. Goal definition specifies the purpose of undertaking and intended audience whilst the scope definition specifies the system boundaries and the functional unit. The second step is LCI, which quantifies the amount of materials and energy consumed in the product manufacturing and the resultant waste by products and emissions. The potential environmental impact associated with inventory results is calculated in the LCIA stage.

Life cycle impact assessment consists of two procedures, which are mandatory; selection of impact categories and classification and characterisation, and two optional procedures namely normalisation and weighting as outlined in Guinée et al., (2002), and ILCD (2010), amongst others. Environmental damages can be classified into impact categories at midpoint or endpoint level. The process in which an emission from a product becomes an environmental impact is referred to as an environmental mechanism (Guinée et al., 2002). A midpoint impact occurs at some point along the environmental mechanism and represents the direct negative effect on the environment such as eutrophication and climate change. Endpoint impact is taken at the end of mechanism and are damage orientated indicators corresponding to damage to human health or ecosystem (Goedkoop et al., 2009). Using multiple midpoint impact categories allows for greater detail on the environmental damage, but endpoint damage orientated indicators may be aggregated into single scores which are easier for non-experts to interpret and understand. There are many impact assessment midpoint and endpoint methods available, such as CML, Impact 2002+, TRACI and EcoIndicator. A gathering of LCA experts in the year 2000 concluded with a consensus that a common framework of impact assessment that presented results at midpoint and endpoint level was required. The resulting method, ReCiPe, was developed, building on the Eco-indicator 99 and CML methods and harmonises modelling principles and choices (Goedkoop et al., 2009).





EM = environmental mechanism

Weighting = dependent on how significant the damage category is viewed to be by company/individual developing the LCA

Figure 2 - Relationship between life cycle inventory results, impact categories, damage categories and single score with simplified CO₂ example

The cultural perspective theories of risk by Thompson, 1990, as explained in (Goedkoop et al., 2009) are used to deal with any uncertainties related to the environmental mechanisms, with three methods available grouping assumptions and choices; viz. egalitarian, hierarchist and individualist. The egalitarian perspective considers a time scale that is extremely long term. Any substance with an indication of ill effect included and damages are considered to be unavoidable and may lead to catastrophic events. The hierarchist perspective considers a long term time scale. Substances are included if there is scientific consensus regarding their ill effect and damages may be avoided with good management. The individualist perspective considers a short-term timescale (≤ 100 years) with substances only included if there is complete proof of their ill effect. Damages are assumed to be treatable by economic and technological development.

As such the ReCiPe LCIA method was used in this study at midpoint and endpoint levels. The hierarchist perspective was selected with an average weighting set as it is the most scientifically and politically accepted method and has been used previously in construction LCA (Blengini & Di Carlo, 2010 (b); De Gracia et al., 2010).

The final step of life cycle assessment is the interpretation of the results of the previous stages. Methodological choices are evaluated for robustness and conclusions and recommendations presented.

2.3 Use of life cycle assessment in construction

A life cycle assessment of a building generally consists of examining the building in three stages; assembly, operation and end of life. The significance of the operational stage of a conventional building in terms issues such as energy use and environmental impact has previously been identified (Sartori & Hestnes, 2007). To reduce this significance and increase the energy efficiency of buildings designers have become more focused on creating low-energy buildings. This is achieved by a number of methods, such as increasing the envelope air-tightness and improving the buildings' thermal efficiency with insulation. Increasing the amount of materials which are energy and resource intensive in manufacture has an effect on the significance of the assembly stage in life cycle assessment. Life cycle assessments on low energy buildings have shown that they have a higher embodied energy than conventional buildings (Ramesh et al., 2010). Sartori & Hestnes, (2007) reviewed 60 case studies examining the operational energy of low energy and conventional buildings and concluded that the trend of decreasing operational energy is accompanied with an increasing embodied energy. Overall the conventional buildings reviewed had an embodied energy in the range of 2 - 38% of its life cycle energy whilst low-energy buildings had a higher embodied energy range of 9 – 46% of its life cycle energy. It should be noted that the life cycle energy of low-energy buildings is much smaller than the life cycle energy of conventional buildings. These studies focus solely on life cycle energy, but it is important to note that the environmental impacts of a building extends beyond the embodied and operational energy with other burdens, such as resource and mineral extraction and fossil fuel use.

Blengini & Di Carlo (2010) considered the changing relevance of stages of LCA in their study of a low energy home and a conventional home in Northern Italy. They concluded that the operational stage accounted for 50% and 80% of life cycle energy use for the low energy home and the standard home respectively. In the context of environmental performance the low energy house outperformed the standard house in environmental indicator categories of ozone depletion potential, global warming potential and photochemical ozone creation potential. Previous life cycle assessments in the UK have focused on energy consumption and carbon emissions and are often not comparable lacking details and consistent boundaries as detailed in Monahan & Powell (2011). Table 1 shows a range of the values specific to the UK, with Monahan & Powell (2011) and Hammond & Jones (2008) looking at embodied energy and carbon associated with the assembly stage whilst Hacker et al. (2008) and NHBC (2011) examining carbon for the assembly and operational stage.

Table 1 – UK specific case studies with assembly and operational carbon and energy consumption

| Author | | No | Embodied Energy (GJ/m ²) | Construction Carbon kgCO ₂ / m ² | Operational Carbon kgCO ₂ /m ² | Predicted Service Life | System Boundaries |
|-------------------------|-------------|----|--------------------------------------|--|--|------------------------|------------------------|
| Monahan & Powell (2011) | UK | 3 | 5.7-8.2 | 405 - 612 | - | - | Cradle to construction |
| Hammond & Jones (2008) | 12UK & 2USA | 14 | 5.34 | 403 | - | - | Cradle to construction |
| Hacker et al (2008) | UK | 4 | - | 492 – 568 | - | 100 | Cradle to occupation |
| NHBC (2011) | UK | 12 | - | 410 - 530 | 690 – 1050 | 60 | Cradle to occupation |
| | | | | 650-780 | 1060-1790 | 120 | |

The end of life stage is often considered the most difficult in the LCA process with credible predictions regarding the future rate of recycling and reuse subject to change and are highly dependent on future recycling policy (Scheuer et al., 2003). Review articles show that this stage is not included in most literature (Sartori & Hestnes, 2007, Ramesh et al., 2010). Allocation of the environmental savings appears to be problematic; there is no common agreement on how energy gains from a demolished building may be allocated (Ramesh et al., 2010). Previous LCA papers, which have included an end of life stage based on assumptions and predictions, have shown that the end of life stage accounts for minimal amounts of total life cycle energy (Scheuer, 2003; Junnilla et al., 2006). Blengini & Di Carlo (2010) however emphasise the importance of the end of life waste scenario, with recycling of construction waste reducing the amount sent to landfill and displacing the effect of the removal of virgin material. Whilst the author recognises the benefit of including such detailed observations it was not possible to gather the extensive detail required. A simplified approach was adopted; where-in the end of life stage saw predictions of 70% of materials being reused / recycled on site and 30% being sent to landfill, a conservative split value based on current rates of recycling within the construction industry (WRAP, 2009).

