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Technical Paper 13

Embodied energy considerations for existing buildings

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September 2011

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This paper should be quoted as:
Historic Scotland Technical Paper 13

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Introduction

Historic Scotland Technical Paper 13 forms one of a series of three reports, Technical Papers 12 to 14, that look at some of the wider issues concerning the existing built environment, and how it is altered to respond to current and emerging pressures regarding energy efficiency. These reports comment on topics that are often not fully investigated in the mainstream discussions on energy efficiency and the domestic housing stock. The topics are thermal comfort and energy efficiency (How do we achieve that, and are there ways of making provision for comfort that can do it better than conventional systems?); Indoor air quality and older structures (What is the balance with factors such as ventilation and health?); and finally the topic of this paper, embodied energy (The wider energy costs associated with our choices of materials used in upgrade work, and are they as durable and long lasting as the elements they replaced?) Whole life analysis is important, for modern upgrade cycles are becoming shorter while maintenance cycles are getting longer. We are essentially using components until they break or fail, and then carrying out wholesale replacement of plant equipment or building element. This uses carbon, and reduction in carbon emissions, or their equivalent, is the focus, not reduction in operational energy alone.

The present requirements on energy use regulate for the energy efficiency of the building fabric and installed building services, and are calculated based upon standards assertions as to the occupancy and use of the building. The energy, or carbon, expended in the manufacture and installation of energy efficiency elements is not addressed, and thus a situation where the end justifies the means is created. The effectiveness of a low carbon project is judged by its energy in use, not the sum total of the energy expended in its retrofit, nor by the cost of removal and disposal of parts considered to be not sufficiently energy efficient. Such interventions have serious impacts on the fabric of existing traditional and historic buildings where durable elements are replaced with components of shorter life and lower durability. The emerging discipline of embodied energy, or carbon counting, has some way to go if upgrade projects are to be properly evaluated in whole carbon terms. This embodied energy report will seek to develop basic arguments on an approach to this topic where whole-life carbon costing should be looked at in addition to energy performance alone.

Some of the themes in this series of papers overlap, and this is deliberate, for in discussion of upgrade options many factors come into play, and in complex systems boundaries are sometimes fluid. The views expressed in these reports are those of the authors, and not necessarily those of Historic Scotland or the Scottish Government.

Historic Scotland Technical Paper 13

Research report

Embodied energy considerations for existing buildings

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September 2011

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Executive summary

This report outlines the importance of life cycle analysis (LCA) in assessing the sustainability of new buildings and of maintaining, refurbishing and replacing existing buildings. Embodied energy and carbon is only one part of a building's life cycle, but is of increasing significance.

The embodied energy and carbon, associated with building construction, is the energy required and carbon emitted to construct a building (including extraction of raw materials, manufacture of building products and construction of the building.) The other stages of a building's full life cycle are operational energy and carbon (relating to the use of a building) and end-of-life energy and carbon (relating to its demolition and disposal).

This report, intending to support a discussion about energy and carbon assessment of existing buildings, provides an introduction to life cycle thinking generally, before presenting considerations specifically for existing buildings.

The report demonstrates that, although embodied energy and carbon is important generally, the energy used and carbon emitted in the past, i.e. the *sunk* embodied energy and carbon, does not matter in achieving the set UK reduction targets for greenhouse gas emissions. Sunk energy and carbon is of no relevance for mitigating the energy consumption and carbon emissions of today and the future.

Nevertheless, there is a strong argument for retaining existing buildings – even if their embodied energy and carbon is of no relevance today. The use of durable, long-lasting materials – as used in many older existing buildings – can reduce refurbishment cycles, therefore requiring less energy and carbon long-term. However, existing buildings need to be affordable to occupy and maintain, and energy-efficiency upgrades might be needed to achieve this. A LCA is required to choose the best long-term upgrade solutions. For this, the building's construction type must be taken into account, as some upgrade options might be unsuitable for use in traditional buildings.

There will be an argument for replacing some existing buildings with new ones. However, this decision should not be taken lightly. A full LCA should be conducted for the replacement building and should include the end-of-life energy and carbon of the existing structure.

Decisions for energy-efficiency upgrades of existing buildings should be made on grounds of energy, carbon and financial costs, but other factors need to be considered, too. Historic buildings, for example, have a cultural and educational value, due to they can play a strong role in creating identity and have a significant economic impact for regeneration and tourism.

The sustainable use of existing buildings must be a national and global priority. Replacing a building has significant energy, carbon and financial cost implications. The retention of the existing building stock is, therefore, preferred, where its energy performance is good or can be improved to appropriate levels. Retaining existing buildings and seeking to enhance their energy performance in sensitive ways is in keeping with building conservation, sustainability and progress towards a low carbon society.

1. Introduction

The Scottish and UK parliaments have introduced legislation to cut greenhouse gas emissions that cause climate change. The *Climate Change (Scotland) Act 2009* sets out two major targets for reduction of these emissions: 42% reduction by 2020, and 80% reduction by 2050. The current UK commitment is 34% and 80% by 2020 and 2050 respectively (Department Of Energy And Climate Change, 2011).

Carbon dioxide (CO_2) is a significant greenhouse gas and, consequently, these emission reduction targets apply to CO_2 emission, often simply referred to as carbon emissions. These emissions are inextricably linked to energy consumption, when energy is produced through the combustion of fuels. Buildings require large quantities of energy for operation: around 40% of UK energy is used in buildings. The construction industry is also, globally, the highest consumer of materials, using around 6 tonnes of material per person per year.

It is, therefore, not surprising that, relating to energy use in and carbon emissions from buildings, a number of policies, directives, regulations, guides and incentives have been generated, or substantially amended, over the last ten years, such as the Energy White Paper (Department of Trade and Industry, 2007), the Energy Performance of Buildings Directive (European Union, 2002), *Section 6: Energy* of the Scottish building standards (Scottish Government, 2011) and *Part L: Conservation of Fuel and Power* of the building regulations for England and Wales (HM Government, 2010), the introduction of Energy Performance Certificates (and – in England and Wales – Display Energy Certificates), the Carbon Reduction Commitment, Carbon Trading, and Climate Change Levies.

The construction industry has become proficient at designing and erecting low-energy buildings within a relatively short time period (mid 1990s to date). Coupled with this is a growing understanding by the general public of the need to conserve energy both for security of future supply and to protect the environment. In times of critical financial uncertainty, the general public is acutely aware of energy costs and is particularly eager to cut fuel bills. The 2010 *BP Statistical Review of World Energy* (BP plc, 2010) revealed a decline in the amount of energy used throughout the recent recession; the first decline since 1982.

Unsurprisingly, given all these recent developments, the assessment of energy use and carbon emissions related to the construction of buildings and their operation has developed significantly over the past decades. However, this development has, to date, focused on operational energy, i.e. the energy related to the use of a building. Embodied energy, i.e. the energy related to the construction of a building, has been somewhat neglected. (The same applies to end-of-life energy, i.e. the energy related to the demolition and disposal of a building.)

There are a wide number of technologies, software programs, tools and initiatives now in use to help reduce operational energy and carbon, but the practical application of methods to assess and reduce the embodied energy and carbon of building construction is still in relative infancy.

Energy and carbon assessment in the construction industry has also focused much on the construction of new buildings. Assessing the energy and carbon related to existing buildings was all too often limited to only operational energy. The energy and carbon associated with the maintenance and repair, upgrade and refurbishment, and demolition and replacement of existing buildings is not that often assessed properly, if at all.

This report highlights the importance of embodied energy and carbon related to building construction and intends to support a discussion about the energy and carbon assessments of existing buildings. Aimed at practitioners in the building professions and construction industry, the report provides an introduction to state-of-the-art life cycle thinking generally (Sections 2 to 5), before presenting considerations specifically for existing buildings (Section 6) and conclusions (Section 7). Section 2 introduces embodied energy and carbon, including the underlying concept of life cycle assessment (LCA); Section 3 briefly outlines the currently used LCA methodologies; Section 4 highlights the importance of the base data used in LCA; and Section 5 describes how LCA is currently being applied and how it might develop in the future. Whereas sections 2 to 5 discuss LCA generally, Section 6 focuses on existing buildings: It discusses why the sunk embodied energy and carbon of existing building – i.e. energy and carbon spent in the past – is of no relevance in achieving the set emission reduction targets; it highlights why, despite this irrelevance, existing buildings do play a major role in achieving emission reductions, through well considered maintenance and repair, and upgrade and refurbishment; and it argues that, when deciding about building replacements, the demolition of existing buildings needs to be properly assessed and considered. Section 6 also briefly considers two particular types of existing buildings: historic and traditional buildings. Section 7 summarises the considerations outlined in this report.

2. Life cycle assessment (LCA) and embodied energy and carbon

The embodied energy and carbon of a building are one part of the overall energy and carbon of the building, measured over its complete life (life cycle). So it is important, firstly, to introduce the terms energy and carbon, and then describe the concept of life cycles and their assessment, before discussing in more detail embodied energy and carbon, and, finally, what impacts on them.

2.1 Energy and carbon

Energy is needed to construct and operate a building. This energy is often produced through the combustion of fossil fuels, such as coal, gas and oil. The combustion process generates the energy used, for example, in the construction and operations of a building. However, this process also produces, as by-products, CO_2 and other gases, emitted into the atmosphere. It is these CO_2 emissions which are, generally, referred to in shortened form as ‘carbon’. In other words, energy, generally measured in joules (J) or mega joules (MJ), is converted into carbon, measured in kilograms (kg) or tonnes (t). Energy ‘consumption’ is, therefore, inextricably linked to carbon emissions, when (fossil) fuels are used. However, other forms of energy exist, for example, solar energy (a form of radiant energy) or wind energy (a form of kinetic energy), which do not generate carbon emissions when converted.

Physically, energy is neither consumed nor produced, but converted from one form of energy into another. Energy can be in the form of, by example, thermal energy (heat), electrical energy (electricity) and kinetic energy (movement).

CO_2 is only one of several greenhouse gases impacting on climate change through global warming. Instead of using CO_2 only, when assessing global warming, equivalent carbon dioxide (CO_2e) is frequently used as a measure. This is a way of describing how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount, or concentration, of CO_2. Put simply, if CO_2 has a global warming potential (GWP) of 1, then methane has a GWP of 25 and nitrous oxide a GWP of 298.

