A BSRIA guide

Embodied Carbon

The Inventory of Carbon and Energy (ICE)

By Prof. Geoffrey Hammond and Craig Jones
Ed. Fiona Lowrie and Peter Tse

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PREFACE

We are all now very familiar with the targets for reducing carbon. We have heard how we must make our buildings more energy efficient and are building to much higher standards than we were five years ago. But that concerns energy use. Another important factor in the climate change argument that we must take into account in buildings is the carbon in materials used in construction.

But how do we achieve this? The first thing to do is to find out how much carbon is actually embodied in these materials.

The report provides a lot of data and points you to lots more. It also demonstrates some of the complexities of making embodied carbon assessments. But just because the matter is complex we cannot ignore it. European legislation on carbon is tightening all the time: we must have a knowledgeable industry in the UK who are on top of the issues and deliver the best solutions to meet whatever targets are required – for energy use or for embodied carbon.

This report compiled by the University of Bath and edited by BSRIA is a welcome contribution to the development of this knowledge.

Dr Phillip Lee
Member of Parliament for Bracknell and Member of the Select Committee for Energy and Climate Change 2010

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BSRIA is delighted to have been given the opportunity to publish this guide for the University of Bath. We have produced ICE in print to encourage the industry to consider embodied carbon, (not just operational) and for people to learn more about embodied carbon before legal requirements are imposed.

Building services engineers need to understand about embodied energy and carbon when they are involved in life cycle analysis, and to understand the trade-offs between high embodied carbon and low operational carbon and vice versa.

We also want to draw much wider attention to the ICE open source database, which is an ideal resource for any carbon design tool. We have been delighted to have the database available for our own research with the iCAT (Interoperable Carbon Assessment Toolkit) team.

This document is intended to give readers a flavour of the data and to indicate the main watch points. To use the data readers will need to refer to the most up-to-date and detailed version of the ICE database at www.bath.ac.uk/mech-eng/sert/embodied/. This document is based on version 2.0 of the ICE database.

For helping with this publication, we would like to thank:

- The team working on the iCAT project, which is part funded by the Technology Strategy Board under the Low Impact Buildings Programme
- Our industry reviewers, including Mitch Layng from Prudential Property Managers, Andrew Minson from the Concrete Centre, Andrew Pitman of TRADA, and John Dowling of British Constructional Steelwork Association
- The BSRIA production team, Alex Goddard and Ruth Radburn.

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- John Dowling and Nick Coleman (Tata Steel Europe) for extensive feedback on the steel data
- The many other industry experts who have provided useful feedback and finally the many hundreds of ICE database users who have provided feedback and messages of gratitude.

AUTHORS

Geoffrey Hammond is Professor of Mechanical Engineering and Director of the Institute for Sustainable Energy & the Environment (I-SEE) at the University of Bath.

Professor Hammond is a mechanical engineer with a multidisciplinary background, including environmental engineering and management. During the 1960s and early 1970s he worked as a design and development engineer in the UK refrigeration industry, before commencing an academic career at Uganda Technical College (under the auspices of Voluntary Services Overseas) teaching mainly in the field of applied thermodynamics. He held various academic appointments within the Applied Energy Group at Cranfield University (1976-1989) before moving to the University of Bath, where he took up a new Professorship partially supported by British Gas plc. Geoffrey Hammond's own research interests are mainly concerned with the technology assessment of energy systems, using a toolkit of methods derived from the engineering and environmental sciences (such as carbon and environmental footprinting, environmental life-cycle assessment, and thermodynamic analysis).

In recent years he has advised the UK Government's Department of Energy and Climate Change, Department for Environment, Food and Rural Affairs, and the Government Office of Science on issues concerned with energy and the environment: environmental footprinting, renewable energy systems, sustainable production, and industrial energy efficiency. Professor Hammond is the joint recipient of the Dufton Silver Medal for one of his publications, and is the Joint PI of the first E.ON UK / EPSRC research consortium on 'Transition Pathways to a Low Carbon Economy'.

Craig Jones is a highly motivated, innovative, and intelligent individual with a strong academic background and a genuine enthusiasm for environmental issues. After achieving a First Class Honours (MEng) degree in Mechanical Engineering at the University of Bath, Craig stayed at the university to work on the 'Carbon Vision Buildings' project under the supervision of Professor Geoffrey Hammond. It was on this project that Craig created the ICE database and had the vision of making it freely available on the internet. Since its first release the ICE database has gone from strength to strength and Craig has since become a world leading figure in embodied carbon assessment.

Craig has presented on the subject of embodied carbon to varied audiences around the world and his research is far reaching, appearing in countless books, media articles and carbon tools. He has also published many scientific articles on the methodology and application of embodied carbon, carbon footprinting, and life cycle assessment (LCA). The latter offering a truly holistic approach.

In 2010 Craig moved into industry to work for Sustain Ltd, a leading carbon reduction company based near Bristol in the UK. Craig will maintain good links with the University of Bath and he will be an integral part of the future development of the ICE database. Craig joined his new employers as a Senior Associate in Environmental Accounting, which includes embodied carbon, carbon footprinting and LCA.

GLOSSARY

Allocation	The sub-division of input and output flows between one or more product systems. Also applies to recycling methodology (see Annex B).
Biogenic	Derived from living organisms, but not from fossil origin, e.g. biomass is considered biogenic, but coal is not.
(System) Boundaries	A set of criteria that defines which processes are included within the (boundaries of) assessment.
By-product	Material that is a sub-derivative of the processing operations but is considered to have an economic value (e.g. facilitated by an application and market demand).
Calorific value (CV) of energy	The energy content of a fuel (as may be released through combustion). It may be expressed as a gross calorific value (GCV) or net calorific value (NCV). The former is always larger than (or equal to) the latter. The difference is due to latent heat (energy) remaining in condensation (water vapour) after combustion. The difference is typically 5-10 per cent (e.g. 10 per cent for natural gas, 5 per cent for coal).
Capital energy	Energy required to manufacture capital inputs (e.g. ancillary infrastructure, such as buildings, machinery, tools).
Carbon dioxide equivalent (CO_2e)	See global warming potential (GWP).
Carbon sequestration	The extraction of carbon from the atmosphere, for example from trees and plants.
Co-product	Material/product that is produced alongside the investigated product, i.e. co-production.
Cradle	The cradle is defined as being the earth, i.e. material deposits within the ground.
Cradle-to-gate	Encompasses all input and output flows (as applicable from the system boundaries) between the confines of the cradle up to the factory gate of the final processing operation.
Cradle-to-gate + end-of-life	Cradle-to-gate plus the end of life processes. This excludes the use phase.
Cradle-to-grave	Cradle-to-gate plus operation plus end of life processes. A complete study.
Cradle-to-site	Cradle-to-gate plus delivery to the site of use (installation site).
Delivered energy	Energy that is delivered to a consumer, e.g. a barrel of oil, kWh of delivered electricity, m^3 natural gas, all at the point of use.
Downstream impacts	Impacts associated with processes that occur at future, downstream, points in the system relative to the process under investigation. For example, in the case of a finished product sitting in storage its eventual delivery is a downstream process.
Embodied carbon (EC)	Embodied carbon is the sum of fuel related carbon emissions (i.e. embodied energy which is combusted – but not the feedstock energy which is retained within the material) and process related carbon emissions (i.e. non-fuel related emissions which may arise, for example, from chemical reactions). This can be measured from cradle-to-gate, cradle-to-grave, or from cradle-to grave. The ICE data is cradle-to-gate.
Embodied energy (EE)	Is defined here as the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate.

GLOSSARY

Feedstock energy	Feedstock energy is derived from fuel inputs that have been used as a material rather than a fuel. For example, petrochemicals may be used as feedstock materials to make plastics and rubber. The energy is not released but retained and therefore feedstock energy may often be (partially) recovered at the end of product lifetime (e.g. through incineration).
Fuel related carbon dioxide emissions	Carbon dioxide emissions emanating from the combustion of fossil fuels.
Functional unit	A reference unit of study normally used for comparative purposes, e.g. "1 m^2 of carpet over a lifetime of 10 years". A fair functional unit is necessary for such assessments. See Section 5.1 for further discussion.
Global warming potential (GWP)	The release of GHGs into the atmosphere gives rise to climate change. There are many GHGs and each has a different level of potency. Each gas is normalised relative to the impacts of one unit of carbon dioxide. For example each unit of methane is considered to be 25 times more harmful than a single unit of carbon dioxide (on a 100 year timescale), consequently it has a global warming potential of 25 ($kgCO_2e$).
Greenhouse gases (GHGs)	Gases that when released into the atmosphere absorb and emit thermal infrared radiation. These gases trap heat within the atmosphere thus contributing to climate change.
Heating value (HV) of energy	See calorific value (CV). An alternative name for GCV is higher heating value (HHV). Net calorific value is equivalent to lower heating value (LHV). They are equal metrics often expressed in Joules.
Life cycle assessment (LCA)	A 'tool' where the energy and materials used and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle (ideally) from cradle-to-grave.
Primary electricity	Electricity that has been generated without the need for secondary (fossil) fuel inputs, e.g. hydro, PV, wind.
Primary energy	Energy that has been traced back to the cradle. Delivered energy is traced upstream into its primary equivalents i.e. including the upstream impacts of delivery, refining, extraction.
Process carbon dioxide emissions	Non-fuel related carbon dioxide emissions, i.e. derived from chemical or physical reactions during manufacturing processes, such as the carbon released from limestone in the kiln of cement clinker production.
Recycled content	The fraction of material retained within the product that was derived from recycled materials. This differs from material recycling and recovery rates (i.e. metal recycling rates), which neglect to consider the difference between the quantity of material recovered and the changes in total market demand of material.
Renewable energy	Energy (including electricity) extracted from renewable resources, such as wind, solar, water.
System expansion	The expansion of system boundaries to include other processing operations (e.g. indirectly affected activities). This is often applied to assess the benefit of avoided burdens (see Annex B).
Upstream burdens	Impacts associated with processes that occurred at previous points in the system (upstream). For example, in the case of a finished product sitting in storage material extraction, processing, previous transportation and fabrication are all upstream processes.
Waste product	Material that is a sub-derivative of the processing operations and is considered to have no economic value (i.e. with no application or market demand).

FOREWORD

Climate change is the most serious global sustainability issue and the energy required to operate buildings is a major component of global emissions, with 40 per cent of total carbon emissions coming from buildings. However, aside from climate change, our energy reserves are limited, and renewable energy alone is unlikely to be the answer to reducing carbon emissions to prevent the "lights going out" at some point in the future.

Therefore reducing our carbon emissions by assessing the whole life cycle of a building will become an increasingly important factor that will need to be assessed if we are to understand and manage the carbon emitted from buildings as a whole.

What is embodied carbon? It is the energy used, converted to carbon emissions plus the additional non-fuel related carbon, for the extraction of raw materials, the processing of these materials into products, the transport of the products to site, the installation of the material or product, the maintenance of the material product and the end of life disposal.

Previously, embodied carbon has typically made up between 20 per cent and 50 per cent of the total carbon footprint of a building, and so the Government has concentrated on the operational aspect of the carbon emissions in terms of regulation. However, as buildings become more efficient, and improve in operational performance towards zero carbon, the embodied carbon will increase to become the major proportion of the overall emissions. Added to this, if the calculation which is used to convert KWh to CO_2 by the national grid is reduced in 2050, as proposed by the Committee on climate change, then the proportion of operational versus embodied will reduce even further.

There are a number of different modelling tools on the market currently being developed, that deal with the complexity of data associated with the range of materials involved, and enable assessments to be made on achieving the best or most appropriate solution. These methods can also be used to assess total carbon emitted when looking at redeveloping a building, which may have an implication on whether to totally redevelop of refurbish. The Inventory of Carbon and Energy (ICE) is an established and recognised inventory that is used in the industry.

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1 INTRODUCTION

1.1 EMBODIED CARBON IN CONSTRUCTION

What it is and why it matters

Modern society is underpinned by an intricate web of economic and social activities; commerce, transport and leisure intertwine providing support to not only sustain, but also enhance our way of life. However, we have created unprecedented environmental impacts and significant demands upon our natural resources. Much of this is associated with our intense consumption activities, which require vast quantities of resources and thus places great burdens upon our natural environment. Clearly concerted action must be taken: not only to limit, but also to reverse any long term damage, and thus ensuring that we live on this planet in a sustainable manner.

In the coming years the United Kingdom (UK) faces significant challenges to meet its objective of reducing its carbon dioxide emissions by at least 80 per cent by 2050 against a 1990 baseline, and with significant progress to be made by 2020. Each sector will have an important role to play. The built environment is a significant contributing sector which underpins the needs of modern society by supporting commerce, education, entertainment, and provides accommodation to the masses. In sustaining these activities the UK has accessed an estimated 25·5 million domestic and 1·98 million non-domestic buildings (Brown *et al.* 2009). The UK building sector is responsible for more than 40 per cent of the UK's final energy demand. However, such figures only consider the operational impacts. Improving energy standards, *Building Regulations*, cleaner fuels, along with targets for all new build homes to be zero carbon by 2016 and non-domestic buildings by 2019 will reduce operational impacts. The further energy required to construct materials, as embodied within these buildings, should begin to gain more attention.

Additional impacts may arise, for example, from the extraction, processing, transportation and fabrication of construction materials and is known as the embodied (energy/carbon) impact. Embodied energy (carbon) may be defined as:

"Embodied energy (carbon) is defined here as the total primary energy consumed (carbon released) from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate."

The ICE database has the boundaries of cradle-to-gate but a robust assessment of carbon released would consider whole life implications, including operation and end of life, i.e. cradle-to-grave.

There are several embodied energy and embodied carbon material databases on the market but on the whole they are proprietary subscription based resources. If a serious attempt at accounting for embodied carbon is to be made, we need a transparent, robust and reliable database covering a broad range of construction materials and openly available to the general public. This guide and the ICE database aims to meet these needs.

1.2 THE RISE OF EMBODIED CARBON

Embodied carbon is a subject of rising importance. There are various recent activities to support this, including:

- The UK Low Carbon Construction Innovation and Growth Team (IGT), which was chaired by Paul Morrell (the UK Government Chief Construction Advisor), published its final report in Autumn 2010. The IGT was tasked by the government to consider how the construction sector could meet the low carbon agenda. They made a number of wider recommendations but specifically on embodied carbon:

  Recommendation 2.1: That as soon as a sufficiently rigorous assessment system is in place, the Treasury should introduce into the Green Book a requirement to conduct a whole-life (embodied + operational) carbon appraisal and that this is factored into feasibility studies on the basis of a realistic price for carbon

  Recommendation 2.2: That the industry should agree with Government a standard method of measuring embodied carbon for use as a design tool and (as Recommendation 2.1 above) for the purposes of scheme appraisal

- The Institution of Structural Engineers (IStructE) is publishing a short guide on embodied carbon for their members. The guide will highlight some important issues and highlight what a structural engineer can do to save embodied energy and carbon

- RICS has established a working group to examine embodied carbon and to also link it to the New Rules of Measurement (NRM) framework being developed by the QS and Construction professional group to ensure consistency and comparability of the data being produced. The first stage will be to incorporate environmental measures, including embodied carbon, into the NRM framework before tackling the more complex issues of developing a more detailed methodology and database to underpin the calculations

- The Institute of Civil Engineers (ICE) Civil Engineering Standard Method of Measurement 3 (CESMM3) now includes carbon and prices for every material and unit of work. This enables users to calculate not just the economic, but also the embodied carbon of projects. The ICE database was used as one of the data sources

- The Hutchins 2010 UK Building Blackbook (The Capital Cost and Embodied CO_2 Guide, Volume two: major works) also now includes both cost and embodied carbon for construction works. The ICE database was used as one of the data sources

- BS 8903:2010 *Principles and Framework for Procuring Sustainably* was released in August 2010. Carbon footprinting is discussed extensively throughout this new standard.

Upcoming international standards

There are new environmental and carbon footprinting standards expected from the International Standards Association (ISO), the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). A new French environmental labelling initiative, a revised version of *PAS 2050* is due in 2011 and finally, of most relevance to construction, the *CEN TC 350* series of standards on the sustainability assessment of construction works is due to be rolled out in Spring 2011. For further details of these standards see Section 6.

1.3 THIS GUIDE

Meeting needs of industry
BSRIA is committed to assisting the construction industry in accounting for embodied carbon and energy. There are two main aims for this guide.

Firstly, the guide aims to provide industry with necessary data. This guide is a summary of the Inventory of Carbon and Energy (ICE), developed by Geoffrey Hammond and Craig Jones from the University of Bath, and contains vital information for its effective use. The data in this guide is based on ICE version 2.0. This Inventory contains a summary of approximately 1800 records of embodied carbon and energy for 34 classes of materials used in construction. As explained in Section 2, the raw data has been collated from independent sources and open literature and has been rigorously analysed to give users confidence in the reliability of the values. This raw data is then presented in a way that is readily usable in calculations, and examples of the 'profiles' of the most widely used construction materials are included in this guide. All the data is freely available on the internet at www.bath.ac.uk/mech-eng/sert/embodied and is updated. The data contained in this guide was up to date at the time of printing.

Secondly, BSRIA intends to show how the embodied carbon and energy of the construction industry can be accounted for and included in an assessment. It is acknowledged that there are other sources of embodied carbon data that users may prefer to use, rather than ICE data. Section 4 of this guide contains case studies that demonstrate how such data can be used to calculate embodied burdens and hence enable informed choices to be made about material selection. Section 5 gives further guidance on some of the more contentious issues relating to embodied carbon and energy.