3 DESCRIPTION OF CASE STUDIES

3.1 Retrofit house – Victorian house

A red brick solid wall three storey mid-terrace Victorian house was studied prior to and after retrofitting. The house is a typical example of the Victorian terraces that are common across the UK. An extension completed in 1985 was constructed of double leaf block walls, with a 75mm cavity and 25mm insulation. The house consists of three bedrooms, a bathroom, kitchen, living and dining room; further details are provided in Table 2.

Whilst there are some UK guidelines and specifications for retrofitting practices provided by the Energy Saving Trust (2010), National Refurbishment Centre (2011) and the currently under draft PAS 2030 for improving the energy specification of existing buildings, the house is being retrofitted to *PassivHaus* standard, a German construction standard developed by the Passiv House Institut (Passive House Institute, 2006). A house built or retrofitted to the *PassivHaus* standard has exceptionally low energy consumption - maximum annual space heating requirements of 15kWh/m² and total primary energy demand (including space and water heating, electricity, lighting, fans and pumps) of 120kWh/m². Heat losses are minimised with airtight and thermally efficient building envelope with low air change rates comparatively to conventional buildings.

As a house in a mixed terrace of social and private dwellings external wall insulation was unsuitable, instead the internal masonry walls were parged with the bonding of a vapour barrier to provide an airtight seal. A combination of phenolic and aerogel insulation was used with additional flanking insulation to minimise thermal bridging at the junctions of the internal and external walls. The roof was treated in a similar fashion fitted with air-tight barrier and insulation. The original floor slab which had no insulation was removed and replaced with one atop of 200mm phenolic insulation, PassivHaus certified triple glazed windows and external doors were used throughout with thermal bridging with masonry minimised by inserting aerocell and closed cell foam insulation around the edges of the frames. Given the expected low air change rate on completion a mechanical ventilated heat recovery (MVHR) system has been installed to eliminate potential humidity issues, ensure sufficient air quality and allowing heat recovered from air being removed to heat incoming air. An eight module photovoltaic panel was mounted on the south facing roof with a predicted annual yield of 1.462kWh. More detailed information about this project and other low energy building projects is available from the Low Energy Building Database (2011).

3.2 New build house

The new build reported case study is a semi-detached block of two houses achieving a B2 Building Energy Rating, the official energy assessment method of Ireland. Each house is an identical 2.5 storey four bedroom dwelling. The attic space conversion to a master bedroom, *en-suite* and dressing room, results in the optimal use of a house foot print that would typically be used for a three bedroom house. The building envelope consists of double leaf precast concrete walls with a 40mm cavity and 100mm high density insulation shot fixed to the inner leaf. Internal walls and the shared party walls were constructed of precast concrete panels. Floors are precast prestressed concrete units. All precast items were manufactured locally and were lifted by crane into place, with stainless steel brackets connecting and securing panels and flooring. This method of construction allows for rapid construction and produces very little construction waste onsite. A pitched timber roof was constructed and finished with vapour barrier, sarking felt, battens and concrete roofing tiles. Further details are provided in Table 2.

Table 2 - General details of pre / post-retrofit & new build case studies

| | Units | Pre-retrofit ^a | Post-retrofit ^b | New build |
|---|----------------------|---------------------------|----------------------------|-----------------------|
| Usable floor area | m ² | 91.68 | 91.68 | 144.158 ^c |
| Volume | m ³ | 219.319 | 217.4208 | 353.1871 ^c |
| Number of floors | | 3 | 3 | 3 ^c |
| Air change rate (test results at 50 Pa) | ACH | 12.21 | 1 | 10 ^d |
| Indoor temperature | °C | 18-21 | 18-21 | 18-21 |
| U-Values | | | | |
| Ground floor | W/(m ² K) | 0.48 | 0.1 | 0.6 ^e |
| Walls | W/(m ² K) | 1.20 | 0.15 | 0.6 ^e |
| Roof | W/(m ² K) | 2.22 | 0.1 | 0.3 ^e |
| Door | W/(m ² K) | 3 | 1 | 3.0 ^e |
| Windows(average) | W/(m ² K) | 4 | 0.9 | 3.0 ^e |

^{a & b} Information for pre/post-retrofit Eco-Energy NI, *pers comm.* (2010).

^c Information for New Build Owens Group, *pers comm.* (2010)

^d New Build Air Change Rate – figure based on reasonable upper performance limit for air permeability of the Irish Building Regulations (Department of Environment, Heritage & Local Government, 2008, p.20).

^e New Build U-value figures based on maximum elemental u-values of the Irish Building Regulations (Department of Environment, Heritage & Local Government, 2008, p.17)

4 METHODOLOGY

Despite the well defined methodology of life cycle assessment, journal articles do not have to adhere to the requirements of ISO14040, with much of the literature non comparable due to varying assumptions and methodological choices. Optis & Wild (2010) on completion of a review of the adherence of 20 journal articles to ISO14041 concluded that the majority did not present sufficient information, limiting their potential use to others and the advancement of LCA use. To reduce uncertainty, in so far as possible international standards and guidelines as per ISO14040, Guinée et al. 2002, ILCD, 2010 were adhered to in this paper, with any deviations highlighted. Table 3 shows details of the functional unit and life span modelled for the study.

Table 3 - Functional unit & life span modelled

| | Definition & modelling procedure | Reference |
|------------------------|---|--|
| Functional unit | Identified function of a product, allows analysis and comparisons between alternatives. To allow for the significant difference in size of the buildings the environmental impact and energy consumption is expressed in terms of habitable living area, per m ² . | Guinée et al., 2002 |
| Life span | Life spans of 50 & 80 years modelled for both case studies. | Sartori & Hestnes, 2007; Ramesh et al., 2010 |

4.1 System boundary and assumptions

The recently released European Standard, Sustainability Assessment of Buildings BS EN 15643-1:2010, is the first in a series of standards from the CEN TC/350 Sustainability of Construction Works currently under development. It sets out a framework to examine the sustainability of a building by studying the environmental, economic and social performance

of the building using a life cycle approach. It recommends that the building life cycle is divided into three stages:

- the before use stage (referred to as the assembly stage in this paper) - consists of raw materials, transports, manufacturing process and construction process.
- the use stage (referred to as the operational stage in this paper) - consists of maintenance, material replacement rates, operational energy; heating, lighting, appliances and hot water heating.
- the end of life stage - consists of demolition/deconstruction process, material reuse/recycling/refusing.

Figure 3 shows the system boundaries used in the modelling process, with items outside the thick broken line excluded from modelling whereas items inside this line were included. Whilst some of the excluded items would be of environmental significance, such as operational water use, operational waste production, waste transport and reprocessing of recyclable materials, these were neglected from the modelling process as primary data could not be gathered for both case studies. Including these items would have required a large number of assumptions to be applied to both case studies which would have eventually been negated with any comparison between the two buildings.