It is important not to confuse the term ‘carbon’, as generally used in this report, with the chemical element of the same name. Carbon, in the context of this report, refers to CO_2 emissions. However, the word ‘carbon’ can also refer to the chemical element ‘carbon’ (chemical symbol C), which occurs as element in form of graphite, diamond or amorphous carbon (the element’s free, reactive form), or as a compound in, by example, CO_2, carbonate rock (e.g. limestone, dolomite and marble) and hydrocarbons (e.g. coal, petroleum and natural gas). Plants can absorb CO_2 from the air, storing the carbon element in form of carbohydrates (sugar). This storing of carbon is referred to as carbon sequestration or carbon capture. That means that chemical carbon can be contained, as a chemical compound, in materials which are used in building construction, e.g. building stones and timber. However, this storage of carbon in a (raw) material does not relate to the CO_2 emissions released in the process of making a building product out of the (raw) material. So, when in this report the term carbon is used, it refers to CO_2 emissions and not to the chemical element.

2.2 What is LCA?

To create a building, energy is needed for the extraction of raw materials, the manufacture of building products and the construction of the building on site. Energy is also needed to operate a building in use, e.g. for heating, lighting, cooking and working. And energy is needed at the end of the life of a building for its demolition and disposal. Figure 1 illustrates the various life cycle stages of a building.

If a boundary is drawn around this life cycle of a building, an assessment of the inputs and outputs which cross this boundary can be made. Such an assessment is called life cycle assessment or **life cycle analysis (LCA)**. It includes the entire life cycle of a product, process or system: encompassing the extraction and processing of raw materials; manufacturing, transportation and distribution; and use, reuse, maintenance, recycling and final disposal (Consoli et al., 1993). The execution of a LCA relies heavily on data generally provided in **life cycle inventory (LCI)** databases. (LCIs are discussed in more detail in Section 4.1.)

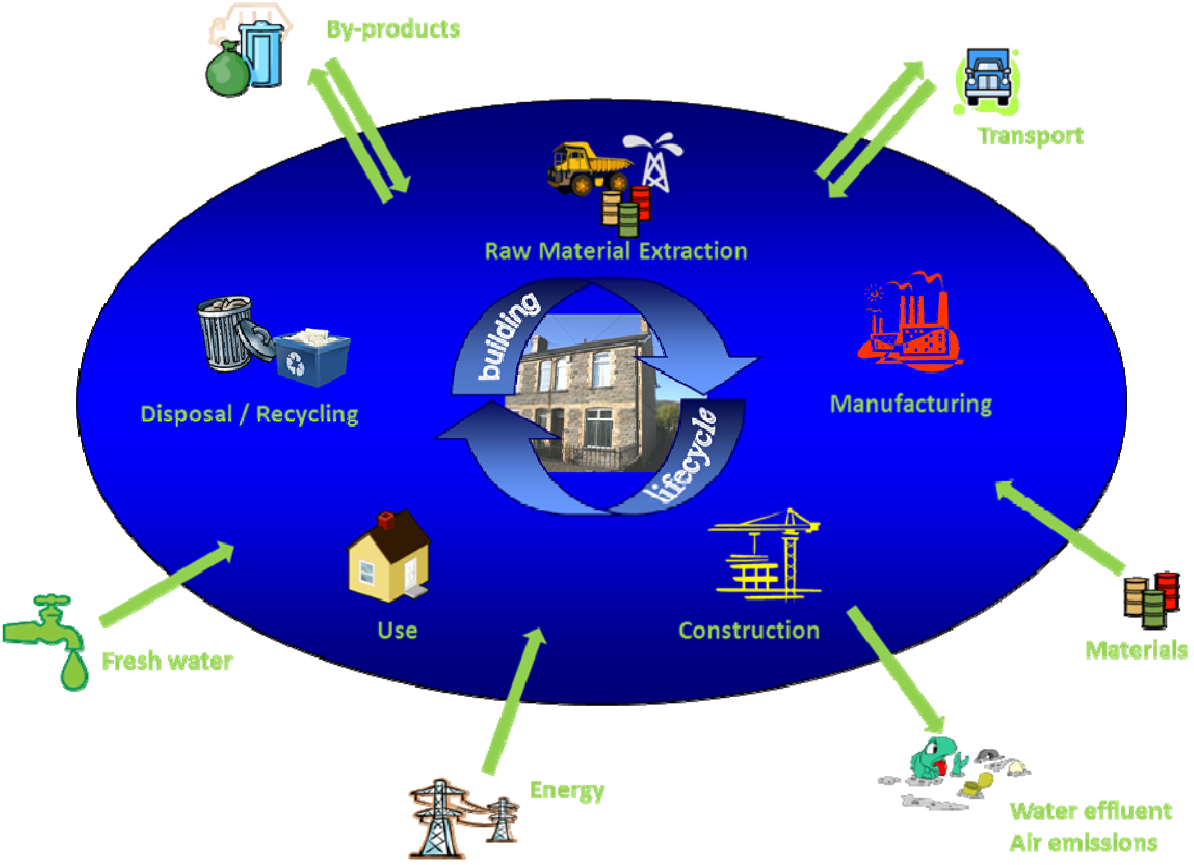


Figure 1 Life cycle stages of a building with associated inputs and outputs

LCA can be used as an accounting methodology to quantify energy use and carbon emissions for the whole life cycle of a building. In this context, LCA often utilises accountancy-speak: energy and carbon can, for example, be expended, invested or spent.

LCA is a much-explored concept and has been used as an environmental management tool worldwide since the late 1960s. It is an internationally recognised tool for assessing the environmental impact of products, processes and activities, using environmental impact indicators. LCA based, for example, on the BRE's *Environmental Profiles* methodology (BRE, 2011) identifies 13 environmental impact indicators, as listed in Table 1. It is worth noting that 'climate change' (or global warming) is only one of them and accounts for just less than 25% of the impacts.

Life cycle energy analysis (LCEA) emerged in the late 1970s and focuses on energy as the only measure of environmental impact of buildings or products. The purpose of LCEA is to present a more detailed analysis of energy attributable to products, systems or buildings. It is not developed to replace LCA, but to compare and evaluate the initial (capital, embodied) and recurrent (operational) energy in materials and components. **End of life (EoL)** issues should also be considered, i.e. the energy required to recycle and reprocess materials, or to dispose of them safely. LCEA is often used to estimate the energy use and savings over a product or building life, and to compare energy payback periods.

Table 1 LCA environmental impacts (Anderson et al., 2009)

Climate Change	Water extraction	Mineral resource extraction
Stratospheric ozone depletion	Human toxicity	Ecotoxicity to fresh water
Nuclear waste	Ecotoxicity to land	Waste disposal
Fossil fuel depletion	Eutrophication	Photochemical ozone creation
Acidification		

Life cycle carbon assessment (LCCA) is likened to LCEA and relies on prevailing energy structures to convert mega joules (MJ) of energy to kilograms (kg), or tonnes (t), of CO_2.

Life cycle assessments can be carried out for a 'full' life cycle, from extraction of raw materials to disposal or recycling of the end product after use. However, often life cycle assessments are only carried out for parts of the full life cycle. Such commonly used assessment variants are shown in Table 2.

Table 2 Life cycle variants commonly used in LCA

Cradle to Gate	describes the impacts associated with products, materials or processes up to the point at which they are packaged and ready for delivery to site.
Cradle to Site	describes the impacts associated with suppliers (raw materials), transportation to manufacturing centre, manufacturing, packaging and transportation to site. In the case of construction impacts, this would also include any processing required on site to make use of the product or component.
Cradle to Grave	describes all the processes which a product or component goes through from raw material extraction to obsolescence and final disposal. It assumes no end-of-life residual value.
Cradle to Cradle	is similar to Cradle-to-Grave', but assumes that an obsolete building, product or component has a residual value at the end of its *first* life. It assumes that construction waste can be recycled and used to provide raw materials for the re-manufacture of the same product or the manufacture of a new and different products.

2.3 What is embodied energy and carbon?

Generally speaking, a building product (i.e. construction material, product or component) has three main stages to its Cradle-to-Cradle energy life cycle: embodied energy, operational energy and end-of-life energy.

Embodied energy is the energy related to the construction of a building; **operational energy** is associated with the use of a building; and **end-of-life energy** is related to the disposal or recycling of a building. The sum of embodied, operational and end-of-life energy is referred to as **overall energy** or total energy footprint.

Carbon is a conversion of energy from mega joules to kilograms of CO_2. Consequently, **embodied carbon** relates to the construction of a building, **operational carbon** to its use, and **end-of-life carbon** to its disposal or recycles. The sum of all three is the **overall carbon** or total carbon footprint.

In other words, embodied carbon can also be defined in relation to life cycle variants as a Cradle-to-Gate or Cradle-to-Site analysis (see Table 2), based on energy inputs only (i.e. those energy inputs relating to raw material extraction, transportation, processing, manufacturing and packaging).

Product manufacturers may give embodied energy figures for their products which take into account only some of these stages. The definition of the boundaries of a LCA is critical in drawing useful conclusions on the embodied energy of a product. In general, the more manufacturing processes a product undergoes the higher its embodied energy will be. For example, laminated timber products have a significantly higher embodied energy than the equivalent dimensions of sawn timber, as illustrated in Table 3.

Table 3 Embodied energy and carbon of selected timber products (Cradle-to-Gate variant) (Hammond et al., 2011)

Material	Embodied energy MJ/kg	Embodied carbon kg CO_2e / kg
High density fibreboard	16.0	0.58
Glued laminated timber	12.0	0.45
Plywood	15.0	0.65
Sawn softwood	7.4	0.39

Energy and carbon has been spent in the past, is being spend now and will be spent in the future. If spent in the past, this is referred to as **sunk energy and carbon**. A building which is planned, but not yet built, has no sunk energy and carbon. When built and ready to be used, the building has sunk embodied energy and carbon, but not yet any operational energy and carbon. A building at the end of its life, but not yet demolished, has sunk embodied and operational energy and carbon. The relevance of sunk embodied energy and carbon, when assessing existing buildings, is discussed in more detail in Section 6.1 below.