This guide is aimed at a wide range of professionals involved in the construction industry and should be especially relevant to designers, architects, building engineers, building owners and end users, as well as manufacturers of building materials and products.

1.4 USING THIS GUIDE

This guide contains sections that are part reference and part reading text. Readers already familiar with the ICE database may be more comfortable to dip in and out of the document at any appropriate point. However, new readers to the subject and to the ICE database may wish to read from the beginning. Sections 1 and 2 are background to the subject of embodied carbon and the ICE database. Section 3 contains the main embodied energy and carbon data, as a reference source. Section 4 onwards contains information that will be useful to apply to the database, including several examples, case studies, and further resources.

2 THE CREATION OF A MATERIALS DATABASE

2.1 BACKGROUND

The Inventory of Carbon and Energy (ICE) was initially created by the University of Bath during a research project funded by the Carbon Trust and the Engineering and Physical Sciences Research Council (EPSRC). The project assessed the implications of embodied energy and carbon in construction for new UK buildings. The Inventory was created to provide a freely available, robust and reliable source of data for the materials used in the construction process. It soon became obvious that this data would be of interest to a wide range of users beyond the project partners. Subsequently, in 2006 the ICE database was made available for download from the authors' website. Since then it has been downloaded by over 10 000 professional users from industry, academe, government departments and agencies around the world.

Feedback from these users enabled the database to be refined and it continues to be developed and expanded as new information becomes available. In fact, during this update the authors of the database held discussions with representatives of key material sectors. These discussions have been important to the development of the database. The University of Bath welcomes further constructive input from industry that will enhance future versions of the Inventory.

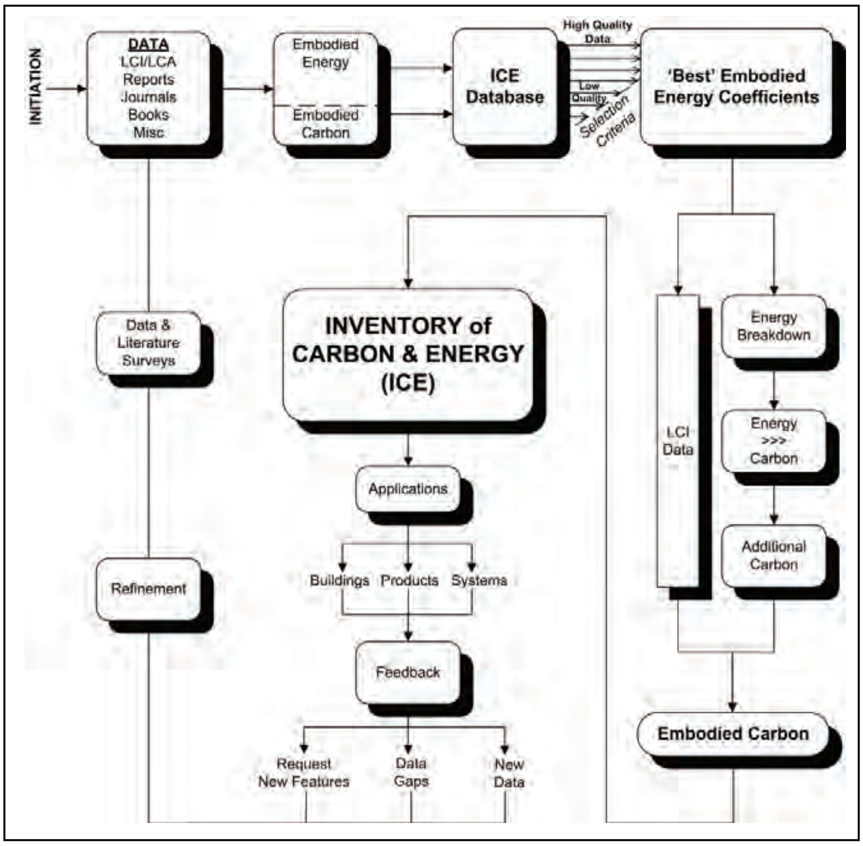
2.2 SELECTION AND QUALITY OF DATA

The formation and refinement of the Inventory took several stages, as illustrated in Figure 1. The first stage was to collate embodied energy and carbon input data. The majority of the input data originated from secondary data resources, such as journal papers, technical reports and monographs. Subscription based resources were avoided due to potential copyright issues. It was important to use a consistent method of extracting this data and the rules applied are described in the rest of this section. The data was stored in a database, including: values of embodied energy, carbon, and relevant information about the data source (i.e. country of data, year, boundaries, report details, notes). At the time of publishing the ICE database contained approximately 1800 records on embodied energy and carbon.

The collected data was of variable quality and the next stage was to assess and rate the quality of the data (see 'Ideal criteria for data sources').

Once the data had been quality rated, the best embodied energy coefficients could be derived. In many cases these were then used to calculate the embodied carbon values. Thus both embodied energy and carbon coefficients could be entered into the Inventory for public use.

Figure 1: Creation and refinement method of the ICE database.



Source: Hammond & Jones 2008

Ideal criteria for data sources

Once enough data was collected, the process of selecting best values began. All available data on embodied energy and carbon for materials was collected by the University of Bath; some of which was higher quality than others. Selection criteria were required to assess if each data point was high or low quality. These needed to be flexible enough to deal with difficulties in the data (e.g. varying boundary conditions and authors not reporting enough detail on the scope of their study) but also to maintain an ideal standard. Consequently five criteria formed the starting point of a quality assessment:

- **Compliance with approved methodologies/standards**
  Preference was given to data sources that complied with accepted methodologies, for example *ISO 14040/44 Environmental Management. Life Cycle Assessment. Principles and Framework*. However, since studies that comply with the ISO standards may follow different methodologies, this criterion alone was not enough to ensure data consistency.

- **System boundaries**
  System boundaries define what is and what is not included within the scope of a study and are used to identify the appropriate embodied energy and carbon inputs. Basic boundary conditions include cradle-to-(factory) gate, cradle-to-(installation) site, and cradle-to-grave. The cradle is defined as the earth and ideally all burdens should be traced back to the earth (see 'Tracing impacts

upstream'). The ICE database uses cradle-to-gate system boundaries and these are described in more detail in Annex A.

In the ICE database, feedstock energy (see Glossary for a definition) has been included only if it represents a permanent loss of non-renewable resources, such as fossil fuel use. For example, fossil fuels utilised as feedstock material in the production of plastics were included (although identified separately), whereas the calorific value of timber has been excluded. This approach is consistent with a number of other studies. The effects of carbon storage in timber were considered but were not integrated into the ICE (cradle-to-gate) data. For further details on carbon storage in timber see Section 8.

Finally, the ICE database accounts for non-fuel related carbon emissions which may arise from chemical reactions during manufacturing processes.

- **Country of origin**
  Ideally the ICE data for carbon and energy would have been sourced from within the British Isles. However, for most materials this was not feasible and embodied energy data from international sources had to be adopted, by using, for example, European or worldwide averages. National differences however in fuel mixes and electricity generation meant that a stronger preference was given to embodied carbon data from UK sources.

- **Age of the data sources**
  Preference was given to modern sources of data, especially for the embodied carbon. This is because historical changes in fuel mix and carbon coefficients associated with electricity generation cause greater uncertainty in the embodied carbon values.

  The data in the ICE database, including the material profiles given in Section 3, reveal something of the historical level of interest in energy analysis. For example, the data shows a period in the 1970s where energy analysis was topical. This was stimulated in part by the global oil crisis which started in 1973. During this period key research was undertaken in the UK, for example: Boustead and Hancock, 1979; Chapman, 1976; and Slesser, 1978. There followed a period of dwindling interest. It was not until the early 1990's that a clear resurgence in research can be observed. This was perhaps stimulated, in part, by the rise of Life Cycle Assessment (LCA). The first attempts to standardise LCA were attempted in the early 1990s and the first globally recognised standards by the International Standards Organisation (ISO) appeared in the late 1990s.

- **Embodied carbon**
  Ideally the embodied carbon data would be obtained from a study that has considered the life cycle carbon emissions. Examples of such studies include detailed Life Cycle Assessments (LCA). However, such data is not always widely available. Thus in many cases values had to be estimated using the typical fuel split for the particular UK industrial sector. British emission factors were applied to estimate the fuel-related carbon. Finally, additional process related carbon emissions (see Glossary for definition) were included.

Market representation
In addition to these selection criteria, the data represented typical materials employed in the British construction market. In the case of metals, products use a combination of virgin and recycled material. A recycled content was assumed for the metals typically used in the marketplace. A further example of the market representation is in cases where there are several specific types of material, for example timber can be in the form of plywood, chipwood, softwood or other materials. The UK consumption of the various types was used to calculate a single 'representative' value. This value can then be used in studies where the specific type of material is not known. Finally, data that represented readily usable construction products was selected wherever possible. For example, semi-fabricated components such as sheets or rods which are usable without further processing were preferred to (immediately) unusable products such as steel billet or aluminium ingot.

Tracing impacts upstream
In embodied energy and carbon assessments it is important for all activities to be traced back to the cradle as far as possible, i.e. traced upstream. The importance of this can be illustrated with the example of driving a car. A consumer may believe that they achieve 50 miles to the gallon (mpg) fuel economy (5·7 litres per 100 km). This belief is based on the distance they cover using the amount of fuel purchased. However, this does not represent the full environmental burden. There is a host of additional activities that lead up to the delivery of fuel into their vehicle, in a usable format and at a convenient location. Progression up the production tree would reveal activities, such as: fuel pumping, delivery, refining, shipping, storage, oil well operations, and drilling and exploration activities. Once the impact of such activities is accounted for, the actual (or 'true') fuel economy may be reduced to 45 mpg (6·3 litres per 100 km).

Boundary consistency
It was not always possible to determine complete boundary conditions for the embodied energy and carbon data in the original resources. A common example was energy that was not traced completely back to the earth, or electricity that was not traced all the way upstream. However, incomplete data often contained enough information to be used in estimating embodied energy coefficients.

Of the collected data, cradle-to-gate was the most commonly specified boundary condition and it was selected as the ideal scope of this study. It was difficult to maintain the same boundary conditions for the entire inventory due to the intricate nature of some data and inconsistencies across the resources. Therefore in a few cases cradle-to-grave has been specified.

In many instances, and certainly for materials with high embodied energy and high density, the difference between cradle-to-gate and cradle-to-site could be considered fairly negligible. By contrast, the difference is large for materials with a very low cradle-to-gate embodied energy per kilogram, such as aggregates and sand. See Annex A for further details of the boundary conditions of the ICE database.

Uncertainty

The Inventory contains both embodied energy and carbon data, but the embodied energy coefficients are more accurate for several reasons. One reason is the variation in fuel mixes used in processing. For example, two factories could manufacture the same product, resulting in the same embodied *energy* per kilogram of product made. However, the total *carbon* emitted by both could vary widely dependent upon the mix of fuels consumed by the factory. Another reason is that the majority of the collected data was for embodied energy and not embodied carbon. Only 40 per cent of the data collected by the University of Bath specified the embodied carbon, a global warming potential (or similar method of greenhouse gas measurement) or a fuel mix (from which the carbon emissions could be estimated). Consequently the author had less data to verify embodied carbon coefficients. This was representative of past data but recent studies (late-2000s) are now concentrating only on carbon; this is at the expense of data on energy. This is further encouraged by the rise of carbon footprinting and standards that focus purely on carbon. An example of this is the Publicly Accessible Standard (PAS) developed by the Carbon Trust on the carbon footprinting of products, *PAS 2050* (BSI, 2008). Ideally both energy and carbon should be considered side by side.

Due to the historical lack of data on embodied carbon for many materials, it was necessary to estimate the embodied carbon from the embodied energy. Ideally the values would be derived from an accurate life cycle assessment (LCA) but this was not possible in many cases. Many of the ICE embodied carbon coefficients were estimated by the University of Bath using the typical fuel mix in the relevant UK industries. It is acknowledged that this method is not perfect. However it is a vastly superior method to applying a common conversion factor from embodied energy to embodied carbon across the whole dataset.

The nature of this work and the problems outlined above made selection of single values difficult. In fact, data ranges would have been far simpler to select but then less useful to apply in calculations. There are other openly available inventories similar to this one and many more subscription based ones. Comparison of the selected values in these inventories would show many similarities but also many differences. It must be accepted that uncertainty is a part of any embodied energy and carbon analysis. That said, independent feedback has confirmed that the results from the Inventory of Carbon and Energy have generally proved to be robust when compared to those of other databases.

ICE internet resources and database version number

To download excel copies of ICE, including all materials profiles, visit: www.bath.ac.uk/mech-eng/sert/embodied/.

At the time of publishing this guide the ICE database is version 2.0 and all the data on this guide is based on that version. However the intention is to keep the database up-to-date and readers are encouraged to go the website for the most up to date version. The most significant update for this version was the conversion of the data to consider a basket of greenhouse gases (on a 100 year timescale). The main summary table retains both the old carbon dioxide only data (CO_2) and the new data in carbon dioxide equivalents (CO_2e). See Section 10 for further information.

To contribute to the development of the ICE database, provide feedback and suggest improved data, use the ICE Wiki: https://wiki.bath.ac.uk/display/ICE/Home+Page.

The University of Bath encourage the use of the Wiki as the first point of contact. To discuss life cycle costing analysis, contact peter.tse@bsria.co.uk.

3 THE INVENTORY OF CARBON AND ENERGY

3.1 MAIN SUMMARY TABLES

Table 1: Inventory of Carbon and Energy (ICE) main summary.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Aggregate				
General (Gravel or Crushed Rock)	0·083	0·0048	0·0052	Estimated from measured UK industrial fuel consumption data.
Aluminium Main data source: International Aluminium Institute (IAI) LCA studies (www.world-aluminium.org)				
General	**155**	**8·24**	**9·16**	**Assumed (UK) ratio of 25·6% extrusions, 55·7% rolled and 18·7% castings. Worldwide average recycled content of 33%.**
Virgin	218	11·46	12·79	
Recycled	29·0	1·69	1·81	
Cast Products	**159**	**8·28**	**9·22**	**Worldwide average recycled content of 33%.**
Virgin	226	11·70	13·10	
Recycled	25·0	1·35	1·45	
Extruded	**154**	**8·16**	**9·08**	**Worldwide average recycled content of 33%.**
Virgin	214	11·20	12·50	
Recycled	34·0	1·98	2·12	
Rolled	**155**	**8·26**	**9·18**	**Worldwide average recycled content of 33%.**
Virgin	217	11·50	12·80	
Recycled	28	1·67	1·79	
Asphalt				
Asphalt, 4% (bitumen) binder content (by mass)	2·86	0·059	0·066	1·68 MJ/kg Feedstock Energy (Included). Modelled from the bitumen binder content. The fuel consumption of asphalt mixing operations was taken from the Mineral Products Association (MPA). It represents typical UK industrial data. Feedstock energy is from the bitumen content.
Asphalt, 5% binder content	3·39	0·064	0·071	2·10 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 6% binder content	3·93	0·068	0·076	2·52 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 7% binder content	4·46	0·072	0·081	2·94 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 8% binder content	5·00	0·076	0·086	3·36 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Bitumen				
General	51	0·38 - 0·43 (?)	0·43 - 0·55 (?)	42 MJ/kg Feedstock Energy (Included). Feedstock assumed to be typical energy content of Bitumen. Carbon dioxide emissions are particularly difficult to estimate, range given.
Brass				
General	**44·00**	**2·46 (?)**	**2·64 (?)**	**Poor data availability. It is believed that the data may be largely dependent upon ore grade. Poor carbon data, making estimate of embodied carbon difficult.**
Virgin	80·00	4·47 (?)	4·80 (?)	
Recycled	20·00	1·12 (?)	1·20 (?)	