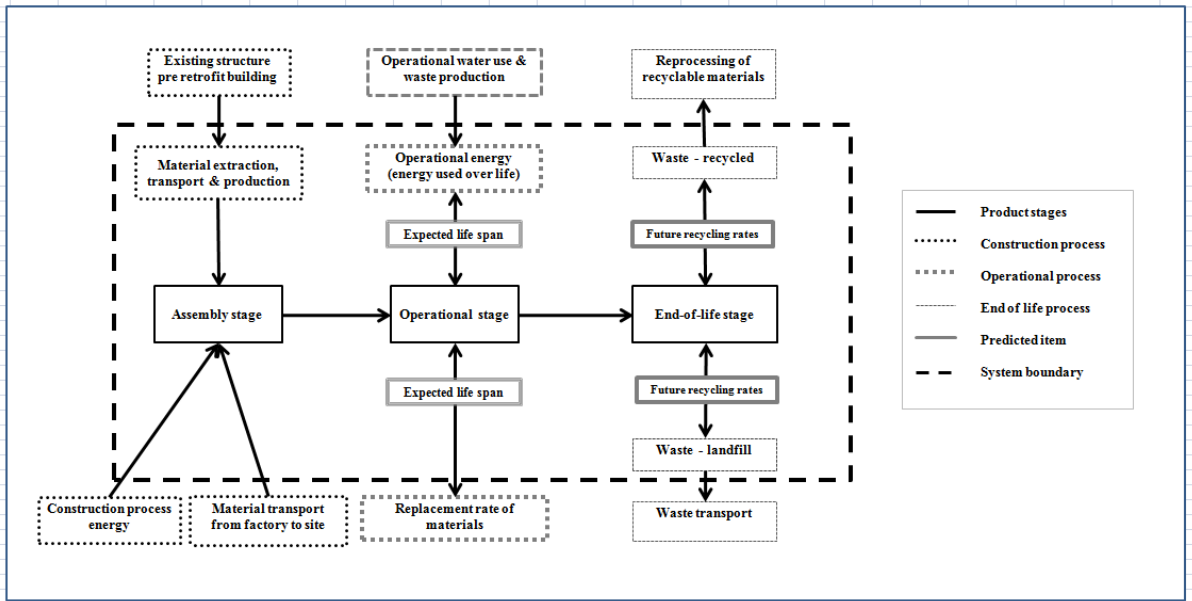


Figure 3 - System boundary included in study

The remaining items excluded from the system boundary were not part of the modelling process because it has been shown in previous literature that they have only a small environmental impact, as listed in Table 4.

Table 4 - Rationale for excluding items from study

| Item | Reason for exclusion | References |
|---|---|---|
| Replacement rates of materials | Replacement rate is low (75-80 years) for structural elements and high for internal finishes. Internal finishes not modelled. | Scheuer et al., 2003; Kellenberger & Althaus, 2009. |
| Construction process impacts | No comprehensive primary data for both studies available. Scheuer et al., (2003) reviewing others estimated construction process was 1.2-10% of embodied energy. Kellenberger & Althaus (2009) concluded that it could be ignored. Thus given low relative impact of assembly stage it is felt that neglecting this is not significant. | Scheuer et al., 2003; Kellenberger & Althaus, 2009. |
| Material transportation from factory to site | Previous literature has shown that less than 1% of primary energy and environmental impacts are associated with the transport of materials. | Scheuer et al., 2003; Sartori & Hestnes, 2007. |

4.2 Life cycle inventory and data assumptions

4.2.1 Assembly materials

The bill of quantities and design drawings were received for both the retrofit and new build houses. Using the SimaPro 7.2 LCA software application, primary data was amalgamated along with secondary data from the Ecoinvent database and the inventory modelling was undertaken. The Ecoinvent database compiles a broad range of products and services from Swiss and Western European manufacturers and service providers (further information available at www.ecoinvent.ch). Due to its large range of construction materials and processes it has been used in a number of recent LCA (Bribián et al., 2009; Blengini & Di Carlo, 2010 (b); De Gracia et al., 2010). Processes in the Ecoinvent database contain information about the raw material usage, extraction, production and transportation of construction material and all associated environmental impacts, such as emissions to air and water. Of the 2,500 processes available in the Ecoinvent database, 30 were used to model the life cycle inventory of the retrofit and new build case studies. Whilst the author recognises that use of the Ecoinvent database is not ideal for the UK, with many of the entries based on mid-Europe processes, the lack of comprehensive and transparent life cycle assessment details for processes in the UK resulted in its use. One exception to the use of the Ecoinvent database was in the case of the precast concrete components used in the new build where Ecoinvent was supplemented by details from the Inventory of Carbon and Energy (Hammond & Jones, 2008) to compensate for additional energy required and carbon produced in the precast process.

Table 5 – Quantities of materials used in retrofit and new build case studies

| Material | Unit | Retrofit | New Build |
|-----------------------|----------------|-----------------|------------------|
| Insulation | kg | 1112.67 | 3168.23 |
| Steel | kg | 1368.45 | 3614.47 |
| Oriented strand board | m ³ | 2.85 | 0.00 |
| Doors | m ² | 13.04 | 38.51 |
| Window frame | m ² | 2.34 | 4.74 |

| | | | |
|-----------------------|----------------|----------|----------|
| Sarking felt | kg | 271.83 | 875.16 |
| Gypsum plaster board | kg | 1919.42 | 688.75 |
| Softwood timber | m ³ | 1.54 | 6.02 |
| Lead | kg | 33.15 | 60.01 |
| Concrete | m ³ | 5.70 | 156.43 |
| Glazing | m ² | 9.14 | 26.86 |
| Plastics | kg | 139.60 | 1788.09 |
| Ventilation equipment | no | 1.00 | 0.00 |
| Copper | kg | 5.09 | 13.76 |
| Photovoltaic panel | m ² | 1.39 | 0.00 |
| Base plaster | kg | 1402.16 | 22641.00 |
| Concrete roof tile | kg | 696.78 | 2162.16 |
| Inverter | no | 1.00 | 0.00 |
| Gravel | kg | 12768.00 | 75600.00 |
| Sand | kg | 1938.00 | 8500.00 |

4.2.2 Operational consumption

Table 6 shows the operational consumption for both the retrofit and the new build in terms of the space heating, domestic hot water (DHW) and electricity consumption. In the case of the retrofit detailed SAP calculations were available giving the predicted energy consumption and electricity generation from the PV roof panel. In the case of the new build the operational consumption was calculated using Dwelling Energy Assessment Procedure (DEAP) similar to the UK Standard Assessment Procedure (SAP) and was rated a B2 equivalent to a consumption of 125kWh/m²/year. A detailed breakdown was not available and based on average Irish household consumption patterns a 78%/22% split between electricity and space heating and DHW was used. (Sustainable Energy Ireland, 2008)

Table 6 - Retrofit & new build operational energy

| House | Unit | Yearly |
|-------------------------|--------------------------|--------|
| Retrofit | kWh/m² | |
| Space heating and DHW | | 46.83 |
| Electricity demand | | 32.27 |
| PV Generation | | 47.39 |
| New Build | kWh/m² | |
| Space heating and DHW | | 97.50 |
| Electricity consumption | | 27.50 |

The retrofit electricity demand being offset by the PV with the surplus electricity, approximately 15kWh/m²/year, being fed into the electricity grid. The net environmental benefit of this renewable energy source is outside the system boundary of the project and is not included.