2.4 Why does embodied energy and carbon matter?

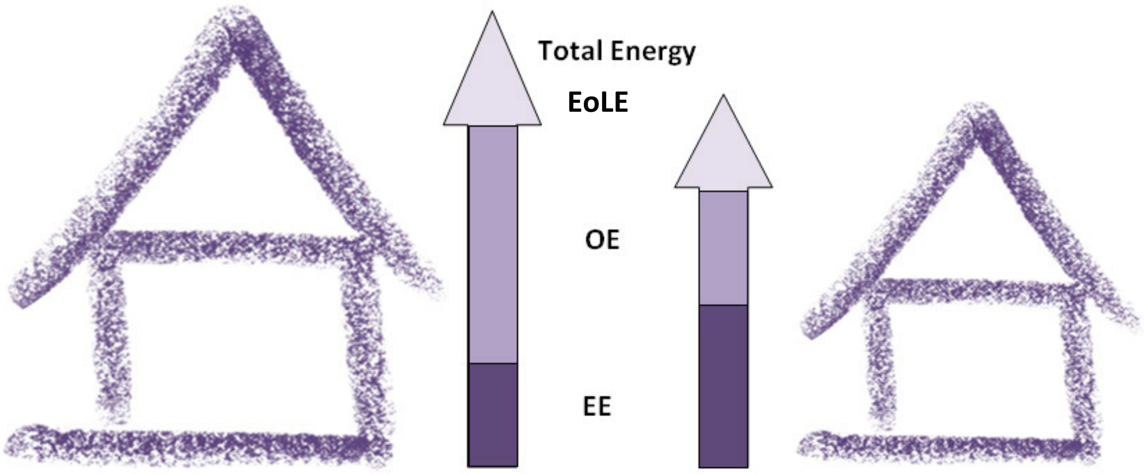
The embodied energy of a building is generally important, because it is an integral and unavoidable part of constructing buildings for use by their occupants. The significance of embodied energy within LCEA has also increased, due to higher energy efficiency levels during a building's operational life and improvements in LCEA methodologies, as will be illustrated in more detail below. (However, although embodied energy and carbon is generally important, Section 6.1 will discuss why *sunk* embodied energy and carbon does not matter for mitigating the energy use and carbon emissions of today and the future.)

It is possible that measures to reduce the operational energy of buildings will result in an increase of embodied energy: using additional embodied energy, for example through the responsible selection of building products, may significantly reduce operational energy and overall energy. This can be illustrated with the following example: To improve the thermal performance of external walls, the thickness of the insulation layer could be increased. Using more insulation means that more embodied energy and carbon is needed. The improved thermal performance of the wall will result in a reduction of the operational energy. So, in this example, an increase in embodied energy resulted in a reduction of operational energy.

As the energy life cycle is made up of embodied energy plus operational energy plus end-of-life energy, a decrease in operational energy can result in an increase in embodied energy in percentage terms (i.e. the ratio of embodied to operation energy). A building's operational energy obviously depends on its life time, whereas embodied energy and end-of-life energy are, generally, independent of this. The longer the building's life time the more significant the operational energy becomes in comparison to the embodied energy and end-of-life energy. Therefore, an increased embodied energy can be justified (recouped / paid back) through savings in operational energy over the life time of the building, if the life time assumed is long enough. This is illustrated in Figure 2 and Figure 3.

Building design decisions, other than insulation, which can increase the embodied energy, but reduced the operational energy, can include thermal mass of a building (which helps to control temperature changes within a building), solar gain (through choice of glazing and shading devices) and building form and finishes. (Expanding on these important issues is, unfortunately, outside the scope of this report.)

In 1991, BRE estimated that, for a then typical 3-bed detached house, the operational energy would overtake the embodied energy of materials and construction in a period of two to five years (Department of Communities and Local Government [CLG], 2006, p.3). Assuming the house had a life of 60 years before requiring major refurbishment, the energy in use would exceed the embodied energy by 12 to 30 times. Embodied energy was estimated to account for approximately 10% of total life cycle energy (total energy footprint) over a 60 year period. Within two decades this percentage has changed markedly and – subject to current and future building regulations – will continue to shift. For new, well-insulated, energy-efficient buildings, embodied energy can account for 40 to 60% of the total energy footprint and can even exceed the operational energy use (Dixit et al., 2010).



Building with, say, 100mm insulation, resulting in lower EE but higher OE

Building with 200mm insulation, resulting in higher EE but lower OE

Figure 2 Comparison of total energy of two buildings with different embodied energy values resulting in different operation energy values: over the same building lifetime, the building with a higher embodied energy, but a lower operational energy can have a lower total energy. (EE = Embodied energy; OE = operational energy; and EoLE = end-of-life energy)

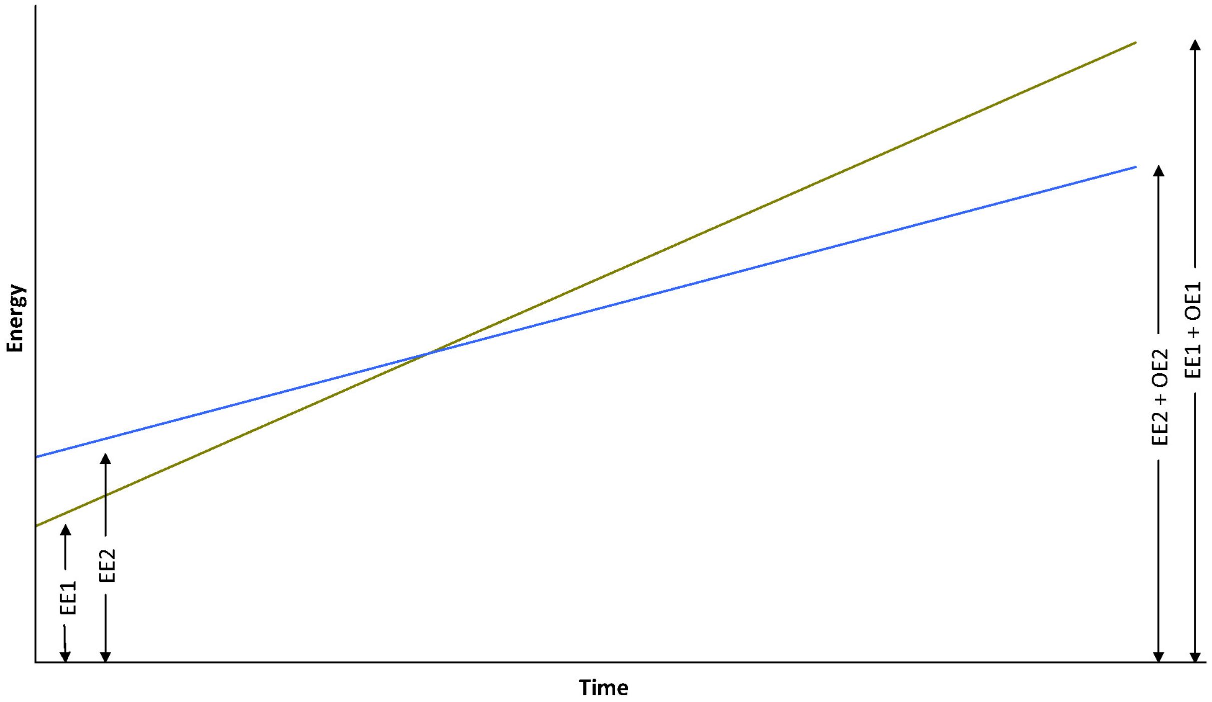


Figure 3 Comparison of life cycle energy of two buildings (with end-of-life energy not considered): Building 1 has less insulation and therefore less embodied energy (EE1) but more operational energy (OE1) (per time unit) than building 2, which has more insulation and therefore more embodied energy (EE1) but less operational energy (EE2).

The importance of embodied energy can also be dependent upon the building type and the use to which it is put. For example, distribution warehouses do not consume large amounts of energy for heating and lighting (low operational energy), which means that the embodied carbon component within the building lifecycle is comparatively high. Sturgis Associates, calculated, for example, that the embodied carbon in a distribution warehouse is 60% of its total (life time) carbon footprint; a supermarket, which is energy intensive (high operational energy), has an embodied carbon content of 20%; whereas a house has approximately 30% (Lane, 2010). This draws out an important argument in favour of absolute embodied energy values, rather than percentage of life cycle energy terms: it is possible that two buildings could have the same percentage of embodied to operational energy, yet have vastly different absolute values. An argument can perhaps be made for varying benchmarks based upon building use and type. It certainly supports an argument for considering LCA techniques in building design, renovation and upgrade works.

The closer we progress towards the ambition of zero carbon buildings, the bigger the percentage that embodied carbon contributes to the total carbon footprint. Therefore, by the end of 2019 embodied carbon will make up 100% of a building's footprint (in theory). If the determination is to make all buildings zero carbon within the next eight years, embodied energy must be recognized for its importance. Designing buildings to emit no net CO_2 on an annual basis without due regard for the embodied carbon will not satisfy the intended progress towards the 2020 and 2050 emission reduction targets.

2.5 What impacts on embodied energy and carbon?

The embodied energy of a building, as has already been pointed out, is the energy and carbon spent for raw material extraction, manufacturing of building materials and construction of the building itself – including the energy and carbon spent on the transport associated with these activities. It, therefore, becomes clear that the quantity and type of energy used in these activities is of importance. In the following, three aspects impacting on embodied energy and carbon will be described in more detail: the opportunities for the use of recycled materials, the relevance of the carbon intensity of the energy used, and the importance of low carbon supply chains.

Use of recycled materials

To make any product, energy is, first of all, needed for the extraction of the raw materials the product is made from. That means that, if a product is made from existing materials, no raw materials are needed and the associated energy is 'saved'. This can be illustrated with the energy needed to produce an aluminium window. Aluminium is generally associated with a very high embodied energy. However, as Table 4 below shows, if made from 33% recycled material, a reduction of embodied energy and carbon of approx. 86% can be achieved. Similarly, manufacturing steel from 39% recycled material reduces the energy and carbon required; however, because virgin steel has a much lower embodied energy and carbon compared to aluminium, the associated energy and carbon 'saving' is also less, approx. 30%.

Table 4 Embodied energy and carbon of virgin and partly recycled aluminium and steel (data from ICE database; see Section 4.1 and also compare to Table 6)

Material		Embodied energy MJ / kg	Embodied carbon kg CO_2e / kg
Aluminium	(100% virgin)	218	12.79
Aluminium	(33% recycled)	29	1.81
Steel	(100% virgin)	35.4	2.89
Steel	(39% recycled)	25.3	1.95

Carbon intensity of energy supplies

How energy is generated has an immense impact on the quantity of carbon emission associated with its generation. Energy generated from fossil fuels generally produces more carbon emissions than biomass. When generated with solar, wind or hydro power, there is no carbon emissions associated with the energy. This means that, using again the example of the aluminium window, such a window would have a significantly lower embodied carbon if produced, e.g., with hydroelectric power. Unfortunately, it is often not easily established from data, such as that provided in Table 4, what forms of energy have been taken into account when converting energy into carbon.