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	**EC - $kgCO_2/kg$**	**EC – (GHG) $kgCO_2e/kg$**	**EE = Embodied Energy, EC = Embodied Carbon**
Bricks				
General (Common Brick)	3·00	0·23	0·24	
EXAMPLE: Single brick	6·9 MJ per brick	0·53 $kgCO_2$ per brick	0·55	Assuming 2·3 kg per brick.
Limestone	0·85	?	-	
Bronze				
General	69·0 (?)	3·73 (?)	4·0 (?)	Average of the only two references.
Carpet				
General Carpet	74 (187 per sqm)	3·9 (9·8 per sqm)	-	For per square metre estimates see material profile. Difficult to estimate, taken from Ref. 94.
Felt (Hair and jute) underlay	19·00	0·97	-	Ref. 94.
Nylon (Polyamide), pile weight 300 g/m^2	130 MJ per sqm	6·7 (GWP) per sqm	6·7 (GWP) per sqm	Total weight of this carpet 1477 g/m^2. See Refs. 277 and 279. These carpets (inc. below) are a tufted surface pile made of 100% nylon (polyamide) with a woven textile backing and flame proofed on the basis of aluminium hydroxide.
Nylon (Polyamide), pile weight 500 g/m^2	180 MJ per sqm	9·7 (GWP) per sqm	9·7 (GWP) per sqm	Total weight of this carpet 1837 g/m^2. See Refs. 277 and 279.
Nylon (Polyamide), pile weight 700 g/m^2	230 MJ per sqm	12·7 (GWP) per sqm	12·7 (GWP) per sqm	Total weight of this carpet 2147 g/m^2. See Refs. 277 and 279.
Nylon (Polyamide), pile weight 900 g/m^2	277 MJ per sqm	15·6 (GWP) per sqm	15·6 (GWP) per sqm	Total weight of this carpet 2427 g/m^2. See Refs. 277 and 279.
Nylon (Polyamide), pile weight 1100 g/m^2	327 MJ per sqm	18·4 (GWP) per sqm	18·4 (GWP) per sqm	Total weight of this carpet 2,677 g/m^2. See Refs. 277 and 279.
Carpet tiles, nylon (Polyamide), pile weight 300 g/m^2	178 MJ per sqm	7·75 (GWP) per sqm	7·75 (GWP) per sqm	Total weight of this carpet 4123 g/m^2. See Refs. 277 and 279. These carpet tiles (inc. below) are a tufted surface pile made of 100% nylon (polyamide) fleece-covered bitumen backing and flame-proofed on the basis of aluminium hydroxide.
Carpet tiles, nylon (Polyamide), pile weight 500 g/m^2	229 MJ per sqm	10·7 (GWP) per sqm	10·7 (GWP) per sqm	Total weight of this carpet 4373 g/m^2 See Refs. 277 and 279.
Carpet tiles, nylon (Polyamide), pile weight 700 g/m^2	279 MJ per sqm	13·7 (GWP) per sqm	13·7 (GWP) per sqm	Total weight of this carpet 4623 g/m^2. See Refs. 277 and 279.
Carpet tiles, nylon (Polyamide), pile weight 900 g/m^2	328 MJ per sqm	16·7 (GWP) per sqm	16·7 (GWP) per sqm	Total weight of this carpet 4873 g/m^2. See Refs. 277 and 279.
Carpet tiles, nylon (Polyamide), pile weight 1100 g/m^2	378 MJ per sqm	19·7 (GWP) per sqm	19·7 (GWP) per sqm	Total weight of this carpet 5123 g/m^2. See Refs. 277 and 279.
Polyethyl-terepthalate (PET)	106·50	5·56	-	Includes feedstock energy.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Polypropylene	95·40	4·98	-	Includes feedstock energy, for per square metre see material profile.
Polyurethane	72·10	3·76	-	Includes feedstock energy.
Rubber	67·5 to 140	3·61 to 7·48	-	
Saturated Felt Underlay (impregnated with Asphalt or tar)	31·70	1·65	-	Ref. 94.
Wool	106·00	5·53	-	For per square metre see material profile. See Refs. 63, 201, 202 and 281 (Same author).
Cement				
General (UK weighted average)	4·5	0·73	0·74	Weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. This data has been estimated from the Mineral Products Association (MPA) factsheets (see Ref. 59). 23% cementitious additions on average.
Average CEM I Portland Cement, 94% Clinker	5·50	0·93	0·95	This is a standard cement with no cementitious additions (i.e. fly ash or blast furnace slag). Composition 94% clinker, 5% gypsum, 1% minor additional constituents (mac's). This data has been estimated from the British Cement Association's factsheets (see Ref. 59).
6-20% Fly Ash (CEM II/A-V)	5·28 to 4·51	0·88 (@ 6%) to 0·75 (@ 20%)	0·89 to 0·76	See material profile for further details.
21-35% Fly Ash (CEM II/B-V)	4·45 to 3·68	0·74 to 0·61	0·75 to 0·62	
21-35% GGBS (CEM II/B-S)	4·77 to 4·21	0·76 to 0·64	0·77 to 0·65	
36-65% GGBS (CEM III/A)	4·17 to 3·0	0·63 to 0·38	0·64 to 0·39	
66-80% GGBS (CEM II/B)	2·96 to 2·4	0·37 to 0·25	0·38 to 0·26	
Fibre Cement Panels - Uncoated	10·40	1·09	-	Few data points. Selected data modified from Ref. 107.
Fibre Cement Panels - (Colour) Coated	15·30	1·28	-	
Mortar (1:3 Cement:Sand mix)	1·33	0·208	0·221	Values estimated from the ICE Cement, Mortar and Concrete Model.
Mortar (1:4)	1·11	0·171	0·182	
Mortar (1:5)	0·97	0·146	0·156	
Mortar (1:6)	0·85	0·127	0·136	
Mortar (1:½:4½ Cement:Lime: Sand mix)	1·34	0·200	0·213	
Mortar (1:1:6 Cement:Lime: Sand mix)	1·11	0·163	0·174	
Mortar (1:2:9 Cement:Lime: Sand mix)	1·03	0·145	0·155	
Cement stabilised soil @ 5%	0·68	0·060	0·061	Assumed 5% cement content.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Cement stabilised soil @ 8%	0·83	0·082	0·084	Assumed 8% stabiliser contents (6% cement and 2% quicklime).
Ceramics				
General	10·00	0·66	0·70	Very Large data range, difficult to select values for general ceramics.
Fittings	20·00	1·07	1·14	Ref. 1.
Sanitary Products	29·00	1·51	1·61	Limited data.
Tiles and Cladding Panels	12·00	0·74	0·78	Difficult to select, large range, limited data. See Ref. 292.
Clay				
General (Simple Baked Products)	3·00	0·23	0·24	General simple baked clay products (inc. terracotta and bricks).
Tile	6·50	0·45	0·48	
Vitrified clay pipe DN 100 and DN 150	6·20	0·44	0·46	
Vitrified clay pipe DN 200 and DN 300	7·00	0·48	0·50	
Vitrified clay pipe DN 500	7·90	0·52	0·55	
Concrete				
General	0·75	0·100	0·107	It is strongly recommended to avoid selecting a 'general' value for concrete. Selecting data for a specific concrete type (often a ready mix) will give greater accuracy, please see material profile. Assumed cementitious content 12% by mass. Assumed use of weighted average UK cement.
16/20 MPa	0.70	0·093	0·100	Using UK weighted average cement (more representative of 'typical' concrete mixtures).
20/25 MPa	0.74	0·100	0·107	
25/30 MPa	0.78	0·106	0·113	
28/35 MPa	0.82	0·112	0·120	
32/40 MPa	0.88	0·123	0·132	
40/50 MPa	1.00	0·141	0·151	

% Cement Replacement - Fly Ash	EE 0%	EE 15%	EE 30%	EC 0%	EC 15%	EC 30%	EC (GHG) 0%	EC (GHG) 15%	EC (GHG) 30%	Note 0% is a concrete using a CEM I cement (not typical)
GEN 0 (6/8 MPa)	0·55	0·52	0·47	0·071	0·065	0·057	0·076	0·069	0·061	Compressive strength designation C6/8 MPa. 28 day compressive strength under British cube method of 8 MPa, under European cylinder method 6 MPa. Possible uses: Kerb bedding and backing. Data is only cradle to factory gate but beyond this the average delivery distance of ready mix concrete is 8·3 km by road (see Ref. 244).
GEN 1 (8/10 MPa)	0·70	0·65	0·59	0·097	0·088	0·077	0·104	0·094	0·082	Possible uses: mass concrete, mass fill, mass foundations, trench foundations, blinding, strip footing.
GEN 2 (12/15 MPa)	0·76	0·71	0·64	0·106	0·098	0·087	0·114	0·105	0·093	-
GEN 3 (16/20 MPa)	0·81	0·75	0·68	0·115	0·105	0·093	0·123	0·112	0·100	Possible uses: garage floors.
RC 20/25 (20/25 MPa)	0·86	0·81	0·73	0·124	0·114	0·101	0·132	0·122	0·108	-
RC 25/30 (25/30 MPa)	0·91	0·85	0·77	0·131	0·121	0·107	0·140	0·130	0·115	Possible uses: reinforced foundations.

Materials	Embodied Energy and Carbon Coefficients									Comments
	EE - MJ/kg			**EC - $kgCO_2/kg$**			**EC – (GHG) $kgCO_2e/kg$**			**EE = Embodied Energy, EC = Embodied Carbon**
RC 28/35 (28/35 MPa)	0·95	0·90	0·82	0·139	0·129	0·116	0·148	0·138	0·124	Possible uses: reinforced foundations, ground floors.
RC 32/40 (32/40 MPa)	1·03	0·97	0·89	0·153	0·143	0·128	0·163	0·152	0·136	Possible uses: structural purposes, in situ floors, walls, superstructure.
RC 40/50 (40/50 MPa)	1·17	1·10	0·99	0·176	0·164	0·146	0·188	0·174	0·155	Possible uses: high strength applications, precasting.
PAV1	0·95	0·89	0·81	0·139	0·129	0·115	0·148	0·138	0·123	Possible uses: domestic parking and outdoor paving.
PAV2	1·03	0·97	0·89	0·153	0·143	0·128	0·163	0·152	0·137	Possible uses: heavy duty outdoor paving.
% Cement Replacement - Blast Furnace Slag	0%	25%	50%	0%	25%	50%	0%	25%	50%	Note 0% is a concrete using a CEM I cement (cement)
GEN 0 (6/8 MPa)	0·55	0·48	0·41	0·071	0·056	0·042	0·076	0·060	0·045	See fly ash mixtures.
GEN 1 (8/10 MPa)	0·70	0·60	0·50	0·097	0·075	0·054	0·104	0·080	0·058	
GEN 2 (12/15 MPa)	0·76	0·62	0·55	0·106	0·082	0·061	0·114	0·088	0·065	
GEN 3 (16/20 MPa)	0·81	0·69	0·57	0·115	0·090	0·065	0·123	0·096	0·070	
RC 20/25 (20/25 MPa)	0·86	0·74	0·62	0·124	0·097	0·072	0·132	0·104	0·077	
RC 25/30 (25/30 MPa)	0·91	0·78	0·65	0·131	0·104	0·076	0·140	0·111	0·081	
RC 28/35 (28/35 MPa)	0·95	0·83	0·69	0·139	0·111	0·082	0·148	0·119	0·088	
RC 32/40 (32/40 MPa)	1·03	0·91	0·78	0·153	0·125	0·094	0·163	0·133	0·100	
RC 40/50 (40/50 MPa)	1·17	1·03	0·87	0·176	0·144	0·108	0·188	0·153	0·115	
PAV1	0·95	0·82	0·70	0·139	0·111	0·083	0·148	0·118	0·088	
PAV2	1·03	0·91	0·77	0·153	0·125	0·094	0·163	0·133	0·100	

COMMENTS

The first column represents standard concrete, created with a CEM I Portland cement. The other columns are estimates based on a direct substitution of fly ash or blast furnace slag in place of the cement content. The ICE Cement, Mortar and Concrete Model was applied. Please see important notes in the concrete material profile.

REINFORCED CONCRETE - Modification Factors

	For reinforcement add this value to the appropriate concrete coefficient for each 100 kg of rebar per m^3 of concrete			
	1·04	0·072	0·077	Add for each 100 kg steel rebar per m^3 concrete. Use multiple of this value, i.e. for 150 kg steel use a factor of 1·5 times these values.
EXAMPLE: Reinforced RC 25/30 MPa (with 110 kg per m^3 concrete)	1.92 MJ/kg (0·78 + 1·04 * 1·1)	0·185 $kgCO_2/kg$ (0·106 + 0·072 * 1·1)	0·198 $kgCO_2e/kg$ (0·113 + 0·077 * 1·1)	With 110 kg rebar per m^3 concrete. UK weighted average cement. This assumes the UK typical steel scenario (59% recycled content). Please consider if this is in line with the rest of your study (goal and scope) or the requirements of a predefined method.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
PRECAST (PREFABRICATED) CONCRETE - Modification Factors				
	For precast add this value to the selected coefficient of the appropriate concrete mix			
	0·45	0·027	0·029	For each 1 kg precast concrete. The example is using a RC 40/50 strength class and is not necessarily indicative of an average precast product. Includes UK recorded plant operations and estimated transportation of the constituents to the factory gate (38km aggregates, estimated 100km cement). Data is only cradle to factory gate but beyond this the average delivery distance of precast is 155 km by road (see Ref. 244). UK weighted average cement.
EXAMPLE: Precast RC 40/50 MPa	1·50 MJ/kg (1·00 + 0·50)	0·168 $kgCO_2/kg$ (0·141 + 0·027)	0·180 $kgCO_2/kg$ (0·151 + 0·029)	
EXAMPLE: Precast RC 40/50 with reinforcement (with 80kg per m^3)	2·33 MJ/kg (1·50 + 1·04 * 0·8)	0·229 $kgCO_2/kg$ (0·171 + 0·072 * 0·8)	0·242 $kgCO_2/kg$ (0·180 + 0·077 * 0·8)	
CONCRETE BLOCKS (ICE CMC Model Values)				
Block - 8 MPa Compressive Strength	0·59	0·059	0·063	Estimated from the concrete block mix proportions, plus an allowance for concrete block curing, plant operations and transport of materials to factory gate.
Block -10 MPa	0·67	0·073	0·078	
Block -12 MPa	0·72	0·082	0·088	
Block -13 MPa	0·83	0·100	0·107	
Autoclaved Aerated Blocks (AAC's)	3·50	0·24 to 0·375	-	Not ICE CMC model results.
NOMINAL PROPORTIONS METHOD (Volume), Proportions from BS 8500:2006 (ICE Cement, Mortar and Concrete Model Calculations)				
1:1:2 Cement:Sand: Aggregate	1·28	0·194	0·206	High strength concrete. All of these values were estimated assuming the UK average content of cementitious additions (i.e. fly ash, GGBS) for factory supplied cements in the UK, see Ref. 59, plus the proportions of other constituents.
1:1.5:3	0·99	0·145	0·155	Often used in floor slab, columns and load bearing structure.
1:2:4	0·82	0·116	0·124	Often used in construction of buildings under 3 storeys.
1:2.5:5	0·71	0·097	0·104	
1:3:6	0·63	0·084	0·090	Non-structural mass concrete.
1:4:8	0·54	0·069	0·074	
BY CEM I CEMENT CONTENT - kg CEM I cement content per cubic metre concrete (ICE CMC Model Results)				
120 kg / m^3 concrete	0·49	0·060	0·064	Assumed density of 2350 kg/m^3. Interpolation of the CEM I cement content is possible. These numbers assume the CEM I cement content (not the total cementitious content, i.e. they do not include cementitious additions). They may also be used for fly ash mixtures without modification, but they are likely to slightly underestimate mixtures that have additional GGBS due to the higher embodied energy and carbon of GGBS (in comparison to aggregates and fly ash).
200 kg / m^3 concrete	0·67	0·091	0·097	
300 kg / m^3 concrete	0·91	0·131	0·140	
400 kg / m^3 concrete	1·14	0·170	0·181	
500 kg / m^3 concrete	1·37	0·211	0·224	