4.3 Life Cycle Impact Assessment

As outlined previously the ReCiPe Midpoint and Endpoint LCIA methods were used in the modelling process. For the ReCiPe Endpoint method the hierarchist perspective was selected with an average weighting set. Having used the average weighting factors the endpoint damage categories were aggregated to create single score that reflected the environmental impact of each stage on a point scale.

5 RESULTS AND DISCUSSIONS

The total results of the life cycle assessment showing the environmental performance of the retrofit and new build were examined using ReCiPe at midpoint and endpoint level. The New Build house is represented as **NB** whilst the Retrofit house is represented as **R**. The performance of both houses for the assembly and operational stage is also presented using the ReCiPe Endpoint method as it is easily interpreted. Furthermore, an examination of the relationship between the embodied and operational energies of the new build and retrofit house comparatively to the operational energy of the pre-retrofit house was conducted. These results are discussed in the following sections.

5.1 Retrofit Vs new build

5.1.1 Environmental performance of complete life cycle - endpoint results

Table 7 shows the percentage contribution that each stage to a single score environmental impact using the ReCiPe Endpoint life cycle impact assessment methods over life spans of 50 and 80 years.

The operational stage of both case studies has the most significant environmental impact of the total life cycle, a finding which is in keeping with previous studies (Scheuer et al., 2003, Ortiz et al., 2009, Sartori & Hestnes, 2007, Ramesh et al., 2010). The operational stage accounted for between 89 and 97% of the single score environmental impact. This is due to the long life spans and the expected operational consumption causing significant environmental emissions with fossil fuel based heating/DHW systems and the current electricity generation fuel mix also being fossil fuel intensive. Potential changes to electricity generation fuel mix are discussed further in section 5.3.

The relative percentage importance of the assembly and end of life stage decrease with the increasing life span as the operational stage is lengthened, thus consuming more operational energy. The end of life stage is shown as a negative figure, indicating the positive effect on the environment, with environmental savings being made as materials are expected to be reused / recycled.

Table 7 – Life cycle impacts for retrofit & new build houses: service life of 50 & 80 years

| ReCiPe Endpoint (H/A) (% per stage of total impact) | R 50 Year | NB 50 Year | R 80 Year | NB 80 Year |
|--|------------------|-------------------|------------------|-------------------|
| Assembly | 26.00 | 11.65 | 16.94 | 7.44 |
| Operational | 89.15 | 94.45 | 92.93 | 96.46 |
| End of life | -15.15 | -6.10 | -9.87 | -3.90 |

The breakdown of the scores into the three endpoint damage categories, viz., resources, ecosystem quality and human health are shown in Figure 4, with a maximum score approximately 370. The resources score is high because of the fossil fuel intensive space heating and electricity generation process required during the operational stage. Human health is also high scoring, affected by the type of energy being consumed, with the burning

of fossil fuels a contributor to human health impact categories such as human toxicity, photochemical ozone formation and climate change impacts.

Government initiatives such as the ‘Retrofit for the Future’ competition from the Technology Strategy Board (2009) as well as publications from the Energy Savings Trust have already recognised the vast potential for carbon savings by increasing the energy efficiency of the housing stock. Building a-new or the adoption of retrofitting techniques to large swathes of social and private housing across the UK will allow for improved operational performance with significant savings accumulated over time, which is discussed further in coming sections.

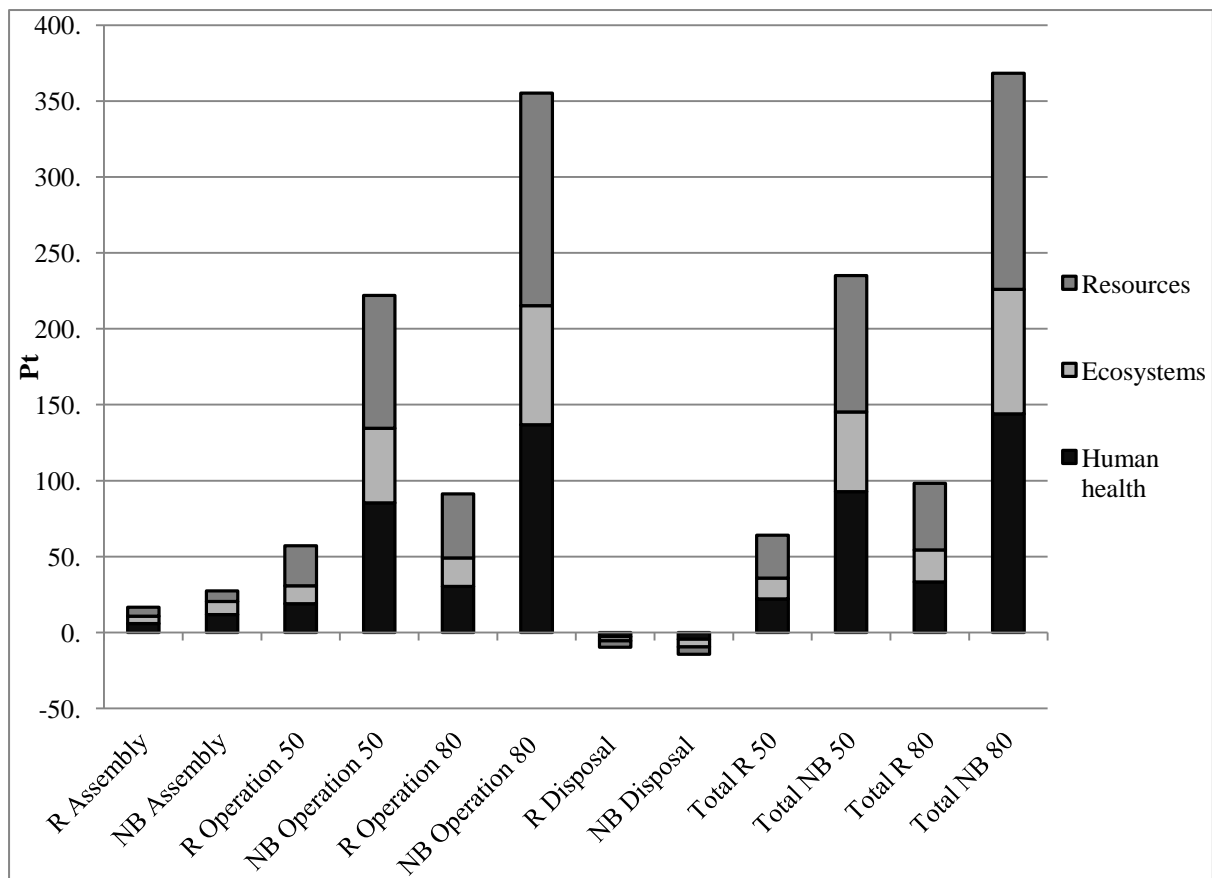


Figure 4 - Environmental impact per m² of retrofit (R) & new build (NB) house by disaggregated single score (ReCiPe Endpoint H/A)

5.1.2 Environmental performance of complete life cycle - midpoint results

ReCiPe Midpoint in the hierarchist (H) -perspective was used to show direct environmental impacts of the total life cycle impact of the retrofit and new build house in terms of the functional unit, m², over life spans of 50 and 80 years as per Table 8. The retrofit performs better than the new build in all impact categories examined. Of particular current relevance is the climate change result expressed in terms of CO₂ eq, with the new build the source of almost four times the amount of CO₂ eq of the retrofit. Table 9 illustrates the breakdown of the total CO₂eq of the life cycle in the assembly, operational and disposal stages. The new build embodied energy and carbon is lower than in the previous studies as detailed in Table 1 due to European inventory processes used in the modelling and system boundaries excluding energy required in the construction process and transport, but are still close to previously reported ranges.