The way how energy in the form of heat and electricity is generated is changing, too. The ‘20:20:20’ initiative aims to generate 20% of EU’s electricity from renewable sources by 2020, i.e. it is aiming to ‘de-carbonise’ electricity. In current calculations, embodied energy and carbon can be treated somewhat similarly, when used as sustainability indicators. However, as the carbon intensity of electricity and heat distribution reduces, the emphasis of focus will change to embodied carbon, rather than energy. Finding more sustainable ways to generate electricity and heat energy is essential to maintaining economic and social sustainability. The ultimate aim is, of course, to contribute to achieving the set 2020/2050 emission reduction targets. However, embodied energy is important, too. Supplying reliable and ‘green’ energy is costly in terms of infrastructure, maintenance and distribution. Conserving low carbon energy is, therefore, critical to a low carbon society.

Low carbon supply chains

A low embodied energy product can have its ‘green’ credentials negated, if it has to travel long distances to its processing centres and to the construction site. For example, a concrete block sourced from a factory in the locality, or a building stone from a quarry near the construction site, will contain less embodied carbon than one from China, because of the energy used to transport it. Different modes of transport have varying CO_2 emissions. Table 5 details average carbon emissions of various means of transport.

Table 5 Transportation embodied carbon (Hutchins UK Building Blackbook, 2010)

Means of transport	Road	Rail	Shipping
Average CO_2 emissions (kg / t km)	0.32	0.04	0.01

Another example, showing how the effects of a low U-value component can be negated by transportation and logistics, is that of a novel double-glazing unit produced in Japan: the unit, manufactured using vacuum technology in place of inert gas infill, has its naturally low embodied energy and carbon cancelled, if the product is transported by air from Japan instead of using container shipping (Menzies, 2010). Ensuring that procurement allows, in this case, for slower means of transport can significantly lower the associated embodied energy and carbon.

The World Economic Forum identified five opportunities for users of logistics and transport services to decarbonise supply chains (World Economic Forum, 2009, p.6):

1. Understand the carbon impact of production locations and raw materials origins – optimising geographical locations in relation to raw material supplies, consumers, manufacturing plant, available energy supplies and available transport networks.

2. Reduce speed requirements – review lead times to allow mode switches and transport speed reductions. The requirement for express delivery in an instant society can significantly influence the embodied energy and carbon of a product.

3. Reduce packaging use – reduce transit and consumer good packaging. Bundling deliveries appropriately can cut down on both individual transport requirements and packaging.

4. Increase use of recycling and reverse logistics – increase the share of end consumer goods which are recycled to encourage closed loop supply chains. This can be significantly improved within the construction industry, but relies on organisations pooling expertise and resources.

5. Revisit distribution channels – increase home delivery where applicable to reduce individual shopping trips. This is less applicable to the construction industry, but the ethos of reducing journey times and frequency is critical.

These five opportunities combine to give a complimentary message: sustainable supply chains are ones in which responsibility is taken from the ‘cradle’ to the ‘grave’, or back to the ‘cradle’. That means that locally sourced materials, which have minimal carbon associated with their manufacture, which are durable over decades of use and which can be recycled or reused with minimal end-of-life processing.

3. LCA methodologies

There are a number of recognised LCA approaches / LCA methodologies. These include process analysis, input-output analysis and hybrid analyses. There are also simplistic / alternative approaches. These LCA approaches are briefly summarised in Figure 4 and described in more detail below.

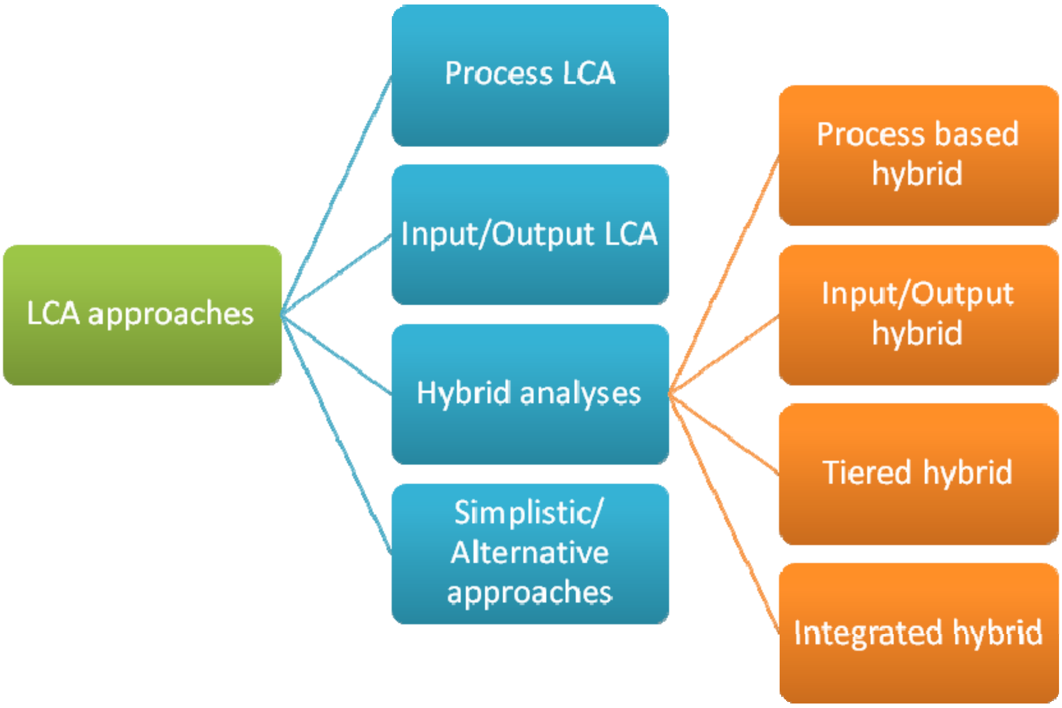


Figure 4 LCA methodologies

3.1 Process analysis

Process life cycle analysis (P-LCA) is the oldest and still most commonly used method, involving the evaluation of direct and indirect energy inputs to each product stage. It usually begins with the final product and works backwards to the point of raw material extraction. The main disadvantages centre on the difficulties in obtaining data, not understanding the full process thoroughly, and extreme time and labour intensity. These result in compromises to system boundary selections (which are generally drawn around the inputs where data is available). Furthermore, it is likely to ignore some of the processes, such as services (banking and insurance, finance), inputs of small items, and ancillary activities (administration, storage). The magnitude of the incompleteness varies with the type of product or process and the depth of the study, but can be 50% or more (Lenzen et al., 2002). For these reasons, results are found to be consistently lower than the findings of other methodologies. P-LCA is better used to assess or compare specific options within one particular sector.

3.2 Input-output analysis

Originally developed as a technique to represent financial interactions between the industries of a nation, the **input-output life cycle analysis (I/O-LCA)** can be used in inventory analysis to overcome the limitations of process analysis. This method is based on tables which represent monetary flows between sectors and can be transformed to physical flows to capture environmental fluxes between economic sectors. The number of sectors and their definition vary within each country. The great advantage of this method is data completeness of system boundaries: the entire economic activities of a nation are represented. However, despite the comprehensive framework and complete data analysis, I/O-LCA is subject to many uncertainties, due mainly to the high level of aggregation of products. Many dissimilar commodities, or sectors containing much dissimilarity, are put into the same category and assumed identical; assumptions are based on proportionality between monetary and physical flows. In some countries I/O tables are not updated frequently, resulting in temporal differences with irrelevant or unrepresentative data. Unsurprisingly, P-LCA and I/O-LCA yield considerably different results. I/O-LCA is suitable for strategic policy making decisions (comparing sectors) as well as providing complementary data on sectors not easily covered by P-LCA. To assess life cycles of older buildings, I/O-LCA would be impractical, as the economic input and output data for the time of construction is not, or at least not easily, available.

3.3 Hybrid analyses

The disadvantages of the previous methods can be reduced if a hybrid LCA method, combining both P-LCA and I/O-LCA methodologies, is employed. In this model, some of the requirements are assessed by P-LCA, while the remaining requirements are covered by I/O-LCA. The main disadvantage of these techniques is the risk of double counting.

There are, generally speaking, four types of hybrid analysis:

Process-based hybrid analysis
This method uses process analysis as the starting point and escapes the excessive amount of time needed to acquire the last few percent of the total, but is criticized for lacking transparency.

Input/output-based hybrid approach
This method uses conventional I/O analysis data as the starting point. Single or groups of data in the I/O matrices are substituted with process analysis data.

Tiered hybrid method
Process analysis is employed for use and disposal phases as well as for several important upstream processes; the remaining input data is taken from an I/O-based LCI. Aside from the risk of double-counting, the interaction between the two methodologies can be difficult to assess in a systematic way.

Integrated hybrid analysis
Process analysis and I/O analysis are developed independently and then systematically merged into one system to form a computational structure and a consistent mathematical framework.

3.4 Simplistic / alternative approaches

Due to the complexities of LCA and the complications in LCI studies, a number of simplistic methods were developed for industrial use, mainly aiming to develop quick decision making tools. Researchers have introduced a 'hotspot' approach, which selects essential issues in the inventory and applies generic data to quickly analyse products. This has been developed into a method of 'screening' and 'streamlining' to restrict LCA scope: data is obtained from a number of sources to identify environmental hotspots. These hotspots are then subject to further and fuller analysis.

3.5 Which LCA methodology should be use?

The most commonly used methodologies for building components and whole new buildings are P-LCA, I/O-LCA and hybrid approaches. In practice it is usual to find a truncated P-LCA approach, whereby the most energy intensive components and processes are captured (e.g. structure, envelope, windows, fit-out) while smaller, less energy intensive components are *ignored* (e.g. certain fittings, signage and ironmongery). I/O-LCA approaches will, by nature of the methodology, be more inclusive, but run the risk of double counting and data quality issues. Hybrid approaches, which capture much of the building through P-LCA and use I/O-LCA to fill in the '*gaps*', have also been used (Treloar et al., 2000b). It is not possible to use I/O-LCA to assess the embodied energy of existing buildings, as I/O data tables are not available for the period in which these buildings were constructed. Upgrades to existing buildings are, normally, most appropriately assessed using P-LCA methodologies.