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
MISCELLANEOUS VALUES				
Fibre-Reinforced	7·75 (?)	0·45 (?)	-	Literature estimate, likely to vary widely. High uncertainty.
Very High GGBS Mix	0·66	0·049	0·050	Data based on Lafarge 'Envirocrete', which is a C28/35 Mpa, very high GGBS replacement value concrete
Copper				
EU Tube and Sheet	**42·00**	**2·60**	**2·71**	**EU production data, estimated from Kupfer Institut LCI data. 37% recycled content (the 3 year world average). World average data is expected to be higher than these values.**
Virgin	57·00	3·65	3·81	
Recycled	16·50	0·80	0·84	
Recycled from high grade scrap	18 (?)	1·1 (?)	-	Uncertain, difficult to estimate with the data available.
Recycled from low grade scrap	50 (?)	3·1 (?)	-	
Glass				
Primary Glass	15·00	0·86	0·91	Includes process CO_2 emissions from primary glass manufacture.
Secondary Glass	11·50	0·55	0·59	EE estimated from Ref 115.
Fibreglass (Glasswool)	28·00	1·54	-	Large data range, but the selected value is inside a small band of frequently quoted values.
Toughened	23·50	1·27	1·35	Only three data sources.
Insulation				
General Insulation	45·00	1·86	-	Estimated from typical market shares. Feedstock Energy 16·5 MJ/kg (Included).
Cellular Glass	27·00	-	-	Ref. 54.
Cellulose	0·94 to 3·3	-	-	
Cork	4·00	0·19	-	Ref. 55.
Fibreglass (Glasswool)	28·00	1·35	-	Poor data difficult to select appropriate value.
Flax (Insulation)	39·50	1·70	-	Ref. 2. 5·97 MJ/kg Feedstock Energy (Included).
Mineral wool	16·60	1·20	1·28	
Paper wool	20·17	0·63	-	Ref. 2
Polystyrene	See Plastics	See Plastics	-	See plastics.
Polyurethane	See Plastics	See Plastics	-	See plastics.
Rockwool	16·80	1·05	1·12	Cradle-to-grave.
Woodwool (loose)	10·80	-	-	Ref. 205.
Woodwool (Board)	20·00	0·98	-	Ref. 55.
Wool (Recycled)	20·90	-	-	Refs. 63, 201, 202 and 281.
Iron				
General	25·00	1·91 (?)	2·03	It was difficult to estimate the embodied energy and carbon of iron with the data available.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Lead				
General	**25·21**	**1·57**	**1·67**	**Allocated (divided) on a mass basis, assumes recycling rate of 61%.**
Virgin	49·00	3·18	3·37	
Recycled	10·00	0·54	0·58	Scrap batteries are a main feedstock for recycled lead.
Lime				
General	5·30	0·76	0·78	Embodied carbon was difficult to estimate.
Linoleum				
General	25·00	1·21	-	Data difficult to select, large data range.
Miscellaneous				
Asbestos	7·40	-	-	Ref. 4.
Calcium Silicate Sheet	2·00	0·13	-	Ref. 55.
Chromium	83	5·39	-	Ref. 22.
Cotton, Padding	27·10	1·28	-	Ref. 38.
Cotton, Fabric	143	6·78	-	Ref. 38.
Damp Proof Course/ Membrane	134 (?)	4·2 (?)	-	Uncertain estimate.
Felt General	36	-	-	
Flax	33·50	1·70	-	Ref. 2.
Fly Ash	0·10	0·008	-	No allocation from fly ash producing system.
Grit	0·12	0·01	-	Ref. 114.
Ground Limestone	0·62	0·032	-	
Carpet Grout	30·80	-	-	Ref. 169.
Glass Reinforced Plastic - GRP - Fibreglass	100	8·10	-	Ref. 1.
Lithium	853	5·30	-	Ref. 22.
Mandolite	63	1·40	-	Ref. 1.
Mineral Fibre Tile (Roofing)	37	2·70	-	Ref. 1.
Manganese	52	3·50	-	Ref. 22.
Mercury	87	4·94	-	Ref. 22.
Molybedenum	378	30·30	-	Ref. 22.
Nickel	164	12·40	-	Ref. 114.
Perlite - Expanded	10·00	0·52	-	Ref. 114.
Perlite - Natural	0·66	0·03	-	Ref. 114.
Quartz powder	0·85	0·02	-	Ref. 114.
Shingle	11·30	0·30	-	Ref. 70.
Silicon	2355	-	-	Ref. 167.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Slag (GGBS)	1·60	0·083	-	Ground Granulated Blast Furnace Slag (GGBS), economic allocation.
Silver	128·20	6·31	-	Ref. 148.
Straw	0·24	0·01	-	Refs. 63, 201, 202 and 281.
Terrazzo Tiles	1·40	0·12	-	Ref. 1.
Vanadium	3710	228	-	Ref. 22.
Vermiculite - Expanded	7·20	0·52	-	Ref. 114.
Vermiculite - Natural	0·72	0·03	-	Ref. 114.
Vicuclad	70·00	-	-	Ref. 1.
Water	0·01	0·001	-	
Wax	52·00	-	-	Ref. 169.
Wood stain/Varnish	50·00	5·35	-	Ref. 1.
Yttrium	1470	84·00	-	Ref. 22.
Zirconium	1610	97·20	-	Ref. 22.
Paint				
General	70·00	2·42	2·91	Large variations in data, especially for embodied carbon. Includes feedstock energy. Water based paints have a 70% market share. Water based paint has a lower embodied energy than solvent based paint.
EXAMPLE: Single Coat	10·5 MJ/Sqm	0·36 $kgCO_2$/Sqm	0·44	Assuming 6·66 Sqm Coverage per kg.
EXAMPLE: Double Coat	21·0 MJ/Sqm	0·73 $kgCO_2$/Sqm	0·87	Assuming 3·33 Sqm Coverage per kg.
EXAMPLE: Triple Coat	31·5 MJ/Sqm	1·09 $kgCO_2$/Sqm	1·31	Assuming 2·22 Sqm Coverage per kg.
Waterborne Paint	59·00	2·12	2·54	Waterborne paint has a 70% of market share. Includes feedstock energy.
Solventborne Paint	97·00	3·13	3·76	Solventbourne paint has a 30% share of the market. Includes feedstock energy. It was difficult to estimate carbon emissions for solventborne paint.
Paper				
Paperboard (General for construction use)	24·80	1·29	-	Excluding calorific value (CV) of wood, excludes carbon sequestration/biogenic carbon storage.
Fine Paper	28·20	1·49	-	Excluding CV of wood, excludes carbon sequestration.
EXAMPLE: 1 packet A4 paper	70·50	3·73	-	Standard 80 g/sqm printing paper, 500 sheets a pack. Doesn't include printing.
Wallpaper	36·40	1·93	-	
Plaster				
General (Gypsum)	1·80	0·12	0·13	Problems selecting good value, inconsistent figures, West et al believe this is because of past aggregation of EE with cement.
Plasterboard	6·75	0·38	0·39	See Ref [WRAP] for further info on GWP data, including disposal impacts which are significant for Plasterboard.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Plastics	Main data source: Plastics Europe (www.plasticseurope.org) ecoprofiles			
General	80·50	2·73	3·31	35·6 MJ/kg Feedstock Energy (Included). Determined by the average use of each type of plastic used in the European construction industry.
ABS	95·30	3·05	3·76	48·6 MJ/kg Feedstock Energy (Included).
General Polyethylene	83·10	2·04	2·54	54·4 MJ/kg Feedstock Energy (Included). Based on average consumption of types of polyethylene in European construction
High Density Polyethylene (HDPE) Resin	76·70	1·57	1·93	54·3 MJ/kg Feedstock Energy (Included). Doesn't include the final fabrication.
HDPE Pipe	84·40	2·02	2·52	55·1 MJ/kg Feedstock Energy (Included).
Low Density Polyethylene (LDPE) Resin	78·10	1·69	2·08	51·6 MJ/kg Feedstock Energy (Included). Doesn't include the final fabrication.
LDPE Film	89·30	2·13	2·60	55·2 MJ/kg Feedstock Energy (Included).
Nylon (Polyamide) 6 Polymer	120·50	5·47	9·14	38·6 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication. Plastics Europe state that two thirds of nylon is used as fibres (textiles, carpets etc) in Europe and that most of the remainder as injection mouldings. Dinitrogen monoxide and methane emissions are very significant contributors to GWP.
Nylon (polyamide) 6,6 Polymer	138·60	6·54	7·92	50·7 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication (i.e. injection moulding). See comments for Nylon 6 polymer.
Polycarbonate	112·90	6·03	7·62	36·7 MJ/kg Feedstock Energy (Included). Doesn't include final fabrication.
Polypropylene, Orientated Film	99·20	2·97	3·43	55·7 MJ/kg Feedstock Energy (Included).
Polypropylene, Injection Moulding	115·10	3·93	4·49	54 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO_2 may reduce to 3·85 $kgCO_2/kg$, and GWP down to 4·41 kg CO_2e/kg.
Expanded Polystyrene	88·60	2·55	3·29	46·2 MJ/kg Feedstock Energy (Included).
General Purpose Polystyrene	86·40	2·71	3·43	46·3 MJ/kg Feedstock Energy (Included).
High Impact Polystyrene	87·40	2·76	3·42	46·4 MJ/kg Feedstock Energy (Included).
Thermoformed Expanded Polystyrene	109·20	3·45	4·39	49·7 MJ/kg Feedstock Energy (Included).
Polyurethane Flexible Foam	102·10	4·06	4·84	33·47 MJ/kg Feedstock Energy (Included). Poor data availability for feedstock energy.
Polyurethane Rigid Foam	101·50	3·48	4·26	37·07 MJ/kg Feedstock Energy (Included). Poor data availability for feedstock energy.
PVC General	77·20	2·61	3·10	28·1 MJ/kg Feedstock Energy (Included). Based on market average consumption of types of PVC in the European construction industry.
PVC Pipe	67·50	2·56	3·23	24·4 MJ/kg Feedstock Energy (Included).
Calendared Sheet PVC	68·60	2·61	3·19	24·4 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO_2 may reduce to 2·56 $kgCO_2/kg$, and GWP down to 3·15 kg CO_2e/kg.
PVC Injection Moulding	95·10	2·69	3·30	35·1 MJ/kg Feedstock Energy (Included). If biomass benefits are included the CO_2 may reduce to 2·23 $kgCO_2/kg$, and GWP down to 2·84 kg CO_2e/kg.
UPVC Film	69·40	2·57	3·16	25·3 MJ/kg Feedstock Energy (Included).

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Rubber				
General	91·00	2·66	2·85	40 MJ/kg Feedstock Energy (Included).
Sand				
General	0·081	0·0048	0·0051	Estimated from real UK industrial fuel consumption data.
Sealants and adhesives				
Epoxide Resin	137·00	5·70	-	42·6 MJ/kg Feedstock Energy (Included). Source: www.plasticseurope.org.
Mastic Sealant	62 to 200	-	-	
Melamine Resin	97·00	4·19	-	Feedstock energy 18 MJ/kg - estimated from Ref 34.
Phenol Formaldehyde	88·00	2·98	-	Feedstock energy 32 MJ/kg - estimated from Ref 34.
Urea Formaldehyde	70·00	2·76	-	Feedstock energy 18 MJ/kg - estimated from Ref 34.
Soil				
General (Rammed Soil)	0·45	0·023	0·024	
Cement stabilised soil @ 5%	0·68	0·060	0·061	Assumed 5% cement content.
Cement stabilised soil @ 8%	0·83	0·082	0·084	Assumed 8% stabiliser content (6% cement and 2% lime).
GGBS stabilised soil	0·65	0·045	0·047	Assumed 8% stabiliser content (8% GGBS and 2% lime).
Fly ash stabilised soil	0·56	0·039	0·041	Assumed 10% stabiliser content (8% fly ash and 2% lime).
Steel	Main data source: International Iron and Steel Institute (IISI) LCA studies (www.worldsteel.org)			
UK (EU) STEEL DATA - EU average recycled content - See material profile (and Annex B) for usage guide				
General - UK (EU) Average Recycled Content	**20·10**	**1·37**	**1·46**	**EU 3-average recycled content of 59%. Estimated from UK's consumption mixture of types of steel (excluding stainless). All data doesn't include the final cutting of the steel products to the specified dimensions or further fabrication activities. Estimated from World Steel Association (Worldsteel) LCA data.**
Virgin	35·40	2·71	2·89	
Recycled	9·40	0·44	0·47	Could not collect strong statistics on consumption mix of recycled steel.
Bar and rod - UK (EU) Average Recycled Content	**17·40**	**1·31**	**1·40**	**EU 3-average recycled content of 59%.**
Virgin	29·20	2·59	2·77	
Recycled	8·80	0·42	0·45	
Coil (Sheet) - UK (EU) Average Recycled Content	**18·80**	**1·30**	**1·38**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	32·80	2·58	2·74	
Recycled	Not typical production route (also applies to galvanised. coil)			

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Coil (Sheet), Galvanised - UK (EU) Average Recycled Content	**22·60**	**1·45**	**1·54**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	40·00	2·84	3·01	
Engineering steel - Recycled	13·10	0·68	0·72	
Pipe- UK (EU) Average Recycled Content	**19·80**	**1·37**	**1·45**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	34·70	2·71	2·87	
Recycled	Not Typical Production Route			
Plate- UK (EU) Average Recycled Content	**25.10**	**1·55**	**1·66**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	45·40	3·05	3·27	
Recycled	Not Typical Production Route			
Section- UK (EU) Average Recycled Content	**21·50**	**1·42**	**1·53**	
Virgin	38·00	2·82	3·03	
Recycled	10·00	0·44	0·47	
Wire - Virgin	36·00 (?)	2·83 (?)	3·02	
Stainless	56·70	6·15	-	World average data from the Institute of Stainless Steel Forum (ISSF) life cycle inventory data. Selected data is for the most popular grade (304). Stainless steel does not have separate primary and recycled material production routes.
OTHER STEEL DATA - 'R.O.W' and 'World' average recycled contents - See material profile (and Annex B) for usage guide				
General - R.O.W. Avg. Recy. Cont.	26·20	1·90	2·03	Rest of World (non-E.U.) consumption of steel. Three year average recycled content of 35·5%.
General - World Avg. Recy. Cont.	25·30	1·82	1·95	Whole world Three year average recycled content of 39%.
Bar and rod- R.O.W. Avg. Recy. Cont.	22·30	1·82	1·95	
Bar and rod - World Avg. Recy. Cont.	21·60	1·74	1·86	
Coil - R.O.W. Avg. Recy. Cont.	24·40	1·81	1·92	Comments above apply. See material profile for further information.
Coil - World Avg. Recy. Cont.	23·50	1·74	1·85	
Coil, Galvanised - R.O.W. Avg. Recy. Cont.	29·50	2·00	2·12	

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Coil, Galvanised - World Avg. Recy. Cont.	28·50	1·92	2·03	Comments on previous page apply. See material profile for further information.
Pipe - R.O.W. Avg. Recy. Cont.	25·80	1·90	2·01	
Pipe - World Avg. Recy. Cont.	24·90	1·83	1·94	
Plate - R.O.W. Avg. Recy. Cont.	33·20	2·15	2·31	
Plate - World Avg. Recy. Cont.	32·00	2·06	2·21	
Section - R.O.W. Avg. Recy. Cont.	28·10	1·97	2·12	
Section - World Avg. Recy. Cont.	27·10	1·89	2·03	
Stone	Data on stone was difficult to select, with high standard deviations and data ranges.			
General	1·26 (?)	0·073 (?)	0·079	ICE database average (statistic), uncertain. See material profile.
Granite	11·00	0·64	0·70	Estimated from Ref 116.
Limestone	1·50	0·087	0·09	Estimated from Ref 188.
Marble	2·00	0·116	0·13	
Marble tile	3·33	0·192	0·21	Ref. 40.
Sandstone	1·00 (?)	0·058 (?)	0·06	Uncertain estimate based on Ref. 262.
Shale	0·03	0·002	0·002	
Slate	0·1 to 1·0	0·006 to 0·058	0·007 to 0·063	Large data range.
Timber	Note: These values were difficult to estimate because timber has a high data variability. These values exclude the energy content of the wooden product (the Calorific Value (CV) from burning). See the timber material profile and the FAQs for guidance on the new data structure for embodied carbon ($_{fos}$ and $_{bio}$).			
General	10·00	$0{\cdot}30_{fos}+0{\cdot}41_{bio}$	$0{\cdot}31_{fos}+0{\cdot}41_{bio}$	Estimated from UK consumption mixture of timber products in 2007 (Timber Trade Federation statistics). Includes 4·3 MJ bio-energy. All values do not include the CV of timber and exclude carbon storage.
Glue Laminated timber	12·00	$0{\cdot}39_{fos}+0{\cdot}45_{bio}$	$0{\cdot}42_{fos}+0{\cdot}45_{bio}$	Includes 4·9 MJ bio-energy.
Hardboard	16·00	$0{\cdot}54_{fos}+0{\cdot}51_{bio}$	$0{\cdot}58_{fos}+0{\cdot}51_{bio}$	Hardboard is a type of fibreboard with a density above 800 kg/m^3. Includes 5·6 MJ bio-energy.
Laminated Veneer Lumber	9·50	$0{\cdot}31_{fos}+0{\cdot}32_{bio}$	$0{\cdot}33_{fos}+0{\cdot}32_{bio}$	Ref 150. Includes 3·5 MJ bio-energy.
MDF	11 (?)	$0{\cdot}37_{fos}+0{\cdot}35_{bio}$	$0{\cdot}39_{fos}+0{\cdot}35_{bio}$	Wide density range (350-800 kg/m^3). Includes 3·8 MJ bio-energy.
Oriented Strand Board (OSB)	15·00	$0{\cdot}42_{fos}+0{\cdot}54_{bio}$	$0{\cdot}45_{fos}+0{\cdot}54_{bio}$	Estimated from Refs. 103 and 150. Includes 5·9 MJ bio-energy.
Particle Board	14·50	$0{\cdot}52_{fos}+0{\cdot}32_{bio}$	$0{\cdot}54_{fos}+0{\cdot}32_{bio}$	Very large data range, difficult to select appropriate values. Modified from CORRIM reports. Includes 3·2 MJ bio-energy (uncertain estimate).
Plywood	15·00	$0{\cdot}42_{fos}+0{\cdot}65_{bio}$	$0{\cdot}45_{fos}+0{\cdot}65_{bio}$	Includes 7·1 MJ bio-energy.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Sawn Hardwood	10·40	$0{\cdot}23_{fos} + 0{\cdot}63_{bio}$	$0{\cdot}24_{fos} + 0{\cdot}63_{bio}$	It was difficult to select values for hardwood, the data was estimated from the CORRIM studies (Ref. 88). Includes 6·3 MJ bio-energy.
Sawn Softwood	7·40	$0{\cdot}19_{fos} + 0{\cdot}39_{bio}$	$0{\cdot}20_{fos} + 0{\cdot}39_{bio}$	Includes 4·2 MJ bio-energy.
Veneer Particleboard (Furniture)	$23_{(fos + bio)}$	(?)	(?)	Unknown split of fossil based and bio-energy fuels.
Tin				
Tin Coated Plate (Steel)	19·2 to 54·7	1·04 to 2·95	-	
Tin	250·00	13·50	14·47	Lack of modern data, large data range
Titanium				
Virgin	361 to 745	19·2 to 39·6 (??)	20·6 to 42·5 (??)	Lack of modern data, large data range, small sample size.
Recycled	258·00	13·7 (??)	14·7 (??)	Lack of modern data, large data range, small sample size.
Vinyl Flooring				
General	65·64	2·29	-	23·58 MJ/kg Feedstock Energy (Included), Same value as PVC calendared sheet.
Vinyl Composite Tiles (VCT)	13·70	-	-	Ref. 94.
Zinc				
General	**53·10**	**2·88**	**3·09**	Uncertain carbon estimates, currently estimated from typical UK industrial fuel mix. Recycled content of general Zinc 30%.
Virgin	72·00	3·90	4·18	
Recycled	9·00	0·49	0·52	
Miscellaneous (No material profiles):				
PV Modules	MJ/sqm	Kg CO_2/sqm		
Monocrystalline	4750 (2590 to 8640)	242 (132 to 440)	-	Embodied carbon estimated from typical UK industrial fuel mix. This is not an ideal method.
Polycrystalline	4070 (1945 to 5660)	208 (99 to 289)	-	
Thin Film	1305 (775 to 1805)	67 (40 to 92)	-	
Roads	Main data source: ICE reference number 147			
Asphalt road - Hot construction method - 40 years	**2509 MJ/Sqm**	**93 $KgCO_2$/Sqm**	**99 $KgCO_2$/Sqm**	**730 MJ/Sqm Feedstock Energy (Included). For more detailed data see reference 147. (Swedish study). The data in this report was modified to fit within the ICE framework. Includes all sub-base layers to construct a road. Sum of construction, maintenance, operation.**
Construction	1069 MJ/Sqm	30·9 $KgCO_2$/Sqm	32·8 $KgCO_2$/Sqm	480 MJ/Sqm Feedstock Energy (Included).
Maintenance - 40 years	471 MJ/Sqm	11·6 $KgCO_2$/Sqm	12·3 $KgCO_2$/Sqm	250 MJ/Sqm Feedstock Energy (Included).
Operation - 40 years	969 MJ/Sqm	50·8 $KgCO_2$/Sqm	54·0 $KgCO_2$/Sqm	Swedish scenario of typical road operation, includes street and traffic lights (95% of total energy), road clearing, sweeping, gritting and snow clearing.
Asphalt road - Cold construction method - 40 years	**3030 MJ/Sqm**	**91 $KgCO_2$/Sqm**	**97 $KgCO_2$/Sqm**	**1290 MJ/kg Feedstock Energy (Included). Sum of construction, maintenance, operation.**
Construction	825 MJ/Sqm	26·5 $KgCO_2$/Sqm	28·2 $KgCO_2$/Sqm	320 MJ/Sqm Feedstock Energy (Included).