Table 8 - Extract of ReCiPe Midpoint (H) results of total life cycle impacts on the environment per m² floor area

| Impact category | Unit (kg) | R 50 Year | NB 50 Year | R 80 Year | NB 80 Year |
|------------------------------------|---------------------|-----------|------------|-----------|------------|
| Acidification | SO ₂ eq. | 0.75 | 6.35 | 1.10 | 10.03 |
| Eutrophication (freshwater) | P eq. | 0.05 | 0.39 | 0.07 | 0.62 |
| Eutrophication (marine) | N eq. | 0.40 | 1.69 | 0.50 | 2.47 |
| Climate change | CO ₂ eq. | 705.85 | 2688.15 | 1084.89 | 4204.94 |
| Human toxicity | 1,4DB eq. | 74.66 | 456.81 | 93.26 | 690.89 |

Table 9 - CO₂ eq per stage of life cycle ReCiPe Midpoint (H) results per m² floor area

| | Unit | R50 Year | NB 50 Year | R80 Year | NB 80 Year |
|--------------------|-----------------------|----------|------------|----------|------------|
| Assembly | kg CO ₂ eq | 141 | 339 | 141 | 339 |
| Operational | kg CO ₂ eq | 631.7375 | 2527.983 | 1010.78 | 4044.773 |
| Disposal | kg CO ₂ eq | -66.887 | -178.833 | -66.887 | -178.833 |
| Total | kg CO ₂ eq | 705.8504 | 2688.15 | 1084.893 | 4204.94 |

5.2 Assembly stage

The contribution to the environmental single score of the each material is presented in Figure 5 for the retrofit and new build house. The impact is expressed in terms of the functional unit of the house area in m^2 . As the retrofit house uses the existing structure of the terraced house it requires fewer materials and therefore performs better in the analysis than the new build. A large quantity of insulation, with a resource and energy intensive manufacturing process, is required to achieve the high quality retrofit and is the largest proportion at 29% of assembly stage environmental damage. The insulation and concrete precast elements are the source of 18% and 43% of the environmental impact associated with the assembly stage of the new build house, an expected outcome due to the significant quantities used and the energy intensive nature of these products.

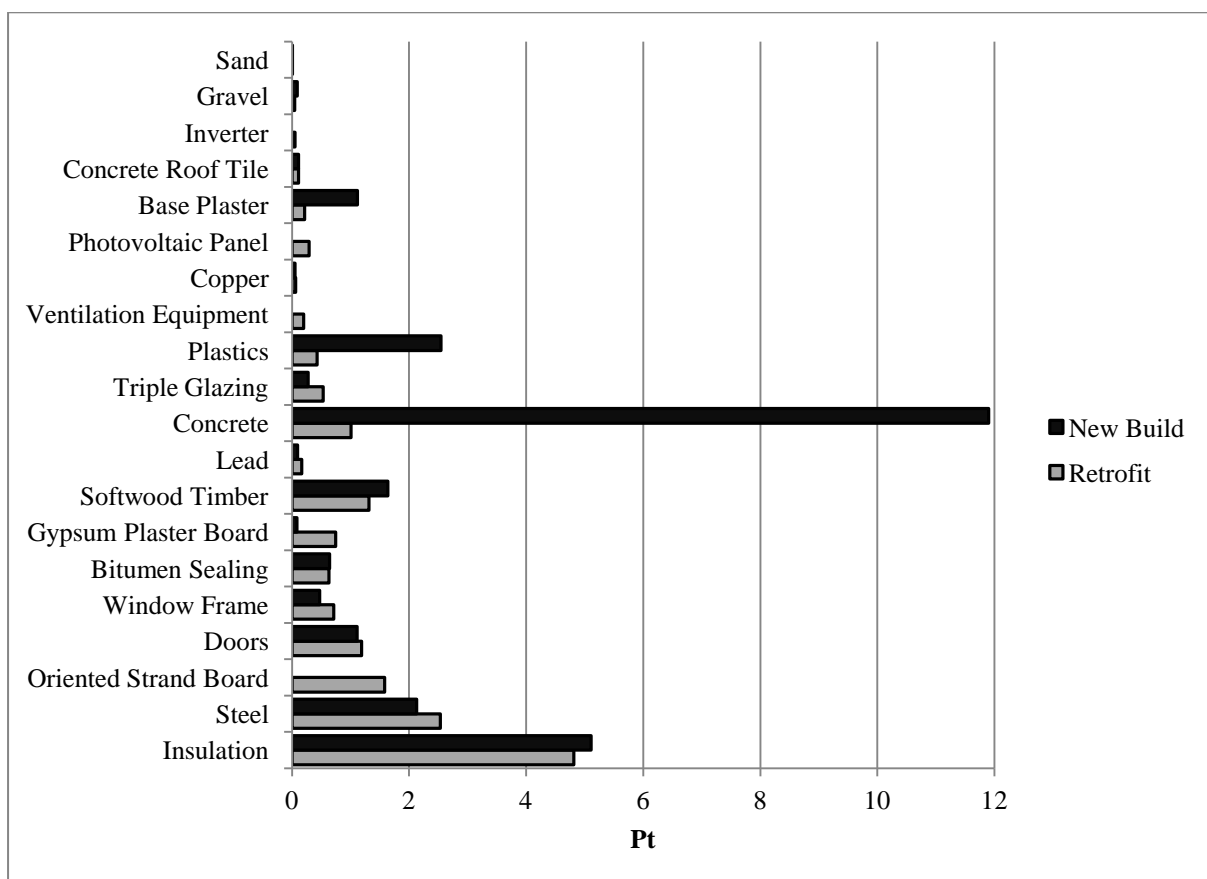


Figure 5 – Relative impact of retrofit construction materials per m^2 (ReCiPe Endpoint H/A)

The overall environmental impact associated with the construction of the new build exceeds that of the retrofit, but when these results are expressed in terms of the functional unit as per Figure 6 the extent of environmental damage associated with the new build is lessened, due to the larger floor area. However, overall the retrofit has marginally less associated damage than the new build. This may be attributable to the fact that the existing materials in the retrofit, the main structure, was not included in the modelling process, given that it would be very difficult to model accurately materials that were over 100 hundred years old. The new build was modelled in its entirety, thus having a higher quantity of materials causing more environmental damage. The energy or waste associated with the construction processes was also not within system boundaries. However, it should be noted that the construction time of the new build was significantly faster than that of the retrofit. The retrofit required the soft striping of the interior of the house, an invasive procedure that required the occupants to leave. As a trial demonstrator project in an emerging field, the retrofit served as a 'learning curve', which if replicated in the future could be improved on with different technologies and methods. This is also true of the new build, which has the potential to improve its energy efficiency by using different materials or more stringent construction details. The massive improvement on the energy performance from pre-retrofit to post-retrofit however clearly indicates the merits of action, as discussed later.