4. Importance on LCA base data

Executing an accurate LCA relies heavily on life cycle data and inventory studies. These may include methodology assessments and database searches, in addition to direct measurements, surveys, questionnaires and possible analysis of historic data. Occasionally, theoretical calculations and personal interviews are required in addition to a clearly defined set of assumptions. Therefore, the following equation becomes clear:

Independent of any tool or methodology used,
Quality of LCA results = Quality of LCI data

4.1 Databases and inventories

A number of databases and inventories exist to supply data for life cycle purposes. Availability of reliable data in LCA studies relates directly to the time, cost and quality of a study's output. Sources of data include academic, industrial, governmental and institutional documents; trade association reports and databases; national databases, such as statistical, economic or environmental inventories; other publicly available databases; consultancies; papers and books; and best engineering judgements. A number of these sources focus specifically on building materials and construction: for example, BRE's *Environmental Profiles* building materials database (BRE, 2011) and their *Green Guide to Specification* (Anderson et al., 2009); the US National Renewable Energy Laboratory's *U.S. Life Cycle*

Inventory Database for commonly used materials, products and processes; and the Canadian Athena Sustainable Materials Institute's *Building Material Life Cycle Inventory Database*. There is much internationally recognised, published work by academics (for example, Lenzen et al. [2000], Buchanan et al. [1994], Alcorn et al., [1998], Treloar et al., [2000a]), much of which needs updated to represent current technology, transportation and means of energy supply.

The LCA methodologies consists, generally, of four distinct, analytical steps:

- defining the goal and scope
- creating the inventory
- assessing the impact
- interpreting the results

These steps are described in a series of international standards, published by the International Standards Organisation (ISO), which include:

- *ISO 14040:2006* *Environmental management – Life cycle assessment – Principles and framework*
- *ISO 14041:1998* *Environmental management – Life cycle assessment – Goal definition and inventory analysis*
- *ISO 14042:2000* *Environmental management – Life cycle assessment – Life cycle impact assessment*
- *ISO 14043 :2000* *Environmental management – Life cycle assessment – Life cycle interpretation*

Despite these standards, large differences between data sources exist and result in significant variation among published LCI studies. For example, the ICE database (Hammond et al., 2011) reports variation in the embodied energy of a brick between 1.5 and 13.8 MJ. Data variation is a fundamental problem in LCA studies. The most common causes include differences in scoping and boundary definitions, variations in assumptions made, and the various methodologies chosen for analysing LCIs.

The Inventory of Carbon and Energy (ICE)

The *Inventory of Carbon and Energy (ICE)*, developed by Hammond and Jones (2011) at the University of Bath, is a comprehensive, but not exhaustive, database of materials which references a wide number of worldwide academic and industrial sources. A range of embodied energy, embodied carbon and equivalent carbon values are presented for various construction and other materials. Some information on study boundaries is offered, i.e. Cradle-to-Gate, Cradle-to-Site and Cradle-to-Grave analysis, and an estimation of the data's sensitivity is offered (typically ranging between 25% and 40%). ICE is not intended for specific construction life cycle analysis, but does contain many individual material properties. This type of database offers useful data for the analyst wishing to perform a process-based LCA study.

The Blackbook

The *Hutchins UK Building Blackbook* (Anon, 2010) is similar in style to BRE's *Green Guide* in that materials are listed as building components. There is no breakdown of individual materials and sources. Whereas the *Green Guide* adheres to LCA practices and has a defined methodology, the *Blackbook* seems rather less transparent in its approach, but does present absolute values, rather than an abstract rating. As with the *Green Guide*, the *Blackbook* is only useful when considering new materials for prospective projects and upgrades; it cannot be applied to older existing buildings due to a lack of data about many of the building materials used in the past.

4.2 Boundary definitions

The accuracy of energy calculations is directly related to, and profoundly influenced by, boundary definitions. Naturally, more comprehensive boundary assumptions result in more precise calculations. The direct energy requirement for manufacturing processes is generally less than 50% of the total embodied energy of a product, but can be up to 80%, while the indirect energy requirement for extracting raw materials is generally less than 40% and the energy needed to make the capital equipment less than 10%. In general, the energy requirement to make the machines that make the capital equipment is very low. Inclusion / exclusion of indirect processes like raw material extraction, embodied energy of manufacturing machinery, transportation, reoccurring embodied energy of materials or the feasibility of recycling and reuse can have a significant effect on overall results.

4.3 Completeness of study

The more processes are included in a study, the more complete and accurate the results become. Indirect energy contributions depend upon many factors, including raw material sources. The ICE database commonly reports data sensitivities of 30% due to varying boundary inclusions and completeness of studies (Hammond et al., 2011).

4.4 Energy supply assumptions

These assumptions can produce significant variations in embodied energy evaluations, whether primary or secondary (delivered or end-use). Coefficients of primary to delivered energy conversion ratios should be clarified, in addition to losses due to refining and distribution, and efficiency of energy production. If primary energy is reported instead of delivered or end-use energy, the value may be 30 to 40% higher for common building materials. Lack of information regarding these factors is one of the main obstacles in comparing LCI results.

4.5 Energy source assumptions

Energy sources inherently have varying carbon coefficients, as has already been outlined in Section 2.4. Generation of electricity from hydroelectric power or other renewable sources have significantly different impacts than conventional, hydrocarbon-based fossil fuel sources. For example, in Canada and Norway, aluminium is produced solely using hydroelectric power. Brick production in Nottinghamshire uses methane from landfill (Smith, 2005) rather than traditional (generally coal fired) energy supplies. Variations in energy source and distribution will impact on both embodied energy values (due to cycle efficiencies) and carbon emissions resulting from energy use. Buchanan and Honey (1994) found that carbon emissions relating to material production could differ by a factor of three depending on assumptions made over energy supply.

4.6 Product specification

Differences in processing and application also generate large variances. Virgin steel consumes significantly more energy than recycled steel (also see Section 2.4), and different processes within the steel manufacturing industry affect embodied energy values.

4.7 Manufacturing differences

Processing efficiency levels improve over time, as a result of technological advances, and can vary depending on the geographical location. Studies following the findings of Buchanan and Honey (1994) in construction materials, summarised by Alcorn and Wood (1998), indicate a continuing downward trend in processing energy for many materials. Conversely, however, there is a trend to make more ‘technical’ specifications for construction projects. Where simple sawn timber was once used, layered and glued laminated ‘engineered’ solutions now prevail; and where exteriors may once have been a simple render or stone walls left exposed, zinc, copper and aluminium cladding are now popular. These engineered solutions often purport to reduce the need for maintenance, but do need careful analysis on embodied energy and longevity claims.

4.8 Complications in economic activities

Significantly increased production or reduced consumption, and fluctuations in economic and sectoral performances, may have vastly different implications in energy use and efficiency levels of production (Pears, 2000). The relative cost of labour compared to that of materials has a large impact on the choice and processing of materials and components and on the methods of construction. Many older buildings were constructed in an era when labour was cheap, but energy, and many building materials, were expensive. The opposite prevails in modern construction practices: labour is expensive, while energy and materials are relatively inexpensive.

5. Current and future use of LCA

5.1 Current use of LCA

Discussions on embodied energy of products, processes and activities are becoming, fortunately, more commonplace. The *Emerging Findings* report, published by the Department for Business, Innovation and Skills (BIS) (2010) and led by Paul Morrell, the UK Government Chief Construction Adviser, contains 18 recommendations on how to reduce the UK's carbon emissions. Included in the contents are the measurement and accounting for embodied carbon. The *Emerging Findings* report argues that this information should be incorporated into *The Green Book*, a guide published by HM Treasury, which sets out a framework for the appraisal and evaluation of all government policies, programmes and projects (HM Treasury, 2003).

2010 also saw the launch of the tool ***Redefining Zero*** (Sturgis Associates, 2010)*,* published by the Royal Institution of Chartered Surveyors (RICS), which offers a calculation method for embodied and operational energy use in buildings, and is based on software using the Simplified Building Energy Model (sBEM), developed by Building Research Establishment (BRE). The *Redefining Zero* report offers a step in the right direction, including embodied carbon and energy from the ICE database (already discussed in Section 4.1) and using sBEM for operational carbon calculations. While the ICE database offers embodied energy and carbon values for a wide range of materials, it is not construction or buildings specific. sBEM software is widely used to demonstrate compliance with Section 6 of the Scottish building standards and Part L of the building regulations for England and Wales, but does not use dynamic simulation as its basis, i.e. it cannot include the effects of thermal mass of a building or the cumulative effect of prolonged warm or cold weather.

The ***Green Guide to Specification*** (Anderson et al., 2009), published by BRE, aims to provide designers and specifiers with easy to use guidance on how to make the best environmental choices when selecting building components. It contains 1200 specifications used in various types of buildings, domestic and commercial. The first edition of the *Green Guide* was launched in 2006 as a response to the scarce availability of guidance and information for specifiers seeking to minimise the environmental impacts of building materials. The *Green Guide* is based on the BRE *Environmental Profiles* methodology (BRE, 2011), which uses, for its LCA, 13 environmental impacts indicators, as already mentioned in Section 2.2 and listed in Table 1.

The *Green Guide*'s ratings are given in qualitative terms (A+ to E ratings), ranked within material and component groupings, and most commonly listed as building components rather than individual materials. This type of data output has been described as 'deskilling' the architect: It renders the designer unable to aggregate or compare across component types, and offers no quantification of absolute values or transparency as to their calculation (May, 2009). In terms of the *Green Guide*'s use for older existing buildings, its value is extremely limited. Construction methods, materials and components have evolved so dramatically as to be unrepresented, although some benefit may be gained from its use in retrofit or extension purposes.

5.2 Future potential for LCA use

Although LCA are much more commonly used today, they are still not used as a mainstream tool and are not (properly) recognised in sustainable building rating systems.

Sustainable building rating systems

In May 2011, a **Scottish sustainability labelling system** was introduced to the Scottish building standards. Applicable to all new buildings, the principles build upon the degree of sustainability already embedded within the building regulations. The labelling system has been designed to reward the achievement of meeting 2010 standards, and of opting to meet higher levels that include energy and carbon emission targets, but also broader issues, such as water efficiency and flexibility in design.

The labelling system in *Section 7: Sustainability* of the building standards rewards new buildings that meet the 2010 building standards with a Bronze level label. Further optional upper levels of sustainability are defined by Silver, Gold and Platinum labels, with Platinum describing a *zero carbon* building, i.e. one which has no carbon emissions associated with its operation. The labelling system has been created through identifying cost-effective benchmarks verifiable by the building warrant system. *Section 7* also includes levels that identify whether buildings incorporate *low and zero carbon generation technology*.

All of the upper levels for energy efficiency, resource usage, building life and maintenance and quality of life requirements have to be complied with for a higher sustainability label to be awarded. The label can be utilised by developers or planners who may wish to demonstrate their environmental commitment by referring to the sustainability labels.