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Maintenance - 40 years	1556 MJ/Sqm	13·9 $KgCO_2$/Sqm	14·8 $KgCO_2$/Sqm	970 MJ/Sqm Feedstock Energy (Included).
Operation - 40 years	969 MJ/Sqm	50·8 $KgCO_2$/Sqm	54·0 $KgCO_2$/Sqm	See hot rolled asphalt.
Concrete road - 40 years	**2084 MJ/Sqm**	**142 $KgCO_2$/Sqm**	-	**Sum of construction, maintenance, operation.**
Construction	885 MJ/Sqm	77 $KgCO_2$/Sqm	-	
Maintenance - 40 years	230 MJ/Sqm	14·7 $KgCO_2$/Sqm	-	
Operation - 40 years	969 MJ/Sqm	50·8 $KgCO_2$/Sqm	-	Swedish scenario of typical road operation, includes street and traffic lights (95% of total energy), and also road clearing, sweeping, gritting and snow clearing.
Note: *The above data for roads were based on a single reference (ref 145). There were other references available but it was not possible to process the reports into useful units (per sqm). One of the other references indicates a larger difference between concrete and asphalt roads than the data above. If there is a particular interest in roads the reader is recommended to review the literature in further detail.*				
Windows	MJ per Window			
1·2 m x 1·2 m Single Glazed Timber Framed Unit	286 (?)	14·6 (?)	-	Embodied carbon estimated from typical UK industrial fuel mix.
1·2 m x 1·2 m Double Glazed (Air or Argon Filled):	--	--	-	--
Aluminium Framed	5470	279	-	
PVC Framed	2150 to 2470	110 to 126	-	
Aluminium - Clad Timber Framed	950 to 1460	48 to 75	-	
Timber Framed	230 to 490	12 to 25	-	
Krypton Filled Add:	510	26	-	
Xenon Filled Add:	4500	229	-	

Note: Not all of the data could be converted to full GHG's. It was estimated that from the fuel use only (i.e. not including any process related emissions) the full CO_2e is approximately 6 per cent higher than the CO_2 only value of embodied carbon. This is for the average mixture of fuels used in UK industry.

3.2 MATERIAL PROFILES

This section contains a guide to the Material Profiles followed by the display of 9 different Material Profiles. These were selected for publication because they were considered to be the most widely used material types in the construction industry. The full version of the Inventory (available for download - see Section 2.2 for details) contains Profiles for an additional 25 material types – 34 in total.

Figure 2 shows a blank profile that has been separated into smaller segments to allow clear annotation of each section.

Figure 2: Guide to the material profiles.

Section 1: Database statistics

The materials were broken down into sub-categories, which reflected how the data is stored within the full database. Most materials have a general category, and some are broken down into more specific forms for example Aluminium general, Aluminium extruded. Each of the sub-categories are then broken down into further classifications according to the recycled/virgin content of the material. In many cases the original data source did not specify the recycled content, hence it was necessary to create an unspecified classification.

Here are statistics from all the data that was collected for the ICE database. They include the number of records, which represents the sample size. This may be used as a (simple) indicator of the quality and reliability of the selected values. Additional statistics include the average embodied energy (EE); this should not be used in place of the main selected values. The data is stored as published by the original reference source, hence each record has different boundary conditions or covers a very specific/rare form of the material. These facts cannot be represented by statistics but only with manual examination of the data records. However, in many cases these statistics are similar to the selected 'best' values. Finally, the standard deviation and a full data range are presented to maintain a level of transparency to this inventory.

Material Profile: Example

Embodied Energy (EE) ICE-Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Material						
Sub-Material Category						
100% Recycled						
50% Recycled						
Other Specification						
Unspecified						
Virgin						

Figure 2 (continued)

Section 2: Selected (or 'best') values of embodied energy and carbon

The values of embodied energy are presented here; the example below is only for materials that can be recycled, i.e. metals. The style of presentation has minor variations according to the needs of the data being presented. The 'general' material classification is the value that should be used in the case of uncertainty about which value to select. The primary material is for predominantly virgin materials and secondary for predominantly recycled materials i.e. many authors allow a slight fraction of recycled material under a primary classification, but these are not always stated. Alternatively a recycled content could be assumed and these values can be used to estimate the embodied energy for any given recycled content.

The embodied carbon has been presented separately. Again the values distinguish between primary (virgin) materials, secondary (recycled) materials and the average value typical of the UK market place.

The best range is what the author of this work believes to be a more appropriate range than the full range given in the database statistics (presented in Section 1 of Figure 2, on the previous page). The selection of the range and the 'best' values of embodied energy was not an easy task, especially with so many holes in data provided by authors, but they provide a useful insight into the potential variations of embodied energy within this material. The selected coefficient of embodied energy may not fall within the centre of the range for a number of reasons. The selected value of embodied energy tries to represent the average on the marketplace. However, variations in manufacturing methods or factory efficiency are inevitable.

Selected Embodied Energy and Carbon Coefficients and Associated Data

Material	Embodied Energy - MJ/Kg			Embodied Carbon - Kg CO_2/Kg			Boundaries	Best EE Range - MJ/Kg		Specific Comments
	UK Typical	Primary	Secondary	UK Typical	Primary	Secondary		Low EE	High EE	
General Material							Cradle-to-gate	(+/-30%)		
Cast Products										
Extruded										
Rolled										
Comments										

Figure 2 (continued)

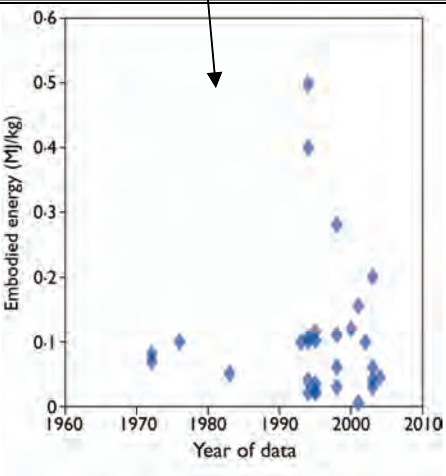
Section 3: Material scatter graphs and fuel split and embodied carbon split

There is a scatter graph for each material (sometimes more than one scatter graph where it is beneficial). The scatter graph plots the year of data versus the value of embodied energy for each data point in the database. This maintains the transparency of this inventory and highlights any historical variations in data values, which may be a result of technological shifts. It could determine whether a small number of data points distort the above database statistics. These values can be used to estimate the embodied energy for any given recycled content.

The fuel split is presented here along with the fraction of embodied carbon resulting from the energy source (or additional carbon released from non-energy sources). Ideally this data will be specified by authors completing a detailed study, but this was seldom the case. In many cases this data was estimated from the typical fuel mix within the relevant UK industry, which was obtained from the Department of Trade and Industry (DTI). In several cases it was not possible to provide a fuel mix or carbon breakdown. Here the typical embodied carbon was estimated based on values specified by authors in the literature.

Where possible the historical embodied carbon per unit fuel (energy) use was calculated as an index of 1990 data. This data is general and was estimated from the typical fuel split in the most appropriate industry. It was not a detailed analysis, in that it is generalised for the entire industry and not for specific products. It illustrates any improvement in carbon emissions since 1990 and the variation in carbon contributions by (fuel) source. This section does not appear on all profiles.

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

Energy source	% of Embodied Energy from Energy Source	% of Embodied Carbon from Source
Coal		
LPG		
Oil		
Natural gas		
Electricity		
Other		
TOTAL	0·0%	0·0%

Comments:

Note space

Historical Embodied Carbon per unit Fuel Use

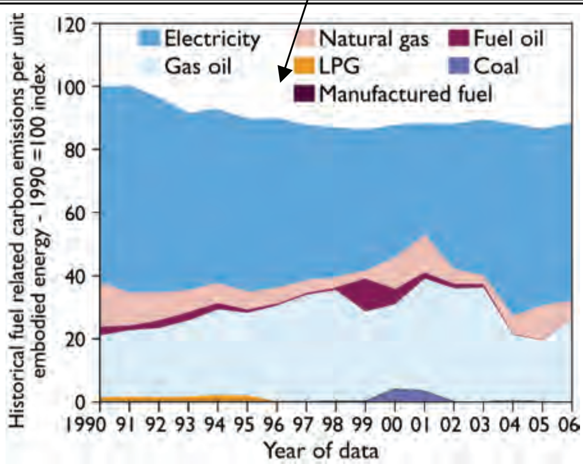


Figure 2 (continued)

Section 4: Material Properties (CIBSE Data)

There is a scatter graph for each material (sometimes more than one scatter graph where it is beneficial). The scatter graph plots the year of data versus the value of embodied energy for each data point in the database. This maintains the transparency of this inventory and highlights any historical variations in data values, which may be a result of technological shifts. It could also be determined whether a small number of data points distort the above database statistics. These values can be used to estimate the embodied energy for any given recycled content.

Material Properties (CIBSE Data)

Material	Condition	Thermal Conductivity (W-m^{-1} K^{-1})	Density (kg m^{-3})	Specific Heat (J kg^{-1} K^{-1})	Thermal Diffusivity (M$^{\wedge 2}$ S^{-1})
Material		230	2700	880	9·68013E-05
Material Galvanised		45	7680	420	1·39509E-05

3.3 SELECTED MATERIAL PROFILES

The full ICE database includes material profiles for 34 materials. A selection of some of the more common materials are presented here. They have been divided into the four separate sections as defined in Figure 2. All profiles are available from the downloadable excel file on the University of Bath website (www.bath.ac.uk/mech-eng/sert/embodied). This section includes the ICE material profiles for:

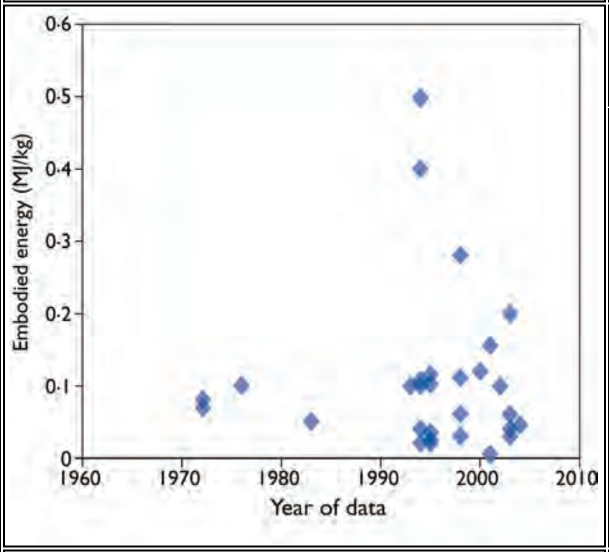
- Aggregates
- Aluminium
- Cement
- Clay and Bricks
- Concrete
- Glass
- Plastics
- Steel
- Timber.

Table 2: Aggregates material profile.

Aggregates						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Aggregate	37	0·11	0·12	0·01	0·50	See the material profiles guide and the FAQs for guidance of these statistics and categories.
General	**37**	**0·11**	**0·12**	**0·01**	**0·50**	
Predominantly Recycled	3	0·25	0·21	0·10	0·40	
Unspecified	17	0·11	0·07	0·02	0·28	
Virgin	17	0·10	0·15	0·01	0·50	

Selected Embodied Energy and Carbon Values and Associated Data						
Material	**Embodied Energy - MJ/Kg**	**Embodied Carbon - Kg CO_2e/Kg**	**Boundaries**	**Best EE Range - MJ/Kg**		**Specific Comments**
				Low EE	**High EE**	
General Aggregate	0·083	0·005	Cradle-to-gate	0·05	0·25	Estimated from UK industrial fuel consumption data.
Comments	It should be noted that the scatter graph does not display all of the data necessary to select a 'best' embodied energy/carbon coefficient, for example the boundary conditions are missing (cradle-to-site, cradle-to-gate etc). These are stored in the full database and were considered during the selection process. Transport is often considered to be a significant contributor for aggregates.					

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

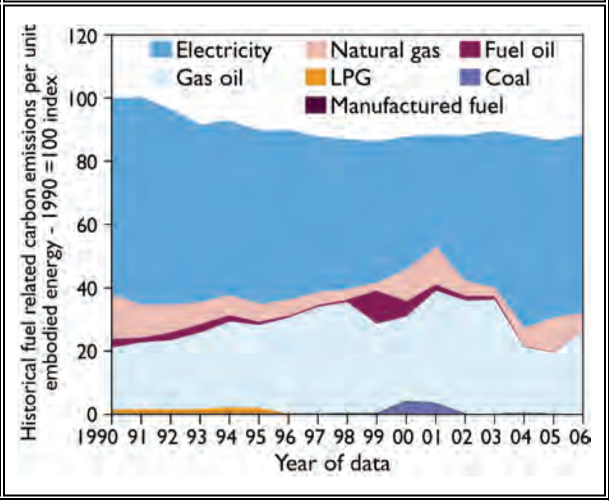
Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	0·0%	0·0%
LPG	0·0%	0·0%
Oil	26·5%	29·8%
Natural gas	8·0%	6·6%
Electricity	65·5%	63·6%
Other	0·0%	0·0%
TOTAL	**100·0%**	**100·0%**

Comments:

The embodied carbon was estimated by assuming the UK typical fuel split in this industry, the resulting value is in agreement with other results in the literature.

Note Space

Historical Embodied Carbon per unit Fuel Use



Material Properties (CIBSE Data)

Material	Condition	Thermal Conductivity (W-m^{-1} K^{-1})	Density (kg m^{-3})	Specific Heat (J kg^{-1} K^{-1})	Thermal Diffusivity (M^{2} S^{-1})
Aggregate	Undried	1·8	2240	840	9·5663E-07
Aggregate (sand, gravel or stone)	Oven dried	1·3	2240	920	6·3082E-07

Source: CIBSE Guide A

Table 3: Aluminium material profile.

Aluminium

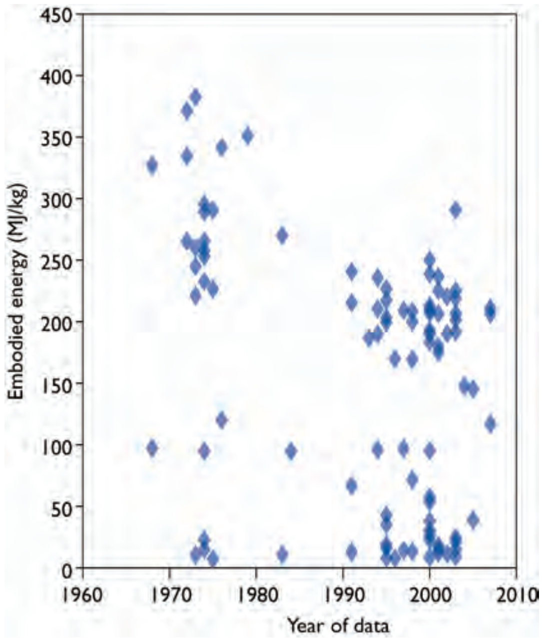
Embodied Energy (EE) Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Aluminium	111	157·1	104·7	8·0	382·7	There was a large sample size, with many high quality data sources. See the material profiles guide and the FAQs for guidance of these statistics and categories.
General	**111**	**157·1**	**104·7**	**8·0**	**382·7**	
50% Recycled	4	108·6	53·4	58·0	184·0	
Other Specification	3	146·5	79·3	55·0	193·5	
Predominantly Recycled	28	17·9	8·7	8·0	42·9	
Unspecified	14	169·1	67·0	68·0	249·9	
Virgin	62	224·1	68·5	39·2	382·7	

Selected Embodied Energy and Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg			Embodied Carbon - Kg CO_2e/Kg			Boundaries	EE Range - MJ/Kg		Specific Comments
	Typical	Primary	Secondary	Typical	Primary	Secondary		Low EE	High EE	
General Aluminium	155	218	29	9·16	12·79	1·81	Cradle-to-gate	(+/-20%)		General aluminium assumed a UK ratio of 25·6% extrusions, 55·7% Rolled and 18·7% castings and a worldwide average recycled content of 33%. For feedstock energy please see the main ICE summary tables at the front of the report.
Cast Products	159	226	25	9·22	13·10	1·45				
Extruded	154	214	34	9·08	12·50	2·12				
Rolled	155	217	28	9·18	12·8	1·79				
Comments	The worldwide average data was obtained from the International Aluminium Institute (IAI) was considered to be the primary data resource, the data is freely available from the IAI website. The averages from the ICE database statistics were in good agreement with the above (selected) values. The data for 'general aluminium' was calculated by assuming the UK consumption split of different forms of aluminium. The selected value for secondary aluminium was towards the top of the full data range. This was because the selected values have a higher level of fabrication than some data resources (i.e. extrusion versus an ingot). Primary aluminium production requires feedstock energy due to the use of coke as a raw material in the production of carbon anodes. **Please see Annex B on recycling methodology.**									

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

Energy source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Electricity	63·6%	57·2%
Other	36·4%	42·8%
TOTAL	**100·0%**	**100·0%**

Comments:

The fraction of energy and carbon from electricity was extracted from the IAI (International Aluminium Institute) data.