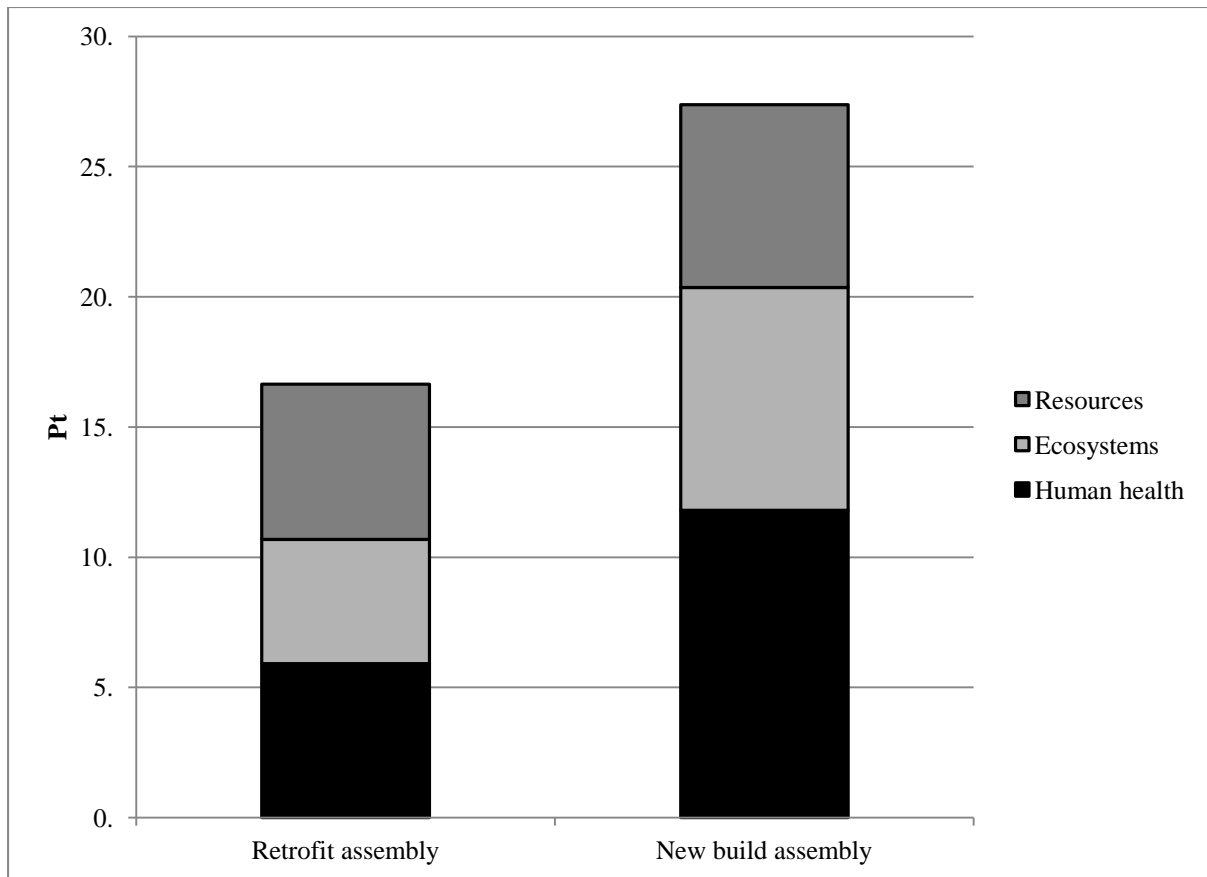


Figure 6 – Comparison of the environmental impacts of construction per m² of retrofit & new build by disaggregated single score (ReCiPe Endpoint H/A)

5.3 Operational stage

A significant proportion of the environmental burdens for both the 50 and 80 year life span are associated with the operational stage. The results are presented in the disaggregated single score form, showing the damage categories of human health, ecosystem quality and resources.

The largest associated environmental impact for the operational stage as shown in Figure 7 is in the form of fossil fuels (included in the resources damage category) with high human health impacts directly related to burning of fossil fuels in the forms of respiratory organics / inorganics and climate change. The ‘electricity, low voltage, production GB, at grid/GB’ of the Ecoinvent database that was used to model the operational energy is based on the energy

fuel mix of the UK in 2007. As can be seen from Table 10, UK electricity generation is dominated by fossil fuels, with coal, oil and gas accounting for 77.63% of electricity production (European Commission, 2010). The UK government White Paper on Energy (2007) indicates the government’s commitment to securing energy supplies and reducing their environmental impacts by increasing the use of renewable and nuclear energy and decarbonising the existing energy mix. A recent study (Jones, 2011) considered the effect of the decarbonisation of the electricity mix with the greenhouse gas (GHG) intensity of electricity improving between now and 2050 and householders adopt some GHG mitigation techniques. A static projection that does not account for the improvement to electricity mix or consumer attitude results in an operational carbon 50% higher than a dynamic projection which does. To consider this further a country that already had high levels of renewable and nuclear power in 2007, when the electricity Ecoinvent database was compiled, was chosen. Sweden as shown in Table 10 has a lower GHG intensity than the UK and was used to consider the differences between a static and dynamic scenario.

Table 10 - Gross electricity generation by fuel type-UK & Sweden (2007) (Based on European Commission, 2010, EU Energy & Transport in Figures- Statistical Handbook, Section 2.4.3 p.43)

| Fuel type | United Kingdom | | Sweden | |
|----------------------|----------------|------------|----------------|------------|
| | Quantity (TWh) | % of Total | Quantity (TWh) | % of Total |
| Coal | 136.70 | 34.51 | 0.70 | 0.47 |
| Oil | 4.70 | 1.19 | 1.10 | 0.74 |
| Gas | 166.10 | 41.93 | 1.50 | 1.01 |
| Other power stations | 1.40 | 0.35 | 0.50 | 0.34 |
| Nuclear | 63.00 | 15.91 | 67.00 | 45.03 |
| Pumped storage | 3.90 | 0.98 | 0.00 | 0.00 |
| Renewable | 20.40 | 5.15 | 78.20 | 52.55 |
| Total | 396.1 | 100 | 148.8 | 100 |

Sweden’s electricity generating process, ‘electricity low voltage, production SE, at grid/SE S’ was used to model the operational energy of both case studies and then compared with the

UK process modelled to show the environmental benefits of two scenarios; 1) immediate adoption of lower GHG intensity/fossil fuel dependent energy mix as per Sweden and 2) adoption of lower GHG intensity energy mix after 30 years.