The Scottish sustainability labelling system has been fully developed for domestic buildings. However, due to the more varied and complex nature, labelling for non-domestic buildings has only been partially developed.

In England, the **Code for Sustainable Homes** (CSH), published by CLG (2006), was introduced in 2006 as a voluntary system to drive a step-change in sustainable home building practice. It acts as a standard for key elements of design and construction which affect the sustainability of new homes. It is designed to form the basis for future developments of the building regulations in relation to carbon emissions from, and energy use in, homes. It is further designed to offer greater regulatory certainty to developers and, as a tool, to differentiate more sustainable buildings, and their developers, from others. The CSH describes six code levels (1 to 6*) describing, amongst other sustainability indicators, carbon emission reductions between 10% and 100% on building regulations Part L (2006). Code level 6 describes a *Zero Carbon* home.

Zero carbon buildings

So what is a *Zero Carbon* building or home? It is often defined as one in which, over a year, the net carbon emissions from all energy use are zero. This includes energy use from cooking, washing and electronic entertainment appliances, heating, cooling, ventilation, lighting and hot water. So, a zero carbon home is one which generates as much power as it uses over the course of a year and, therefore, has net *zero* carbon emissions.

However, to be truly zero carbon, a home would have to generate excess energy, over and above its needs, in order to *pay back* the energy needed for its material sources, manufacturing, transportation, construction and maintenance. This introduces the concept of energy and carbon payback.

Energy and carbon payback

So what is energy and carbon payback? A financial investment incurs a capital cost, which, over time, is repaid and expected to generate an income, i.e. the initial capital investment has a payback period and a rate of return. This concept can also be applied to energy and carbon invested in buildings – be it new-build or refurbishment. For example, the energy used to source and process raw materials for (retrofitted) wall or roof insulation is expected to be recouped through reduced energy consumption during building use. This concept has already been outlined in Section 2.3. Energy efficiency in buildings is now better understood and executed through improved insulation, reduced equipment loads, reduced air infiltration, and low energy lighting and controls. However, as has already been argued in Section 2.3, with such efficiency improvements to reduce the operational energy consumption, the relative weighting (importance over the lifecycle of buildings) of the energy associated with the building materials, the embodied energy, is now increasing.

The use of renewable energy sources, and of *low and zero carbon generating technologies*, helps to decarbonise the energy still needed for a building in use. This means that a zero carbon building can still use energy, as long as the operational energy is generated without carbon emissions. However, such a building might rather be called a *zero operational carbon* building, as the building's embodied energy has not been taken into account. Only if a building is equipped with zero carbon generation technologies and generates more than it uses during operation will it pay back its embodied carbon, over time, in order to, at some point in time, become a *truly zero carbon* building.

That CSH and the Scottish sustainable building labelling system do not (yet) take embodied energy into account shows that LCA is not fully recognised in these systems to date. In *Section 7: Sustainability* of the Scottish building standards, embodied energy assessment is identified as one of the "areas considered inappropriate for inclusion … due to complexity of the subjects related to building design." However, it is also recognised that "the sourcing and embodied energy of construction materials" is "an area flagged up … for future review" and that *Section 7* may develop further in order to "respond in due course to the growing relative importance of embodied energy as the performance of new buildings improves further." (Scottish Government, 2011, items 7.0.3 and 7.0.9)

This shows clearly that embodied energy and carbon is likely to gain more importance in the future and might even be recognised as requirements in building regulations.

6. Existing buildings and embodied energy and carbon

The previous sections have looked at LCA methodologies and at embodied energy and carbon, in general. This section will now consider these topics in the context of existing buildings. Some of the discussion in this section will relate to two particular types of existing buildings, 'traditional buildings' and 'historic buildings', as will be explained in more detail below.

6.1 Why does sunk energy and carbon not matter?

Why embodied energy and carbon is generally important has already been demonstrated in Section 2.3. However, does the embodied energy and carbon that was spent in the past matter today? Does *sunk* embodied energy and carbon matter?

When discussing the embodied energy and carbon of existing buildings, a fundamental question to pose is whether there is benefit in trying to assess the embodied energy and carbon of existing buildings. These buildings already exist, which means that the energy spent to erect them has been used and the associated carbon emissions generated. As previously explained, this energy and carbon spent in the past is referred to as sunk energy and carbon.

Construction techniques and energy generation technologies have changed significantly over the last two decades and unrecognisably over the last century. However, it may be possible, using historic records and the history of construction technology, to evaluate, by rule of thumb and by process analysis, the embodied energy associated with existing buildings, as has been done, for example, to produce the following statement:

> The total energy that has already been used in the construction of a typical Victorian terrace is equivalent to the amount of energy (in fuel terms) that could drive a car five times round the earth, or half the distance from the earth to the moon. Retaining and reusing the existing building stock prevents that energy from being wasted and increases resource productivity. (English Heritage, 2003, p.8)

However, the sunk embodied energy and carbon do not themselves impact on reducing the energy use and carbon emissions of today and the future. They, therefore, do not help in achieving current emission reduction targets. What matters in these targets is the mitigation of carbon (and other greenhouse gas) emissions spend now and in the future. That means that, although embodied energy and carbon is generally important, sunk embodied energy and carbon does not matter.

Therefore, there is little point in evaluating the embodied energy or carbon originally spent when the building was erected. There is, however, significant benefit in evaluating the likely intensities of future energy use and associated carbon emissions – related to building operation (including maintenance), building refurbishments (including energy-efficiency upgrades) and building replacement (including demolition) – to meet the on-going needs of building occupants and to provide clarity for decisions on energy and carbon 'investment'.

However, although the sunk embodied energy and carbon of existing buildings is irrelevance, the existing buildings themselves, and their qualities, *are* of relevance to achieve reductions of future energy and carbon expenditure. The following sections will explain in more detail why the durability and longevity of building materials matter (Section 6.2); why upgrades of traditional buildings might need to be different from those for non-traditional buildings (Section 6.3); and why operational issues are of relevance (Section 6.4). Finally, Section 6.5 will discuss LCA considerations beyond energy and carbon assessment, which should be considered for a particular building type: historic buildings.

6.2 Building operation

Most existing buildings in their original, unimproved state are, generally, not as energy-efficient in their operation as buildings built to meet current building regulations or even better standards (such as CSH described in Section 5.2 above).

Section 6: Energy of the Scottish building standards was introduced, in 2005, to address operational carbon emissions from buildings, namely emissions arising from energy use for space and hot water heating, mechanical cooling, lighting, ventilation and auxiliary building systems. The requirement for energy-efficiency improvements under this section does not only apply to new buildings, but also to the conversion ('change of use') of existing buildings. There is, currently, no legal requirement to improve the energy efficiency of existing buildings (other than conversions). However, there are many reasons why improvements should be made. Obviously, the more energy-efficient a building the less energy it uses in its operation and, therefore, the less it costs to run. However, such economic arguments can even be taken further: Research by the National Energy Foundation has shown that buildings which are difficult or expensive to heat are more likely to be subject to under-heating and, therefore, can suffer from condensation and damp problems. This can result in increased maintenance and repair costs, and likely dissatisfaction from the building occupants. If such buildings contain let premises, this may contribute to lost revenue due to rental default and increased tenancy churn.

If existing buildings are to be retained, they need to be affordable to occupy and sufficiently-heated to minimise maintenance and repairs. To achieve this, most existing buildings will, in the long-term, need energy-efficiency upgrades. Such improvements need to be achieved in line with building regulations and other national policy (e.g. where buildings are in conservation areas or are listed); need to be within reasonable financial constraints; and, equally, need to be improved with embodied energy and carbon as priorities.

6.3 Building maintenance and refurbishment

When deciding on building maintenance (including repairs) and refurbishments (including energy-efficiency upgrades), the energy and carbon associated with such work should be taken into account; and this should best be done with a LCA. This section will discuss some of the consideration to be kept in mind for this type of construction work: the durability and longevity of the building materials used; the need to balance embodied and operational energy and carbon with regard to refurbishments; and improvements of traditional buildings, which are a particular type of existing buildings.

Durability and longevity of building materials

When considering building materials for refurbishments (and equally for use in new-build construction), the key issue is the overall carbon impact of the materials during their life time. Therefore, a high embodied energy product, such as a brick, might have a lower overall impact than a low embodied energy product, such as timber cladding, because brick can last several hundred years and, therefore, longer than timber cladding. Both, BRE's *Green Guide* and the *Redefining Zero* tool by RICS, allocate building elements a lifespan: for example, a structure may be allocated a 75 year lifespan, high performance cladding a 40 year lifespan and the central plant a 20 year lifespan.

The importance of durability and longevity of building materials can also be illustrated with a comparison of windows. Table 6 below shows that the embodied energy of uPVC is 13 times that of sawn softwood. A well maintained softwood window can last for centuries; yet the typical lifespan of a uPVC unit is less than 25 years (Asif et al., 2002). If in a timber

Table 6 Embodied energy and carbon of some commonly used building materials

Material	***ICE database*** **embodied energy MJ/kg**	***ICE database*** **embodied carbon kg CO_2e / kg**	***Hutchins UK Building Blackbook 2010*** **kg/m^2**
Rammed Earth	0.45	0.024	No value
Concrete	0.75	0.107	Floors and roofs: 74-98
Limestone	0.85	No data	No value
Sandstone	1.0	0.06	No value
Clay bricks	3.0	0.24	One brick thick 86
Sawn softwood	7.4	0.59	Timber boarding: 5-7 Ash/oak/maple flooring: 11.5
MDF/particleboard	11.02	1.4	No value
Glass	15	0.91	6 mm thick float: 14
Toughened glass	23.5	1.35	6 mm thick toughened 21
uPVC	94.7	3.16	No value
Steel (100% Virgin)	35.4	2.89	Structural steel framing
Steel (39% recycled)	25.3	1.95	ca. 1.85 kg CO_2/kg
Aluminium (100% virgin)	218	12.79	No value
Aluminium (33% recycled)	29	1.81	No value

window the glass or ironmongery is broken, it can be replaced; but a defect in a uPVC window often needs complete replacement of the window. More frequent replacement cycles increase the embodied energy over the life time of a building.