Material Properties (CIBSE Data)

Material	Aluminium
Condition	-
Thermal conductivity (W-m^{-1} K^{-1})	230
Density (kg m^{-3})	2700
Specific heat (J kg^{-1} K^{-1})	880
Thermal Diffusivity (M$^{\wedge 2}$ S^{-1})	9·68013E-05

Source: CIBSE Guide A

Table 4: Cement material profile.

Cement						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Cement	116	5·20	2·70	0·10	14·20	There was a large sample of data. See the material profiles guide and the FAQs for guidance of these statistics and categories.
Cement Mortar	**11**	**1·54**	**0·91**	**0·10**	**3·49**	
Unspecified	9	1·30	0·70	0·10	2·10	
Virgin	2	2·63	1·22	1·77	3·49	
Cement, Fibre Cement	**1**	**4·60**	**4·60**	**4·60**		
Virgin	1	4·60	4·60	4·60		
Cement, Fibre Cement	**8**	**10·15**	**1·93**	**7·60**	**14·20**	
Unspecified	8	10·15	1·93	7·60	14·20	
Cement, General	**94**	**5·32**	**2·05**	**1·42**	**11·73**	
Market Average	7	5·02	0·66	4·29	6·20	
Unspecified	65	5·46	2·27	1·42	11·73	
Virgin	22	4·88	1·07	3·00	6·50	
Cement, Soil-Cement	**2**	**0·85**	**0·21**	**0·70**	**1·00**	
Unspecified	2	0·85	0·21	0·70	1·00	

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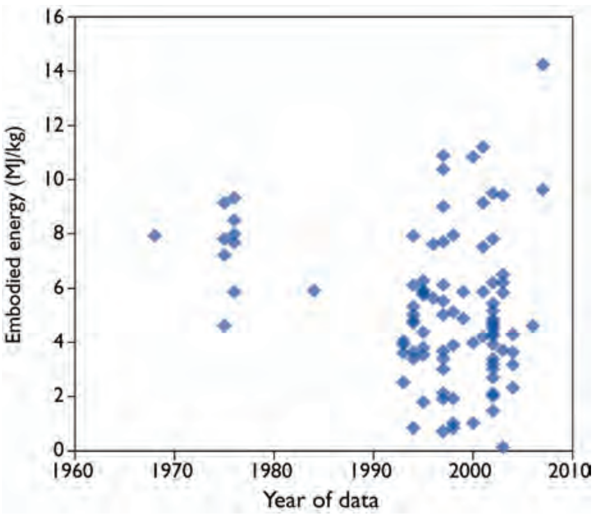
<table>
<tr><th colspan="7">Selected Embodied Energy and Carbon Values and Associated Data</th></tr>
<tr><th rowspan="2">Material</th><th rowspan="2">Embodied Energy - MJ/Kg</th><th rowspan="2">Embodied Carbon - Kg CO_2e/Kg</th><th rowspan="2">Boundaries</th><th colspan="2">EE Range - MJ/Kg</th><th rowspan="2">Specific Comments</th></tr>
<tr><th>Low EE</th><th>High EE</th></tr>
<tr><td>General (UK weighted average)</td><td>4·51</td><td>0·74</td><td rowspan="17">Cradle-to-gate</td><td colspan="2" rowspan="7">(+/- 30%)</td><td>Weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. This data has been estimated from the Mineral Products Association (MPA) factsheets (see Ref. 59). 23% cementitious additions on average.</td></tr>
<tr><td>Average CEM I Portland Cement, 94% Clinker</td><td>5·50</td><td>0·95</td><td>This is a standard cement with no cementitious additions (i.e. Fly ash or blast furnace slag). Composition 94% clinker, 5% gypsum, 1% minor additional constituents (mac's). This data has been estimated from the MPA factsheets (see Ref. 59).</td></tr>
<tr><td>6-20% Fly Ash (CEM II/A-V)</td><td>5·28 to 4·51</td><td>0·89 (@ 6%) to 0·76 (@ 20%)</td><td rowspan="2">Fly ash has a lower embodied carbon than blast furnace slag, however the upper threshold of fly ash content that can be used in a stable mixture is lower than for blast furnace slag. This data has been estimated from the MPA factsheets (see Ref. 59) and the ICE data for fly ash.</td></tr>
<tr><td>21-35% Fly Ash (CEM II/B-V)</td><td>4·45 to 3·68</td><td>0·75 to 0·62</td></tr>
<tr><td>21-35% GGBS (CEM II/B-S)</td><td>4·77 to 4·21</td><td>0·77 to 0·65</td><td rowspan="3">GGBS = ground granulated blast furnace slag. Blast furnace slag has a higher embodied carbon than fly ash, however the upper threshold of blast furnace slag content is higher than for fly ash. This data has been estimated from the MPA factsheets (see Ref. 59) and the ICE data for GGBS.</td></tr>
<tr><td>36-65% GGBS (CEM III/A)</td><td>4·17 to 3·0</td><td>0·64 to 0·39</td></tr>
<tr><td>66-80% GGBS (CEM II/B)</td><td>2·96 to 2·4</td><td>0·38 to 0·26</td></tr>
<tr><td>Fibre Cement Panels - Uncoated</td><td>10·4</td><td>1·09 CO_2</td><td colspan="2" rowspan="2">Estimated range +/- 30%</td><td rowspan="2">Few data points. Selected data modified from Ref. 107. An example application is facade panels.</td></tr>
<tr><td>Fibre Cement Panels - (Colour) Coated</td><td>15·3</td><td>1·28 CO_2</td></tr>
<tr><td>Mortar (1:3 cement:sand mix)</td><td>1·33</td><td>0·221</td><td colspan="2" rowspan="7">(+/- 30%)</td><td rowspan="7">Estimated from the ICE Cement, Mortar and Concrete Model and mix proportions.</td></tr>
<tr><td>Mortar (1:4)</td><td>1·11</td><td>0·182</td></tr>
<tr><td>Mortar (1:5)</td><td>0·97</td><td>0·156</td></tr>
<tr><td>Mortar (1:6)</td><td>0·85</td><td>0·136</td></tr>
<tr><td>Mortar (1:½:4½ Cement:Lime:Sand mix)</td><td>1·34</td><td>0·213</td></tr>
<tr><td>Mortar (1:1:6 Cement:Lime:Sand)</td><td>1·11</td><td>0·174</td></tr>
<tr><td>Mortar (1:2:9 Cement:Lime:Sand)</td><td>1·03</td><td>0·155</td></tr>
<tr><td>Cement stabilised soil @ 5%</td><td>0·68</td><td>0·061</td><td colspan="2" rowspan="2">(+/- 30%)</td><td>Assumed 5% cement content.</td></tr>
<tr><td>Cement stabilised soil @ 8%</td><td>0·83</td><td>0·084</td><td></td><td>Assumed 8% stabiliser contents (6% cement and 2% quicklime).</td></tr>
<tr><td>Comments</td><td colspan="6">The high range is due to the fact that the embodied energy is highly dependent upon the clinker content of cement, manufacturing technology and if additions have been added, such as fly ash, slag etc. Cement is an important building material and is important in the manufacture of concrete. There are a wide range of cement types with a large variation in the embodied energy and carbon, but the typical cement (general category above) provides a reasonable value to use in the absence of knowing the specific type of cement. This typical value is consistent with the database statistics and modern sources of data. The scatter graph shows a large amount of relatively modern data.</td></tr>
</table>

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

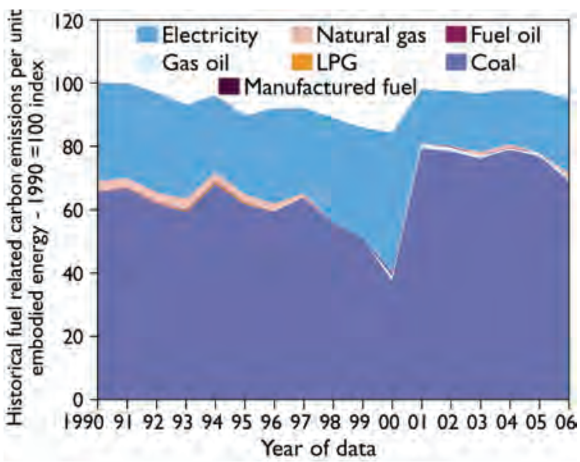
Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	63·4%	32·0%
LPG	0·0%	0·0%
Oil	1·4%	0·5%
Natural gas	2·4%	0·7%
Electricity	32·8%	10·9%
Other	0·0%	55·9%
TOTAL	**100·0%**	**100·0%**

Comments:

0·52 $KgCO_2$/Kg clinker is released by de-carbonation in the manufacture of clinker, which is the main constituent of cement. This has been represented in the row labelled 'other' above.

Note Space

Historical Embodied Carbon per unit Fuel Use



Material Properties (CIBSE Data)					
Material	**Condition**	**Thermal Conductivity (W-m^{-1} K^{-1})**	**Density (kg m^{-3})**	**Specific Heat (J kg^{-1} K^{-1})**	**Thermal Diffusivity (M^2 S^{-1})**
Cement		0·72	1860	840	4·60829E-07
Cement blocks, cellular		0·33	520	2040	3·11086E-07
Cement fibreboard, magnesium oxysulphide binder		0·082	350	1300	1·8022E-07
Cement mortar		0·72	1650	920	4·74308E-07
Cement mortar	Dry	0·93	1900	840	5·82707E-07
Cement mortar		1·5	1900	840	9·3985E-07
Cement/lime plaster		0·8	1600	840	5·95238E-07
Cement panels, wood fibres A	Dry	0·08	350	1890	1·20937E-07
Cement panels, wood fibres B	Moist	0·12	350	3040	1·12782E-07
Cement panels, wood fibres C		0·12	400	1470	2·04082E-07
Cement panels, wood fibres D		0·35	1650	840	2·52525E-07
Cement Screed		1·4	2100	650	1·02564E-06

Source: CIBSE Guide A

Table 5: Clay and bricks material profile.

Clay and Bricks

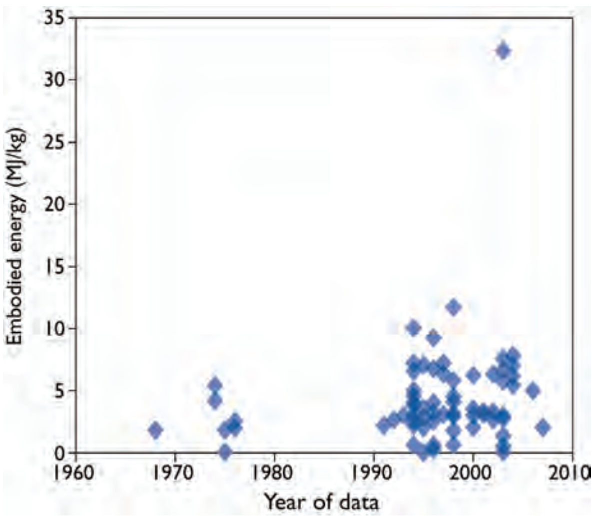
Embodied Energy (EE) Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Clay	80	4·30	4·12	0·02	32·40	There was a good sample size. See Material Profile Guide and FAQs
Clay, General	**80**	**4·30**	**4·12**	**0·02**	**32·40**	
Unspecified	58	4·53	4·57	0·07	32·40	
Virgin	22	3·59	2·22	0·02	7·60	

Selected Embodied Energy and Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO_2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General simple baked clay products	3	0·24	Cradle-to-gate	1	5	None
Tile	6·5	0·48		2·88	11·7	
Vitrified clay pipe DN 100 and DN 150	6·2	0·46		Estimated range +/- 30%		
Vitrified clay pipe DN 200 and DN 300	7	0·50				
Vitrified clay pipe DN 500	7·9	0·55				
General Clay Bricks	3·0	0·24		0·63	6	
EXAMPLE: Single Brick	6·9 MJ per brick	0·55 kgCO_2 per brick		-	-	Assuming 2·3 kg per brick (Brick Development Association estimate).
Limestone Bricks	0·85	?		0·7	1·01	
Comments	Clay products release process related carbon dioxide emissions during their manufacturing. This is dependent upon the type of clay product. There was a large data range associated with all ceramic and brick products.					

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

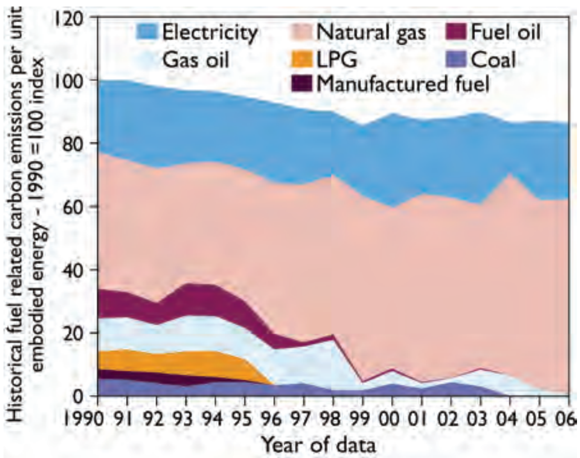
Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	0·0%	0·0%
LPG	0·0%	0·0%
Oil	0·4%	0·2%
Natural gas	74·6%	49·5%
Electricity	25·0%	17·3%
Other	0·0%	33·0%
TOTAL	**100·0%**	**100·0%**

Comments:

The embodied carbon was estimated by using the UK typical fuel split in this industry.

Note Space

Historical Embodied Carbon per unit Fuel Use



Material Properties (CIBSE Data)

Note: Please download a full copy of the ICE database for the 'Materials Properties' data for Clay and Bricks.

Source: CIBSE Guide A

Table 6: Concrete material profile.

Concrete						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Concrete	124	2·92	8·61	0·07	92·50	See the material profiles guide and the FAQs for guidance of these statistics and categories.
Concrete, General	**112**	**3·01**	**9·07**	**0·07**	**92·50**	
Unspecified	85	2·12	2·85	0·07	23·90	
Virgin	27	6·02	18·24	0·59	92·50	
Concrete, Pre-Cast	**12**	**2·18**	**0·78**	**1·20**	**3·80**	
Unspecified	8	2·42	0·84	1·36	3·80	
Virgin	4	1·72	0·42	1·20	2·19	

Selected Embodied Energy and Carbon Values and Associated Data							
Boundaries	**Cradle-to-gate**			**Data Range**	**+/- 30%**		**Specific Comments**
Material	**Embodied Energy - MJ/Kg**			**Embodied Carbon - Kg CO_2e/Kg**			
General	0·75			0·107			It is strongly recommended to avoid selecting a 'general' value for concrete. See comments. Assumed cementitious content 12% by mass. Assumed use of weighted average UK cement.
16/20 MPa	0·70			0·100			Using UK weighted average cement (more representative of 'typical' concrete mixtures)
20/25 MPa	0·74			0·107			
25/30 MPa	0·78			0·113			
28/35 MPa	0·82			0·120			
32/40 MPa	0·88			0·132			
40/50 MPa	1·00			0·151			
FLY ASH							
% Cement Replace. - Fly Ash	**0% (using CEM I)**	**15%**	**30%**	**0% (using CEM I)**	**15%**	**30%**	**Note 0% is a concrete using a CEM I cement**
GEN 0 (6/8 MPa)	0·55	0·52	0·47	0·076	0·069	0·061	Compressive strength designation C6/8 MPa. 28 day compressive strength under British cube method of 8 MPa, under European cylinder method 6 MPa. Possible uses: Kerb bedding and backing. Data is only cradle to factory gate but beyond this the average delivery distance of ready mix concrete is 8·3 km by road (see reference 244).
GEN 1 (8/10 MPa)	0·70	0·65	0·59	0·104	0·094	0·082	Possible uses: mass concrete, mass fill, mass foundations, trench foundations, blinding, strip footing.
GEN 2 (12/15 MPa)	0·76	0·71	0·64	0·114	0·105	0·093	-
GEN 3 (16/20 MPa)	0·81	0·75	0·68	0·123	0·112	0·100	Possible uses: garage floors.
RC 20/25 (20/25 MPa)	0·86	0·81	0·73	0·132	0·122	0·108	-
RC 25/30 (25/30 MPa)	0·91	0·85	0·77	0·140	0·130	0·115	Possible uses: reinforced foundations.
RC 28/35 (28/35 MPa)	0·95	0·90	0·82	0·148	0·138	0·124	Possible uses: reinforced foundations, ground floors.
RC 32/40 (32/40 MPa)	1·03	0·97	0·89	0·163	0·152	0·136	Possible uses: structural purposes, in situ floors, walls, superstructure.
RC 40/50 (40/50 MPa)	1·17	1·10	0·99	0·188	0·174	0·155	Possible uses: high strength applications, precasting.
PAV1	0·95	0·89	0·81	0·148	0·138	0·123	Possible uses: domestic parking and outdoor paving.
PAV2	1·03	0·97	0·89	0·163	0·152	0·137	Possible uses: heavy duty outdoor paving.