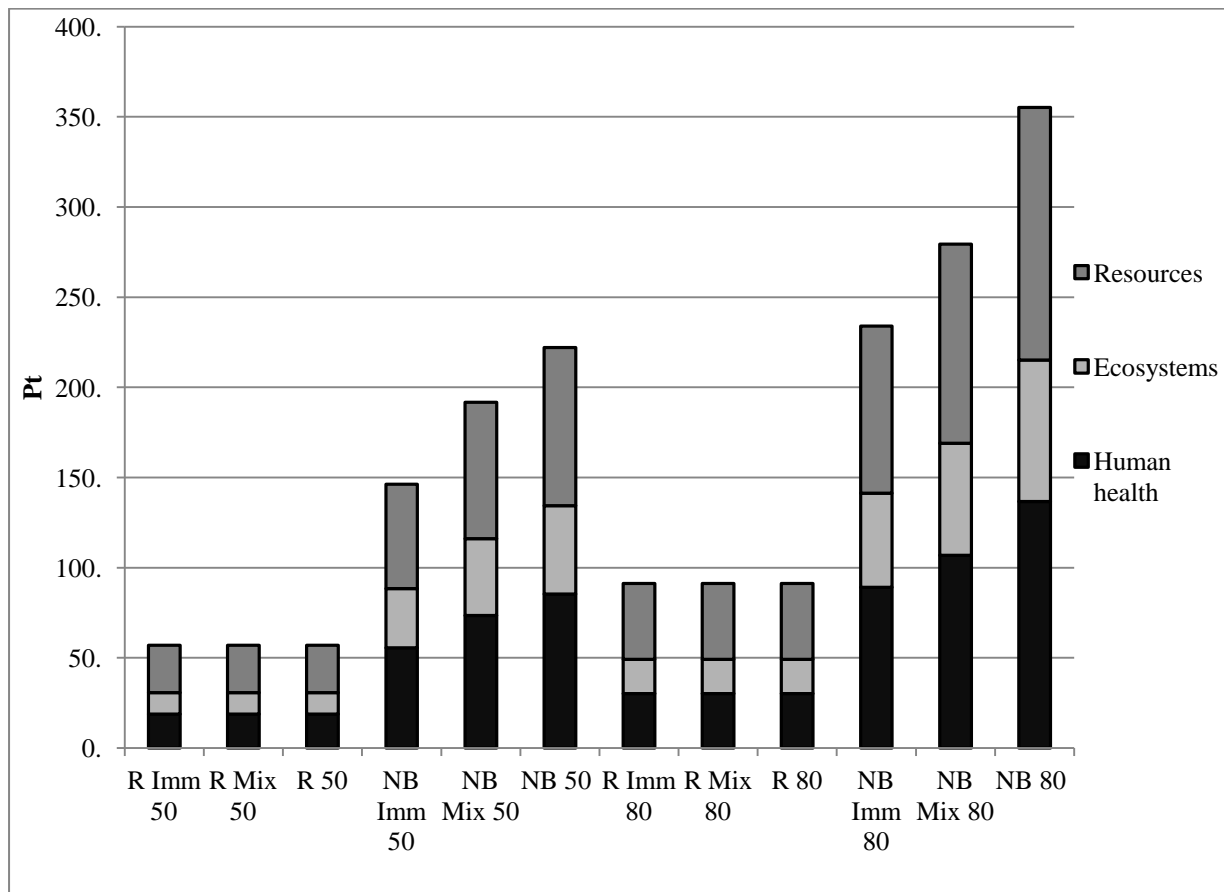


Figure 7 – Environmental impacts per m² of operational stage by damage categories (ReCiPe Endpoint H/A)

*Note: **Mix 50** represents the usage for 30 years of the current UK electricity mix with adoption of Swedish electricity mix for 20 years. **Mix 80** represents the usage for 30 years of the current UK electricity mix with the adoption of Swedish electricity mix for 50 years.*

Figure 7 indicates there is a significant potential reduction in environmental impact on adoption of energy mix that has lower GHG intensity. Over an 80 year life span the UK process has a maximum point score of 355 for the new build as opposed to the entirely

Swedish process, which has a maximum point of score 234. Significant reductions can also be seen in the introduction of less GHG intense energy mix after 30 years with the new build 80 year life span scoring approximately 280 compared to 355 of the original mix. There is a substantial decrease in resources category as would be expected given that only 2.22% of Sweden’s electricity is generated by fossil fuels. However, the overall decrease in environmental impact from using the Swedish mix is accompanied by a doubling of the radiation impact category as included in the human health category, due to a higher nuclear power usage. Overall the decrease in environmental damage from changing the electricity generation mix is significant, with large environmental savings possible over a building's life span emphasising the importance of the decarbonisation of energy production as outlined in Department of Energy & Climate Change, (2009).

6 RETROFIT PERFORMANCE

Given the nature of the Retrofit for the Future Competition the pre and post-retrofit performances were compared with the new build performance. The embodied energy of the post-retrofit and new build were included as per Table 11.

Table 11 - Embodied energy and carbon of retrofit and new build

| Embodied Energy | kWh/m² | GJ/m² | kgCO_{2eq}/m² |
|------------------------|--------------------------|-------------------------|---|
| Retrofit | 959.134 | 3.45 | 140.69 |
| New build | 1284.88 | 4.63 | 340 |

The cumulative operational energy was per Table 12 with Figure 8 displaying the embodied and operational energy.

Table 12 - Operational energy of pre / post-retrofit and new build

| Operational Energy | kWh/m ² /yr | kWh/m ² 50 Years | kWh/m ² 80 Years |
|--------------------|------------------------|--------------------------------|--------------------------------|
| Pre-retrofit | 346 | 17300 | 27680 |
| Post-retrofit | 46.83 | 2341 | 6250 |
| New build | 125 | 6250 | 10000 |