Decisions on which materials to use in construction work should not be based on embodied energy alone. Only by factoring in lifespan can the overall carbon footprint, or embodied carbon efficiency, of materials be evaluated. LCA techniques are needed to compare, on an equal basis, the impacts associated with alternative refurbishment options. For example, a timber floor may last 150 years or more, while a fibreboard floor may break up before 30 years' service. A full LCA of these alternatives would consider a number of impacts, including global warming potential, acidification, water use, health impacts etc. (see Table 1). But even a relatively straightforward LCEA must consider the replacement (5 times) of the fibreboard floor. Despite a lower capital cost of the fibreboard system, the lifecycle costs and the embodied energy and carbon over 150 years will reveal significant differences.

Many older existing buildings have been built from durable, long lasting materials: be it stone walls, slate roofing or high quality timberwork. It is, therefore, not surprising that these buildings can be quite cost effective long-term – in both financial and carbon terms.

> A Victorian terraced house is cheaper to maintain over a 100 year period (at an average of £2,648 per 100m^2 of floor space per year) than a house built in the 1980s (which would cost £3,686 for the same area). This is because of the greater quality and durability of the materials used in the construction of older houses, and the higher standards of their design and construction compared to some modern homes. (English Heritage, 2003, p.8)

A tool is currently being developed by building defects insurer BLP together with Cambridge University. BLP has a comprehensive *Life Cycle Costing* database (BLP, 200?) showing how long products last. It has already been used to develop a tool enabling house builders to calculate the life cycle costs of homes. This will be extended to also calculate embodied and operational energy and carbon, because balancing these is needed to produce truly sustainable refurbishments, as is described in the next section. A database version for new homes is anticipated to be available in 2011, with a second version for existing homes in 2012.

Balancing the energy and carbon associated with refurbishments

Not only the lifespan of the materials used for refurbishment can have an impact on the overall energy and carbon footprint, but as has already been discussed in Section 2.3, the balance of embodied and operational energy and carbon is of importance, too. This will be illustrated in the following paragraph by comparing two double-glazed windows.

The better the thermal performance of a building material the less energy is needed for the operation of the building. The thermal performance of a building material is expressed by its U-value (thermal transmittance). It is a measure of how well the material keeps heat /

coolth inside a building. A low U-value indicates a low thermal transmittance and, therefore, high insulating quality. In temperate climates, like Scotland's, designers are predominantly concerned with maintaining warm conditions within buildings and, generally, seek building components with low U-values. For example, a double-glazed window with a U-value of 1.2 W/m^{2}K would insulate better than a window with a U-value of 1.8 W/m^{2}K. However, it is important that designers are not blinkered by the need to pursue low U-values. A study by Weir (1998) showed that windows which achieved a super-low U-value of 0.83 W/m^{2}K by incorporating heavy inert gases, like xenon, had energy and carbon paybacks in excess of 200 years. In this case it would be better to use a window with a slightly higher U-value if it had significantly lower embodied energy and carbon.

Similarly to the thermal performance of windows, the embodied energy of insulation materials can vary depending on the processing required to produce it. Table 7 shows the embodied energy and carbon for a range of insulation materials. Again, the embodied energy and carbon spend on insulation to improve the thermal performance of a building, need to be balanced against how much this improvement will reduce the operational energy and carbon long-term.

Table 7 Embodied energy and carbon of insulating materials

Insulation	***ICE database* embodied energy (MJ/kg)**	***ICE database* embodied carbon (kg CO_2e / kg)**	**BRE's *Green Guide* rating**	***Hutchins UK Building Blackbook 2010* rating (kg/m^2)**
Cellulose	3.3	not given	A (recycled cellulose A+)	not given
Paper wool	20.2	0.63 CO_2 only	Not given	not given
Recycled wool	20.9	not given	A	not given
Flax	39.5	1.7 CO_2 only	Not given	not given
Mineral wool	16.6	1.28	A+ to C (depending on density)	11.03 (60 mm thick)
Polystyrene	109.2	4.39	A+ (E for HFC blown)	56.6 (100 mm thick)
Polyurethane	101.5	4.26	A	63.1 (100 mm thick)

As with the previously discussed lifespan of materials, a full LCA is required to understand the long-term impact of refurbishment decisions on both embodied and operational energy and carbon footprints. Figure 3 in Section 2.4 has illustrated how the embodied and operational energy of two new buildings, constructed to different insulation levels, compared over time.

Analogously, Figure 5 illustrates, for an existing building, the impact of refurbishment and upgrade measures on the building's embodied and operational energy. Illustrated in this figure are three options: that of an existing unimproved building (as a base line); that of an existing building refurbished twice (with no energy efficiency upgrades); and that of an existing building refurbished twice with energy efficiency upgrade measures implemented during the first refurbishment (but not during the second).

It becomes clear from the graphs in Figure 5 that it is not the actual energy figures which matter, but the energy used over time.

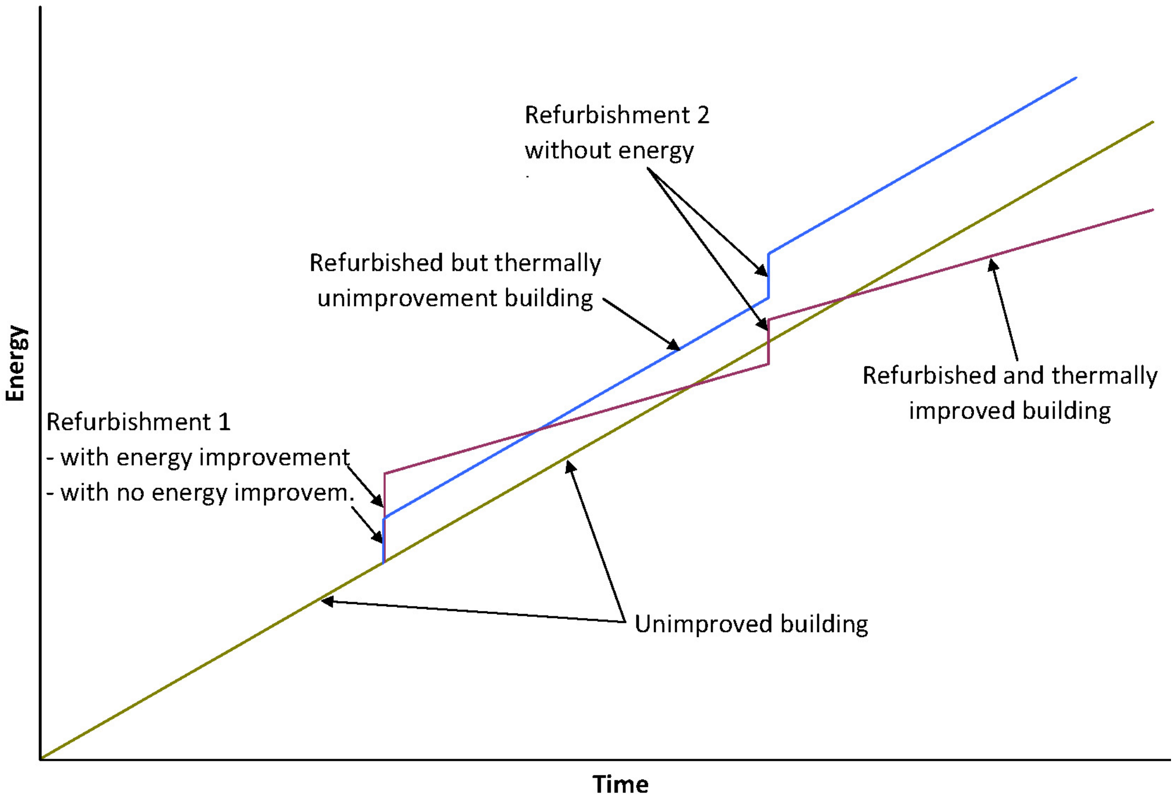


Figure 5 Comparison of two refurbishment scenarios to an unimproved building: For both scenarios, two refurbishments were assumed over time. In one scenario, both refurbishments were overhaul/repair measures with no energy efficiency upgrades; whereas in the other scenario, the first of the two refurbishments included energy efficiency upgrades (increasing the embodied energy of that upgrade, but reducing the operational energy per time unit).

Improvement of traditional buildings

Many older buildings were constructed very differently compared to buildings built today or, indeed, during the more recent past. The first half of the 20th century saw significant changes in building materials and construction techniques: brick and stone were more and more replaced by concrete and steel; instead of using mass walls, cavity wall construction and post-beam systems gained more importance; and instead of 'living' with moisture permeable building components, synthetic membranes were incorporated into these components to make them moisture impermeable. Buildings erected using pre-20th century construction can be referred to as traditional buildings; whereas buildings erected with 20th century construction techniques can be classed as non-traditional.

Traditional buildings can, more precisely, be defined as buildings which are constructed using construction techniques that were commonly in use before 1919 and constructed with permeable materials (without membranes as damp proof courses) in a way that promotes the dissipation of moisture from the building fabric. Around a fifth of Scotland's existing buildings are of such traditional construction.

Whilst recognising the need to improve the energy-efficiency of existing buildings, including both traditional and non-traditional buildings, it is important to understand the long-term impact of energy-efficiency upgrades on the particular type of construction. Some upgrade solutions, which are suitable for non-traditional construction (e.g. cavity fill insulation for cavity wall construction), might not be applicable to traditional construction (i.e. stone walls with no cavity). Furthermore, some upgrade solutions might have, long-term, a detriment impact on the existing building fabric. Traditional stone walls rely on being moisture permeable, which means that any refurbishment measure that 'seals' the surface of such a wall can result, long-term, in moisture accumulation within the building fabric. Such a moisture build-up can cause mould growth and timber decay, which in turn would then require remedial treatment in form of repairs and early refurbishment. This means that the lifespan of materials is reduced, as previously discussed, and that additional embodied energy and carbon is required for remedial works. (And this is to say nothing of mould growth as a health risk.)

A well know example is the use of external cement renders to seal traditional stone walls. However, the use of internal insulation also requires careful consideration to avoid moisture accumulation. Internal wall insulation, which causes moisture to be trapped within the wall fabric, improves the thermal efficiency of the wall, but might also cause mould growth and timber decay requiring increased refurbishment cycles – with associated energy use, carbon emissions and financial costs.

As has been discussed previously, the durability and longevity of building materials is of importance when calculating embodied energy and carbon using full LCA. Energy-efficiency upgrades, which are not suitable for a particular type of construction, such as a traditional stone wall, can result in fabric deterioration, thereby reducing the durability and longevity of the materials, increasing the refurbishment cycle and, therefore, impacting negatively on the LCA results.