Section 2 continued overpage

COMMENT ON ABOVE DATA STRUCTURE
The first column represents standard concrete made with 100% Portland cement (CEM I). The other columns are based on a direct substitution of fly ash or blast furnace slag in place of some of the cement. They have been modelled on the fraction of cement replacement material (fly ash or slag). However there are thresholds on the upper limit that each of these replacement materials can contribute. This threshold is linked to the strength class of the concrete. It is understood that fly ash, which has a lower embodied energy and carbon, cannot be used in the same high fractions as blast furnace slag. In certain circumstances blast furnace slag could reach 70-80% replacement, this is much higher than the upper limits of fly ash. Despite this advantage of slag over flay ash it is encouraged to consider the use of flay ash. Slag rarely ends up in landfill. On the other hand Fly ash is abundant in supply and large quantities are land filled each year. The ICE Cement, Mortar and Concrete Model was used to estimate the above values. The above data is offered as a 'what if' guideline only. The data user must ensure that the quantity of cement substitution is suitable for the specific application in hand. The cement content of a concrete with a specified compressive strength class may vary from the selected content within these above mixtures. The most accurate results are obtained from directly modelling the real concrete mix used within a project. The data is only cradle to factory gate but beyond this the average delivery distance of ready mix concrete is 8·3 km by road (see reference 244).

GGBS

% Cement Replace.- GGBS	**0% (using CEM I)**	**25%**	**50%**	**0% (using CEM I)**	**25%**	**50%**	**Note 0% is a concrete using a CEM I cement**
GEN 0 (6/8 MPa)	0·55	0·48	0·41	0·076	0·060	0·045	See comments for relevant category with fly ash additions (table directly above).
GEN 1 (8/10 MPa)	0·70	0·60	0·50	0·104	0·080	0·058	
GEN 2 (12/15 MPa)	0·76	0·62	0·55	0·114	0·088	0·065	
GEN 3 (16/20 MPa)	0·81	0·69	0·57	0·123	0·096	0·070	
RC 20/25 (20/25 MPa)	0·86	0·74	0·62	0·132	0·104	0·077	
RC 25/30 (25/30 MPa)	0·91	0·78	0·65	0·140	0·111	0·081	
RC 28/35 (28/35 MPa)	0·95	0·83	0·69	0·148	0·119	0·088	
RC 32/40 (32/40 MPa)	1·03	0·91	0·78	0·163	0·133	0·100	
RC 40/50 (40/50 MPa)	1·17	1·03	0·87	0·188	0·153	0·115	
PAV1	0·95	0·82	0·70	0·148	0·118	0·088	
PAV2	1·03	0·91	0·77	0·163	0·133	0·100	

REINFORCED CONCRETE - Modification Factors

For reinforcement add this value to the appropriate concrete coefficient for each 100 kg of rebar per m^3 of concrete	1·04	0·077	Add for each 100 kg steel rebar per m^3 concrete. Use multiple of this value, i.e. for 150 kg steel use a factor of 1·5 times these values.
EXAMPLE: Reinforced RC 25/30 MPa (with 110 kg per m^3 concrete)	1·92 MJ/kg (0·78 + 1·04 * 1·1)	0·198 kgCO$_2$e/kg (0·113 + 0·077 * 1·1)	With 110 kg rebar per m^3 concrete. UK weighted average cement. This assumes the UK typical steel scenario (59% recycled content). Please consider if this is in line with the rest of your study (goal and scope) or the requirements of a predefined method.

PRECAST (PREFABRICATED) CONCRETE - Modification Factors

For precast add this value to the selected coefficient of the appropriate concrete mix	0·45	0·029	For each 1 kg precast concrete. Includes UK recorded plant operations and estimated transportation of the constituents to the factory gate (38 km aggregates, estimated 100 km cement). Data is only cradle to (precast) factory gate but beyond this the average delivery distance of precast is 155 km by road (see Ref. 244). UK weighted average cement.
EXAMPLE: Precast RC 40/50 MPa	1·50 MJ/kg (1·00 + 0·50)	0·180 kgCO$_2$/kg (0·151 + 0·029)	
EXAMPLE: Precast RC 40/50 with reinforcement (80 kg per m^3)	2·33 MJ/kg (1·50 + 1·04 * 0·8)	0·242 kgCO$_2$/kg (0·180 + 0·077 * 0·8)	

CONCRETE BLOCKS (ICE CMC Model Results)

Block - 8 MPa Compressive Strength	0·59	0·063	Estimated from the concrete block mix proportions, plus an allowance for concrete block curing, plant operations and transport of materials to factory gate.
Block - 10 MPa	0·67	0·078	
Block - 12 MPa	0·72	0·088	
Block - 13 MPa	0·83	0·107	
Autoclaved Aerated Blocks (AAC's)	3·50	(0·24 to 0·375) CO$_2$	Not ICE CMC model results.

Section 2 continued overpage

NOMINAL PROPORTIONS METHOD (Volume), Proportions from BS 8500:2006 (ICE Cement, Mortar and Concrete (CMC) Model Results)			
1:1:2 Cement:Sand:Aggregate	1·28	0·206	High strength concrete. All of these values were estimated assuming the UK average content of cementitious additions (i.e. fly ash, GGBS) for factory supplied cements in the UK, see reference 59.
1:1·5:3	0·99	0·155	Often used in floor slab, columns and load bearing structure.
1:2:4	0·82	0·124	Often used in construction of buildings under 3 storeys.
1:2.5:5	0·71	0·104	
1:3:6	0·63	0·090	Non-structural mass concrete.
1:4:8	0·54	0·074	
BY CEM I CEMENT CONTENT - kg CEM I cement content per cubic metre concrete (ICE CMC Model Results)			
120 kg / m^3 concrete	0·49	0·064	Assumed density of 2,350 kg/m^3. Interpolation of the CEM I cement content is possible These numbers assume the CEM I cement content (not the total cementitious content, i.e. they do not include cementitious additions). They may also be used for fly ash mixtures without modification, but they are likely to slightly underestimate mixtures that have additional GGBS due to the higher embodied energy and carbon of GGBS (in comparison to aggregates and fly ash).
200 kg / m^3 concrete	0·67	0·097	
300 kg / m^3 concrete	0·91	0·140	
400 kg / m^3 concrete	1·14	0·181	
500 kg / m^3 concrete	1·37	0·224	
MISCELLANEOUS VALUES			
Fibre-Reinforced	7·75 (?)	0·45 (?)	Literature estimate, likely to vary widely. High uncertainty.
Very High GGBS Mix	0·66	0·050	Data based on Lafarge 'Envirocrete', which is a C28/35 Mpa, very high GGBS replacement value concrete.

Comments

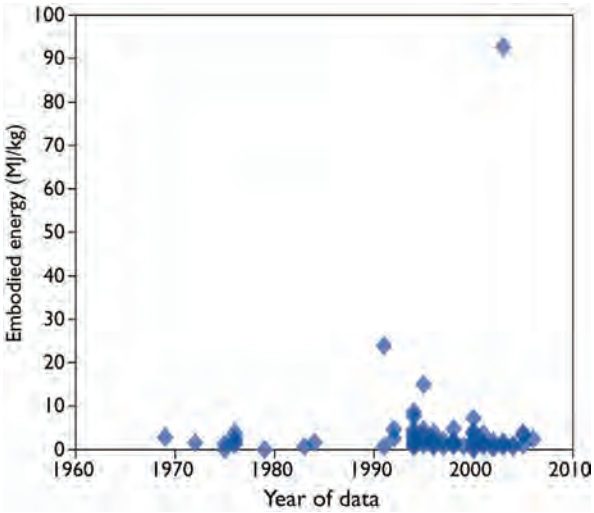
The values of embodied carbon all exclude the re-carbonation of concrete in use, which is application dependent. The majority of these concrete values were taken from the University of Bath's ICE Cement, Mortar and Concrete Model. It operates using the quantities of constituent material inputs and an additional energy requirement of plant operations, transport of constituents and a small allowance for mixing waste. As a result these values are dependent upon the selected coefficients of embodied energy and carbon of cement, sand and aggregates, which are the main constituent materials for concrete.

It may appear that concrete has a confusing array of options, but it is worth determining the strength class or preferably mix of concrete (particularly cement content) used within a project. Even for a specified strength class of concrete the cement content can vary significantly.

Fly ash, which has a lower embodied energy and carbon, cannot be used in the same high fractions as blast furnace slag. In certain circumstances blast furnace slag could reach 70-80% replacement, this is much higher than the upper limits of fly ash. Despite this advantage of blast furnace slag over fly ash it is encouraged to consider the use of fly ash. Slag rarely ends up in landfill. On the other hand fly ash is abundant in supply and large quantities are land filled each year.

If none of the descriptions or comments above help you may wish to apply the above 'general' value, which is for a typical concrete mix. But in doing so (and in an extreme case) you may inadvertently add up to +/-50% additional error bars to your concrete results.

Note: the suggested possible uses of each strength class of concrete are a rough guide only.

Material Scatter Graph	Embodied Energy and Embodied Carbon Split
	The proportions of constituent materials used within concrete mixtures vary so widely that an embodied energy and carbon split would not be representative of the vast majority of concrete products.

Material Properties (CIBSE Data)

Material	Condition	Thermal Conductivity (W-m^{-1} K^{-1})	Density (kg m^{-3})	Specific Heat (J kg^{-1} K^{-1})	Thermal Diffusivity (M^{2} S^{-1})

Note: Please download a full copy of the ICE database for the ‘Materials Properties’ data for Concrete. It includes a comprehensive list of concrete types.

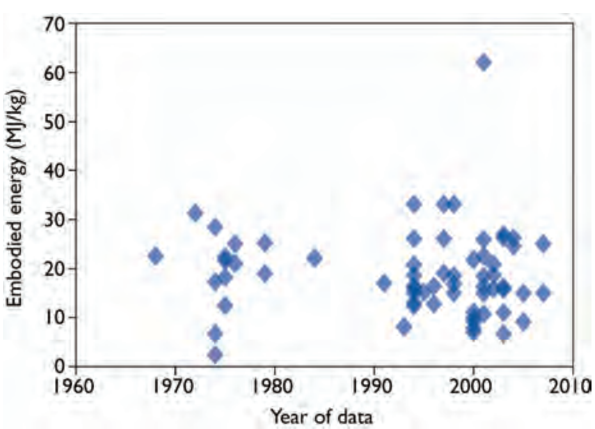
Source: CIBSE Guide A

Table 7: Glass material profile.

Glass						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Glass	97	20·08	9·13	2·56	62·10	See the material profiles guide and the FAQs for guidance of these statistics and categories.
Glass, Fibreglass	**22**	**25·58**	**8·53**	**11·00**	**41·81**	
Market Average	1	30·00	30·00	30·00	-	
Predominantly Recycled	2	11·90	11·90	11·90	-	
Unspecified	16	26·24	8·41	11·00	41·81	
Virgin	3	24·85	10·25	17·60	32·10	
Glass, General	**75**	**18·50**	**8·73**	**2·56**	**62·10**	
50% Recycled	1	7·00	7·00	7·00	-	
Market Average	4	16·81	5·87	12·30	25·09	
Other Specification	1	8·10	8·10	8·10	-	
Predominantly Recycled	5	6·63	4·07	2·56	10·70	
Unspecified	34	20·82	9·96	6·80	62·10	
Virgin	30	17·98	6·15	8·10	31·42	

Selected Embodied Energy and Carbon Values and Associated Data						
Material	**Embodied Energy - MJ/Kg**	**Embodied Carbon - Kg CO_2e/Kg**	**Boundaries**	**Best EE Range - MJ/Kg**		**Specific Comments**
				Low EE	**High EE**	
Primary Glass	15	0·91	Cradle-to-gate	(+/- 30%)		Includes 0·185 $kgCO_2$/kg of process CO_2 emissions.
Secondary Glass	11·5	0·59				EE estimated from Ref 115.
Fibreglass	28	1·54 CO_2		16·5	42	Large data range, but the selected value is inside a small band of frequently quoted values.
Toughened Glass	23·5	1·35		-	1	Only three data sources.
Comments	The primary glass manufacturing process consumes soda ash, limestone and dolomite, which release some of their carbon dioxide in the melting process. This is an additional, non-fuel related, carbon release. It is estimated that primary glass manufacturing releases 0·185 $kgCO_2$/kg during the primary production process (Ref 115). Glass recycling rates are difficult to apply to construction (i.e. flat glass). The most comprehensive statistics are for container glass, where the UK has a closed loop recycling rate of 33·3% (which excludes imported cullet, flat glass and process losses) with an 'overall recycling rate' of 51% in the year 2006 (see ' Glass Sustainability Report 2007, British Glass' for further details). The UK glass recycling rate is at present much lower than many other EU countries.					

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

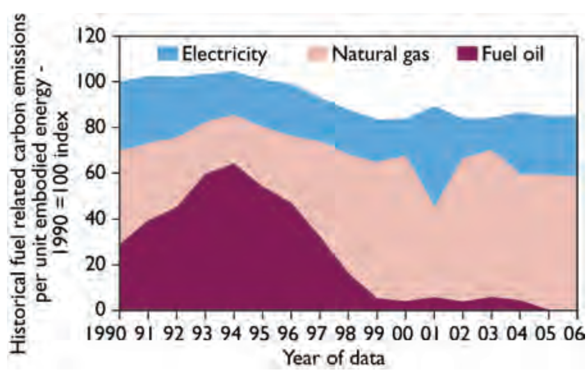
Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	0·0%	0·0%
LPG	0·0%	0·0%
Oil	0·1%	0·1%
Natural gas	71·6%	54·6%
Electricity	28·1%	25·0%
Other	0·0%	20·3%
TOTAL	**100·0%**	**100·0%**

Comments:

This data is for primary glass, which releases 0·185 $kgCO_2$/kg during the primary production process (Additional to energy emissions) this has been considered in the calculations. The fuel mix was estimated from the UK glass industry typical fuel mix.

Note Space

Historical Embodied Carbon per unit Fuel Use



Material Properties (CIBSE Data)

Material	Condition	Thermal Conductivity ($W\text{-}m^{-1}$ K^{-1})	Density ($kg\ m^{-3}$)	Specific Heat ($J\ kg^{-1}$ K^{-1})	Thermal Diffusivity (M^2 S^{-1})
Cellular sheet		0·048	140	840	4·08163E-07
Foam	At 50°C	0·056	130	750	5·74359E-07
		0·052	140	840	4·42177E-07
Solid (soda-lime)	At 10°C	1·05	2500	840	0·0000005
Glass fibre/wool					
Fibre quilt		0·04	12	840	3·96825E-06
Fibre slab		0·035	25	1000	0·0000014
Fibre, strawboard-like		0·085	300	2100	1·34921E-07
Wool	At 10°C	0·04	10	840	4·7619E-06
	At 10°C	0·04	12	840	3·96825E-06
	At 10°C	0·037	16	840	2·75298E-06
	At 10°C	0·033	24	840	1·6369E-06
	At 10°C	0·032	32	840	1·19048E-06
	At 10°C	0·03	48	840	7·44048E-07
	At 10°C	0·031	80	840	4·6131E-07
Wool, resin bonded	At 50°C	0·036	24	1000	0·0000015
Cellular sheet	At 10°C	0·04	10	840	4·7619E-06

Source: CIBSE Guide A

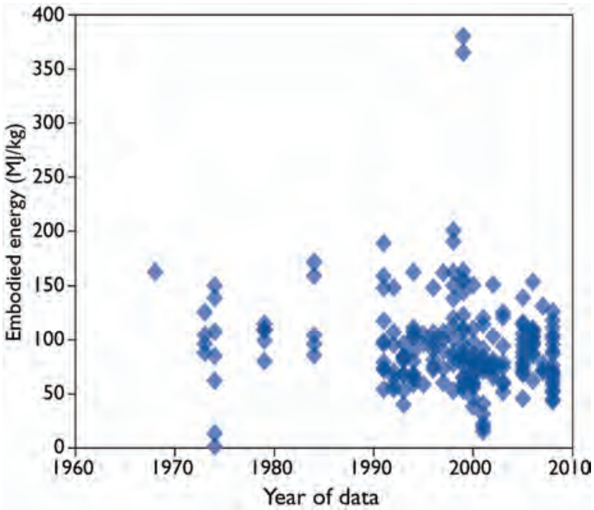
Table 8: Plastics material profile.