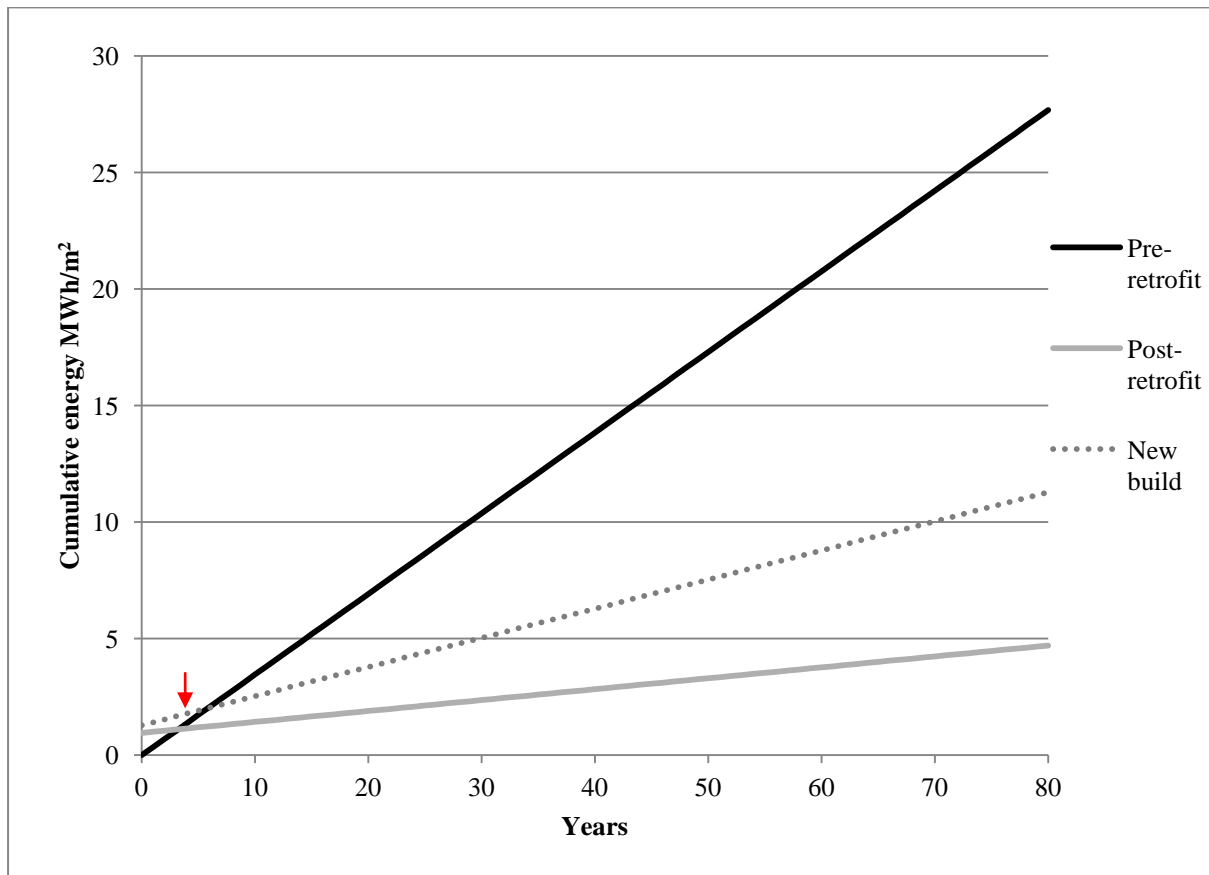


Figure 8 – Comparison of the embodied energy and the operational energy for three houses, (pre-retrofit, post-retrofit and a new build)

The pre-retrofit line represents the operational energy of the house without any modifications or retrofitting, with no initial embodied energy included and hence starts at origin of the graph. The new build line shows the initial embodied energy of the new build house, positioned slightly higher than the retrofit, increasing yearly due to its relatively higher operational energy compared to retrofit house. The post-retrofit line, the lowest line on the

graph, represents the initial embodied energy and the operational energy of the retrofit house. Thus in terms of embodied and operational energy the retrofit house performs relatively better than the new build house. Both the new build and the retrofit significantly outperform the house pre-retrofit, which has an operational energy requirement four times greater than either the new build or the retrofitted. The intersection of all three cases occurs in approximately 4 years after construction, indicating that the additional embodied energy of the retrofit and new build has completed their 'pay-back' period, having saved in operational energy comparatively to the non retrofitted (pre-retrofit) house. Figure 8 further emphasises the idea that taking no course of action in terms of the current housing stock in the UK is not a viable option, with high associated energy wastage.

7 CONCLUSIONS

7.1 Comparison of the new build house with the retrofitted house

The environmental effects of the operational stage of all case studies modelled far outweighed either the assembly or end of life stage. As such, it is felt that reducing the operational stage energy demand in so far as possible is a worthwhile endeavour. The results reported in this paper show the sensitivity of the retrofit house to the optimal level of refurbishment. Overall the results would favour the adoption of a high quality retrofitting scheme to remediate existing stock issues. It should be noted that the retrofit undertaken is of a very high quality and is an intrusive and laborious process. The re-use of the existing embodied energy in the retrofit building allows for the specification of high grades of insulation and other energy saving devices, such as the photovoltaic panels whilst still achieving a lower assembly stage impact than the new build. It must also be noted that the optimal operational level of the new build house must not be neglected. The new build house, though achieving a relatively good environmental performance rating, could potentially achieve a higher performance rating through a more focused low energy and embodied

energy design. In terms of the energy consumption, 78 kWh/m²/year separates the retrofit and new build house, which if altered without significant changes to environmental impacts of the assembly or end of life stage could see the new build outperform the retrofit. Overall these are only two case studies and further case studies on new build and retrofit projects should be undertaken to understand further the influence of new materials and technologies on the overall energy and carbon performance of new and existing housing stock.

7.2 Benefits of retrofitting

The case studies reviewed in this paper reveals that retrofitting will considerably reduce the energy requirement of a house over its life time. The energy 'pay-back' period for retrofitting was shown to be around 4 years for the examples considered in this research. Given that the current housing stock is underperforming, immediate action would allow for optimal savings and go towards the required carbon reductions by 2050.

7.3 Significance of operational energy reductions

Given the long life spans of houses in the UK the operational energy requirements accumulate annually. As the current housing stock is currently underperforming with poor SAP ratings the effect of energy inefficiency is replicated across the UK with large energy losses translating to needless environmental impacts. Improving the condition of the housing affords a better quality of life for the occupants eradicating issues such as fuel poverty whilst also fulfilling the requirements of the Climate Change Act.

7.4 Importance of decarbonising the grid

The energy generation mix of the UK as modelled is heavily fossil fuel dependent. If the energy mix in the UK had larger renewable or nuclear constituents then the associated environmental impacts of the operational stage of both case studies would be significantly different with the potential for the assembly and end of life stage to increase in relative importance. The validity of the results presented in this paper would be affected by such a

change to the energy mix with greater focus required for the increased environmental impacts of the assembly and end of life stages.

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Figure Captions

Figure 1 – Life cycle assessment process – adapted from ISO14044: Flow chart diagram showing relationship between the four steps of life cycle assessment.

Figure 2 - Relationship between life cycle inventory results, impact categories, damage categories and single score with simplified CO₂ example: Two flow chart diagrams showing relationship between inventory results, impact categories, damage categories and single score with example.

Figure 3 - System boundary included in study: Simple box diagram indicating items included and not included in study.

Figure 4 - Environmental impact of retrofit (R) & new build (NB) house by disaggregated single score (ReCiPe Endpoint H/A): Column chart showing environmental impact by the three damage categories of human health, ecosystems and resources, four columns – retrofit 50 year life span, retrofit 80 year life span, new build 50 year life span and new build 80 year life span.

Figure 5 – Relative impact of retrofit construction materials per m² (ReCiPe Endpoint H/A): Bar chart comparing impacts of retrofit and new build construction materials.

Figure 6 – Comparison of the environmental impacts of construction per m² of retrofit & new build by disaggregated single score (ReCiPe Endpoint H/A): Column chart of environmental impacts by damage category

Figure 7 – Environmental impacts per m² of operational stage by damage categories(ReCiPe Endpoint H/A): Column chart by damage category for operational stages of retrofit and new build for 50 and 80 year life spans.

Figure 8 – Comparison of the embodied energy and the operational energy for three houses, (pre-retrofit, post-retrofit and a new build): Line chart with three series representing pre-retrofit, new build and post-retrofit from the bottom up. Pre-retrofit starts at graph origin whilst post-retrofit and new build start further up on the y-axis.