6.4 Building replacement

As has been discussed above, there are good arguments why existing buildings need to be retained and maintained, especially those buildings constructed with durable materials. However, it has also been argued already that existing buildings need to be affordable to occupy and maintain, and that energy-efficiency upgrades might be needed to achieve this.

So, existing buildings should be retained and maintained – but not at any cost: For some existing buildings, energy-efficiency upgrades might not be feasible – financially or in LCA terms. So there will, no doubt, be an argument for replacing some existing buildings with new ones. However, this decision should not be taken lightly. A full and properly conducted LCA would be helpful when deciding on building replacement. Such an analysis would not only take into account the embodied energy and carbon of the replacement building, but would also consider the end-of-life energy and carbon of the existing building, namely the energy and carbon association with the demolition of the existing structure, including the disposal of the materials.

Re-using and recycling of materials from demolished buildings would, obviously, need to be taken into account in a full LCA, too. However, according to the Performance and Innovation Unit (PIU) of the UK government, 70 million tonnes of construction and demolition materials and soil end up as waste. This accounts for 24% of the total waste generated in the UK. Construction and demolition waste (e.g. soils, concrete, bricks, glass, wood, plasterboard, asbestos, metals and plastics) is reported to account for around half of controlled waste is Scotland (Scottish Environment Protection Agency, 2008). The burden of construction and demolition waste is recognised in the *Waste Strategy* for England 2007 (Department of Environment, Food and Rural Affairs, 2008), which identifies the potential to increase resource efficiency in construction and thus reduce waste. Effective waste management strategies always start with the reduction of waste as a first priority over reusing or recycling. The processing of recycled products for secondary use also requires energy (albeit into a different life cycle calculation).

Level Gold of the Scottish sustainable building labelling system recognises the importance of taking the demolition of existing structures into account (through a 'pre-demolition audit'), as well as designing new buildings in such a way that they are more easily recyclable (or "designed for de-construction") (Scottish Government, 2011, item 7.1.6 Aspect Gold 8) However, the labelling system is voluntary and does not (yet) consider embodied carbon.

LCA should be considered when deciding if an existing building is to be replaced. However, to be meaningful, the LCA needs to be properly conducted, including the factors discussed above. It should also be borne in mind that embodied energy and carbon is only one of many factors when deciding on building replacement. Financial costs might be another. A further important factor, which will be discussed in the next section, is the architectural or historic interest of a building.

6.5 Considerations beyond energy and carbon

Decisions on energy-efficiency upgrades of existing buildings should be made on grounds of energy, carbon and financial cost, which are considerations that do not need to be mutually exclusive. However, these considerations are by no means the only ones to be taken into account. An example for consideration beyond energy and carbon, when discussing existing buildings, is that of 'historic buildings'.

Historic buildings are existing buildings which are of architectural or historic interest. They can be of traditional or non-traditional construction, and of any age. The more important historic buildings are legally protected, as *listed buildings* or as part of a *conservation area*. Historic buildings have a cultural and educational value, can play a strong role in urban and rural regeneration (placemaking), and can provide facilities for communities. They can also have a significant economic impact for regeneration and tourism, as has been documented in *Scotland's Historic Environment Audit* (Historic Scotland, 2010) and England's *Heritage Counts* reports (English Heritage, 2010).

If not upgraded, historic buildings, as any other existing building, often have a higher operational energy use and, therefore, cost more to operate. These buildings will need to be suitably upgraded, where possible, if they are to be made more energy and carbon efficient and, hence, more economical to occupy. There will be conservation and technical factors in energy-efficiency upgrades of historic buildings, but improvements can be carried out.

7. Conclusions

This report has outlined the importance of LCA in assessing the sustainability of new buildings and of maintaining, refurbishing and replacing existing buildings. The embodied energy and carbon of a building is only a part of a building's life cycle; but it is this portion of the life cycle which is of increasing significance, the more energy-efficient buildings become in their use. Although the assessment of embodied energy and carbon is still in relative infancy, some LCIs, software programs and other tools are now available. However, embodied energy and carbon is not yet considered in UK building regulations and the more commonly used sustainable building labelling systems.

This report has demonstrated that, although embodied energy and carbon is generally important, the energy used and carbon emitted in the past, i.e. the *sunk* energy and carbon, does not matter for achieving the set reduction targets for greenhouse gas emission.

Nevertheless, there is a strong argument for retaining existing buildings – even if their sunk embodied energy and carbon is irrelevant today. The report has shown that the use of durable, long-lasting materials can reduce the refurbishment cycles of buildings, therefore requiring less energy and carbon long-term. Many older existing buildings were constructed with such durable materials. Existing buildings need to be affordable to occupy and maintain. Energy-efficiency upgrades might be needed to achieve this. Although many upgrade solutions are available, an LCA is required to be able to choose the best solutions long-term. For this assessment, the construction type of the building must to be taken into account, too: Some upgrade solutions might be unsuitable for use in traditional buildings, if, for example, they restrict the moisture permeability of the original building fabric.

Existing buildings should be retained and maintained – but not at any cost: There will be an argument for replacing some existing buildings with new ones. However, this decision should not be taken lightly. A full and properly conducted LCA (for the replacement building) should be conducted and should include the end-of-life energy and carbon of the existing building, thereby factoring into the LCA the costs for demolition and material disposal.

Decisions on energy-efficiency upgrades of existing buildings should be made on grounds of energy, carbon and financial cost, but these are not the only considerations to be taken into account. Other factors should, for example, be considered for historic buildings. These buildings have a cultural and educational value, due to which they can play a strong role in creating urban and rural identity, provide facilities to communities and also have a significant economic impact for regeneration and tourism. Such wider factors, beyond energy and carbon, need to be considered for historic buildings. There will be conservation and technical factors in choices of energy-efficiency upgrades of these buildings, but improvements can and carried out.

The sustainable use of existing buildings must be a national and global priority. Replacing a building has significant energy, carbon and financial cost implications. A new building would have to use many times less energy than the existing one to justify this energy and carbon investment. Retaining the existing building stock is preferred where its energy performance is good or can be improved to appropriate levels. Retaining existing buildings and seeking to enhance their energy performance in sensitive ways is in keeping with building conservation, sustainability and progress towards a low carbon society.

Glossary

Carbon (chemical element)	Carbon is the chemical element with the symbol C.
Carbon (emission)	Carbon or carbon emission is an abbreviation for *carbon dioxide* emission.
Carbon dioxide (CO_2)	Carbon dioxide is a chemical compound with the chemical formula $CO_{2,}$. It is a greenhouse gas and forms part of the Earth's atmosphere. CO_2 emissions are often simply refer to as *Carbon*.
Carbon dioxide equivalent (CO_2e)	Carbon dioxide equivalent is a distinct measure for describing how much global warming a given type and amount of a *greenhouse gas* may cause, using the functionally equivalent amount or concentration of *carbon dioxide* as the reference. (Also see *Global Warming Potential*)
Code for Sustainable Homes (CSH)	The Code for Sustainable Homes is an environmental impact rating system for housing in England and Wales, setting new standards for energy efficiency and sustainability, beyond those which are mandatory under the current building regulations. In Scotland, a similar rating system as been set-up, as part of the Scottish building standards.
Embodied energy and carbon	For a building, embodied energy is the energy related to the construction of a building. It includes raw material extraction, manufacture of building products, and construction on site, as well as any energy for transport associated with the aforesaid activities. Embodied carbon is the amount of *carbon* emitted for the aforesaid activities.
End-of-life energy and carbon	For a building, end-of-life energy is the energy related to the disposal or recycling of a building. End-of-life carbon is the *carbon* emitted for the aforesaid activities.
Global warming potential (GWP)	The global warming potential is a measure to compare the impact of different *greenhouse gases* on global warming. If *carbon dioxide* has a GWP of 1, then methane has a GWP of 25 and nitrous oxide a GWP of 298. (Also see *Carbon dioxide equivalent*)

Greenhouse gas	A greenhouse gas is a gas in an atmosphere that absorbs and emits radiation within the infrared range. The primary greenhouse gases in the Earth's atmosphere are water vapour, *carbon dioxide*, methane, nitrous oxide, and ozone.
Historic building	A historic building is an existing building which is of architectural or historic interest. It can be of traditional or non-traditional construction, and of any age. The more important historic buildings are legally protected, as listed buildings or as part of a conservation area. (Also see *traditional building*)
Input-output life cycle analysis (I/O-LCA)	Input-output *life cycle analysis* is an inventory analysis, based on table which represent monetary flows between sectors and can be transformed to physical flows to capture environmental fluxes between economic sectors.
Inventory of Carbon and Energy (ICE)	The Inventory of Carbon and Energy is a *life cycle inventory*, developed at the University of Bath.
Life cycle analysis / assessment (LCA)	A life-cycle assessment is a technique to assess environmental impacts associated with all the stages of a product's life. There are different forms of LCAs, such as *Process LCA*, *Input-Output LCA*, hybrid analysis and simplistic / alternative approaches. (Also see *Life cycle carbon analysis* and *Life cycle energy analysis*)
Life cycle carbon analysis (LCCA)	Life cycle carbon analysis is a *life cycle analysis* focussing on *carbon emissions* as the only measure of environmental impact. (Also see *Life cycle energy analysis*)
Life cycle energy analysis (LCEA)	Life cycle energy analysis is a *life cycle analysis* focussing on energy as the only measure of environmental impact. (Also see *Life cycle carbon analysis*)
Life cycle inventory (LCI)	A life cycle inventory is an inventory of flows from and to nature for a product system. An example for a LCI is the *Inventory of Carbon and Energy*.
Operational energy and carbon	For a building, embodied energy is the reoccurring energy related to the operation of a building, such as heating and lighting. Embodied carbon is the amount of *carbon* emitted for these activities.

Overall carbon / total carbon footprint	The overall carbon footprint is the total sum of *embodied carbo*n, *operational carbon* and *end-of-life carbon*. (See also *Overall energy footprint*)
Overall energy / total energy footprint	The overall energy footprint is the total sum of *embodied energy*, *operational energy* and *end-of-life energy*. (See also *Overall carbon footprint*)
Process life cycle analysis (P-LCA)	Process *life cycle analysis* is the oldest and still most commonly used method, involving the evaluation of direct and indirect energy inputs to each production state.
Sunk embodied energy and carbon	Sunk embodied energy and carbon is *embodied energy and carbon* spent in the past, i.e. energy used and carbon emitted in the past.
Traditional building	Traditional building is a building constructed using techniques that were commonly in use before 1919 and with permeable components in a way that promotes the dissipation of moisture from the building fabric.

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ISBN 978 1 84917 078 9
(Online publication)