Plastics						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Avg. EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Plastics	239	105·80	60·22	1·24	380·00	Care needs to be taken when examining these statistics, the inclusion or exclusion of feedstock energy is not apparent here, but only when analysing data within the main ICE-Database. The majority of the records include the feedstock energy, hence the statistics should be more representative of the inclusion of the feedstocks. See the material profiles guide and the FAQs for guidance of these statistics and categories.
Plastics, ABS	**8**	**77·83**	**45·17**	**1·24**	**114·20**	
Market Average	1	95·30	95·30	95·30	-	
Predominantly Recycled	2	7·19	8·41	1·24	13·13	
Unspecified	4	99·70	15·19	79·90	112·20	
Virgin	1	114·20	114·20	114·20	-	
Plastics, Acrylic	**3**	**90·67**	**37·82**	**56·00**	**131·00**	
Unspecified	2	70·50	20·51	56·00	85·00	
Virgin	1	131·00	131·00	131·00	-	
Plastics, General	**24**	**105·30**	**37·67**	**45·70**	**162·00**	
Unspecified	11	123·57	41·59	73·60	162·00	
Virgin	13	89·84	26·70	45·70	151·10	
Plastics, High Density Polyethylene (HDPE)	**11**	**79·67**	**25·39**	**18·60**	**103·00**	
Market Average	2	80·55	5·44	76·70	84·40	
Predominantly Recycled	1	18·60	18·60	18·60	-	
Unspecified	6	95·15	8·96	80·98	103·00	
Virgin	2	62·90	16·83	51·00	74·80	
Plastics, Low Den. Polyet. (LDPE)	**7**	**77·72**	**16·26**	**51·00**	**103·00**	
Market Average	2	83·70	7·92	78·10	89·30	
Unspecified	3	82·55	18·28	67·80	103·00	
Virgin	2	64·50	19·09	51·00	78·00	
Plastics, Nylon	**33**	**205·36**	**77·70**	**79·70**	**365·00**	
Market Average	1	138·60	138·60	138·60	-	
Unspecified	31	202·36	73·70	79·70	360·00	
Virgin	1	365·00	365·00	365·00	-	
Plastics, Polyamide Resin (PA)	**1**	**137·60**	**137·60**	**137·60**	**-**	
Unspecified	1	137·60	137·60	137·60	-	
Plastics, Polycarbonate	**5**	**109·30**	**30·59**	**80·30**	**158·51**	
Market Average	1	112·90	112·90	112·90	-	
Unspecified	4	108·40	35·25	80·30	158·51	
Plastics, Polyester	**7**	**103·83**	**122·11**	**53·70**	**380·00**	
Unspecified	6	57·80	9·90	53·70	78·00	
Virgin	1	380·00	380·00	380·00	-	
Plastics, Polyethylene	**14**	**89·72**	**32·77**	**59·04**	**188·59**	
Market Average	1	85·83	85·83	85·83	-	
Unspecified	11	89·96	35·88	59·04	188·59	
Virgin	2	91·00	91·00	91·00	-	
Plastics, Polyethylterepthalate (PET)	**11**	**90·45**	**32·88**	**21·90**	**153·30**	
Predominantly Recycled	1	21·90	21·90	21·90	-	
Unspecified	6	89·18	18·03	59·40	107·00	
Virgin	4	109·50	31·77	77·30	153·30	
Plastics, Polypropylene	**21**	**93·97**	**31·14**	**40·20**	**171·00**	
Market Average	3	95·89	21·06	73·37	115·10	
Unspecified	15	90·89	31·56	40·20	171·00	
Virgin	3	107·44	43·94	62·20	149·95	
Plastics, Polystyrene	**36**	**100·09**	**22·86**	**58·40**	**151·00**	
Market Average	4	92·90	10·90	86·40	109·20	
Predominantly Recycled	1	90·25	90·25	90·25	-	
Unspecified	18	99·38	19·64	74·43	151·00	
Virgin	13	104·03	30·09	58·40	149·35	
Plastics, Polyurethane	**11**	**80·10**	**15·95**	**65·20**	**110·00**	
Unspecified	10	77·66	14·47	65·20	110·00	
Virgin	1	104·60	104·60	104·60	-	
Plastics, PVC	**44**	**70·61**	**21·00**	**15·10**	**120·00**	
Market Average	6	68·95	13·59	57·54	95·10	
Predominantly Recycled	1	15·10	15·10	15·10	-	
Unspecified	27	72·73	19·61	30·83	120·00	
Virgin	10	71·53	23·37	38·20	106·62	
Plastics, Resin	**1**	**200·00**	**200·00**	**200·00**	**-**	
Unspecified	1	200·00	200·00	200·00	-	
Plastics, UPVC	**2**	**94·70**	**35·78**	**69·40**	**120·00**	
Market Average	1	69·40	69·40	69·40	-	
Unspecified	1	120·00	120·00	120·00	-	

Selected Embodied Energy and Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg	Feedstock Energy (Included) - MJ/Kg	Embodied Carbon - Kg CO_2e/Kg	Boundaries	Best EE Range - MJ/Kg Low EE	Best EE Range - MJ/Kg High EE	Specific Comments
General Plastic	80·5	35·6	3.31	Cradle-to-gate	(+/- 30%) (?)		Determined by the average use of each type of plastic used in the European construction industry.
ABS	95·3	48·6	3.76				
General Polyethylene	83·1	54·4	2.54				Based on average consumption of types of polyethylene in European construction
High Density Polyethylene (HDPE)	76·7	54·3	1.93				
HDPE Pipe	84·4	55·1	2.52				
Low Density Polyethylene (LDPE)	78·1	51·6	2.08				Doesn't include the final fabrication
LDPE Film	89·3	55·2	2.6				
Nylon (Polyamide) 6	120·5	38·6	9.14				Doesn't include final fabrication. Plastics Europe state that two thirds of nylon is used as fibres (textiles, carpets etc) in Europe and that most of the remainder as injection mouldings. Dinitrogen monoxide and methane emissions are very significant contributors to GWP.
Nylon (Polyamide) 6,6	138·6	50·7	7.92				Doesn't include final fabrication (i.e. injection moulding). See comments for Nylon 6 polymer.
Polycarbonate	112·9	36·7	7.62				Doesn't include final fabrication.
Polypropylene, Orientated Film	99·2	55·7	3.43				
Polypropylene, Injection Moulding	115·1	54	4·49				If biomass benefits are included the GWP reduces down to 4·41 kg CO2e/kg.
Expanded Polystyrene	88·6	46·2	3·29				
General Purpose Polystyrene	86·4	46·3	3·43				
High Impact Polystyrene	87·4	46·4	3·42				
Thermoformed Expanded Polystyrene	109·2	49·7	4·39				
Polyurethane Flexible Foam	102·1	33·47	4·84				Poor data availability for feedstock energy
Polyurethane Rigid Foam	101·5	37·07	4·26				Poor data availability for feedstock energy
PVC General	77·2	28·1	3·10				Based on market average consumption of types of PVC in the European construction industry
PVC Pipe	67·5	24·4	3·23				
Calendared Sheet PVC	68·6	24·4	3·19				If biomass benefits are included the GWP reduces down to 3·15 kg CO_2e/kg.
PVC Injection Moulding	95·1	35·1	3·30				If biomass benefits are included the GWP reduces down to 2·84 kg CO_2e/kg.
UPVC Film	69·4	25·3	3·16				
Comments	Most of the selected values are from the Association of Plastic Manufacturers in Europe (APME), see www.plasticseurope.org, who have completed many detailed LCA studies for plastics. Their data is available freely on the internet as eco-profiles. With the selected mix of plastics the average density for general plastic was 960 kg/m^3.						

Material Scatter Graph



Embodied Energy and Embodied Carbon Split

Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Electricity	44·8%	42·4%
Oil fuels	22·3%	27·2%
Other fuels	32·9%	30·4%
TOTAL	**100·0%**	**100·0%**

Comments:

The fuel split data was estimated from the data available from the APME and the assumed use of plastic types in the construction industry. The APME did not provide details of the embodied carbon split or information about the emission factors they apply. The above carbon values are an estimation. They all exclude the feedstock energy (59·6% oil, 40·4% oil fuels).

Material Properties (CIBSE Data)					
Material	**Condition**	**Thermal Conductivity ($W\text{-}m^{-1} K^{-1}$)**	**Density ($kg\ m^{-3}$)**	**Specific Heat ($J\ kg^{-1} K^{-1}$)**	**Thermal Diffusivity ($M^2 S^{-1}$)**
Polyvinylchloride (PVC)		0·16	1380	1000	1·15942E-07
Tiles		0·19	1200	1470	1·0771E-07
Foam					
Phenol		0·04	30	1400	9·52381E-07
Phenol, rigid		0·035	110	1470	2·1645E-07
Polyisocyanate		0·03	45	1470	4·53515E-07
Polyurethane		0·028	30	1470	6·34921E-07
Polyurethane, freon-filled		0·03	45	1470	4·53515E-07
Polyvinylchloride		0·035	37	1470	6·43501E-07
Urea formaldehyde		0·04	10	1400	2·85714E-06
Urea formaldehyde resin		0·054	14	1470	2·62391E-06
Plastic tiles		0·5	1050	840	5·66893E-07
Polyurethane, expanded		0·023	24	1590	6·02725E-07
Polyurethane, unfaced	At 10°C	0·023	32	1590	4·52044E-07

Source: CIBSE Guide A

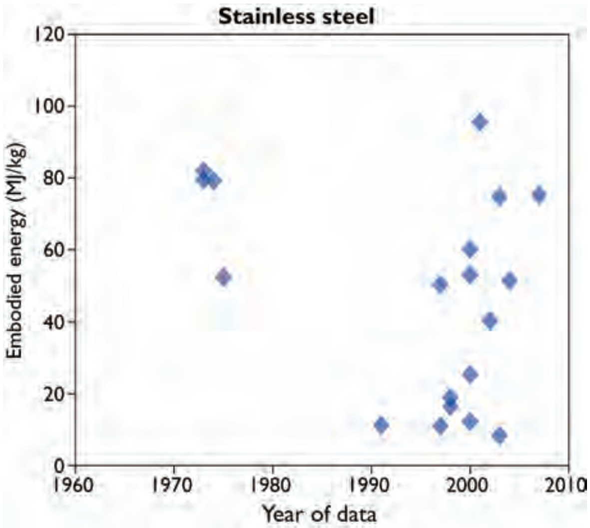
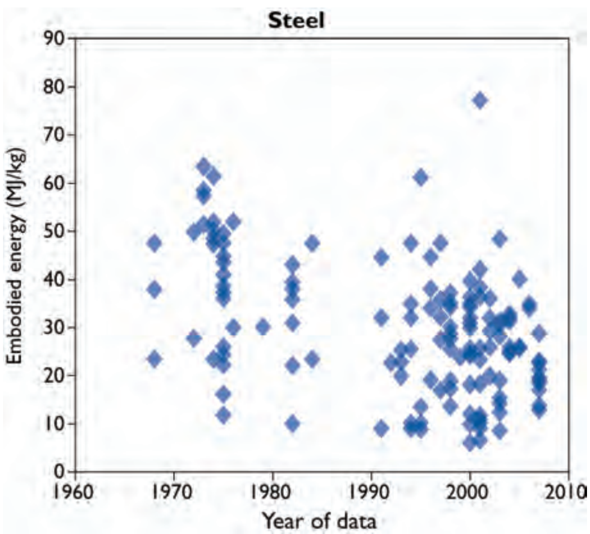
Table 9: Steel material profile.

Steel						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Steel	180	31·25	16·50	6·00	95·70	See the material profiles guide and the FAQs for guidance of these statistics and categories.
Steel, General	**154**	**29·36**	**13·45**	**6·00**	**77·00**	
50% Recycled	2	32·75	20·86	18·00	47·50	
Market Average	11	25·68	5·92	18·20	36·00	
Other Specification	2	19·40	0·71	18·90	19·90	
Predom. Recycled	33	13·60	4·86	6·00	23·40	
Unspecified	49	31·96	10·61	12·50	77·00	
Virgin	57	37·48	12·07	12·00	63·42	
Steel, Stainless	**21**	**45·68**	**28·84**	**8·20**	**95·70**	
Market Average	3	48·36	6·22	40·20	51·48	
Predom. Recycled	2	11·00	0·00	11·00	11·00	
Unspecified	8	43·10	32·21	8·20	95·70	
Virgin	8	57·80	28·76	12·00	81·77	
Steel, Structural	**5**	**30·91**	**3·74**	**25·50**	**35·90**	
Unspecified	2	28·67	4·48	25·50	31·83	
Virgin	3	32·40	3·10	30·00	35·90	

Selected Embodied Energy and Carbon Coefficients and Associated Data														
Material	**Embodied Energy - MJ/Kg**					**Embodied Carbon - Kg CO_2e/Kg**					**Boundaries**	**Best EE Range - MJ/Kg**		**Specific Comments**
	UK Typical - EU 59% Recycled	**R.O.W. Typical - 35·5% Recycled**	**World Typical - World 39% Recycled**	**Primary**	**Secondary**	**UK Typical - EU 59% Recycled.**	**R.O.W. Typical - 35·5% Recycled.**	**World Typical - World 39% Recycled.**	**Primary**	**Secondary**		**Low EE**	**High EE**	
General Steel	20·1	26·2	25·3	35·4	9·40	1·46	2·03	1·95	2·89	0·47	Cradle-to-gate	(+/- 30%)		Estimated from UK's consumption mixture of types of steel (excluding stainless). Doesn't include the final cutting of the steel products to the specified dimensions. Estimated from World Steel Association (Worldsteel) data.
Bar and rod	17·4	22·3	21·6	29·2	8·8	1·40	1·95	1·86	2·77	0·45				Doesn't include the final cutting of the bar/rod to length. Estimated from Worldsteel data.

Section 2 continued overpage

Coil (Sheet)	18·8	24·4	23·5	32·8	NTMR	1·38	1·92	1·85	2·74	NTMR	Cradle-to-gate			NTMR = Not Typical Manufacturing Route. Data doesn't include the cutting of the coil into sheets. Data is as leaves the coil manufacturer. Estimated from Worldsteel data.
Coil (Sheet) - Galvanised	22·6	29·5	28·5	40·0	NTMR	1·54	2·12	2·03	3·01	NTMR				NTMR = Not Typical Manufacturing Route. Data doesn't include the cutting of the coil into sheets. Data is as leaves the coil manufacturer. Estimated from Worldsteel data.
Engineering steel	-	-	-	-	13·1	-	-	-	-	0.72				Estimated from Worldsteel data.
Pipe	19·8	25·8	24·9	34·7	NTMR	1·45	2·01	1·94	2·87	NTMR				NTMR = Not Typical Manufacturing Route. Estimated from Worldsteel data.
Plate	*25·1*	*33·2*	*32·0*	45·4	*NTMR*	*1·66*	*2·31*	*2·21*	3·27	*NTMR*				NTMR = Not Typical Manufacturing Route. Doesn't include the final cutting of the plate. Estimated from Worldsteel data.
Section	21·5	28·1	27·1	38·0	10·0	1·53	2·12	2·03	3·03	0·47				Data doesn't include final fabrication stage (cutting of the section). Data is as leaves the section manufacturer. Estimated from Worldsteel data.
Wire	36 (?)					3·02 (?)								Uncertain data.
Stainless	56·7					6·15 CO_2						11	82	World average data from the Institute of Stainless Steel Forum (ISSF) life cycle inventory data. Selected data is for the most popular grade (304). Stainless steel does not have separate primary and recycled material production routes.
Comments	Please read the recycling methodology guide (Annex B) before using this data, which also contains guidance on end of life issues for steel. The above data is '*Cradle-to-gate*', which excludes the important end of life stage (see Annex B). The majority of this data has been derived from the World Steel Association (formerly International Iron and Steel Institute [IISI]) life cycle inventory (LCI) data, which is the most complete and detailed steel LCI to date and can be obtained free of charge from the IISI website (www.worldsteel.org). Some of the IISI data has been modified to fit within the ICE framework and methodology (e.g. converted to Gross Calorific Value). It should be noted that the data for 'primary steel' is a purely hypothetical 100% primary steel, this enables the recycled content approach to be easily implemented. In practise all steel contains at least a small recycled content, even if sourced from a 'primary production route' (Blast Furnace), on average blast furnace steel has a recycled content of approx 13% (*e.g. general steel @13% recycled content = BF route = 32 MJ/kg*). On the other hand a 100% recycled steel is realistic. Only steel CONSUMPTION WITHIN the EU 27 countries may apply the EU 27 3-year average recycled content of 59%. If applying this recycled content a 'rest of the world' recycled content should be applied to non-EU 27 steel (for consistency within the same project), the 3-year average ROTW recycled content is 35·5%. Alternatively the 3-year world average recycled content of 39% may be applied for all steel products, but this cannot be mixed with the EU 27 average within the same project. For further guidance please see Annex B.													

<table>
<tr><th>Material Scatter Graph</th><th>Embodied Energy and Embodied Carbon Split</th></tr>
<tr><td>
</td><td rowspan="2">A breakdown of fuel use or carbon emissions was not possible. This is because the steel industry is complicated by the production of by-products (which may be allocated energy or carbon credits), excess electricity production (they produce some of their own electricity) and non-fuel related emissions (from the calcination of lime during the production process).</td></tr>
<tr><td>
</td></tr>
</table>

Material Properties (CIBSE Data)					
Material	**Condition**	**Thermal Conductivity ($W \cdot m^{-1} K^{-1}$)**	**Density ($kg\ m^{-3}$)**	**Specific Heat ($J\ kg^{-1} K^{-1}$)**	**Thermal Diffusivity ($M^{\wedge 2} S^{-1}$)**
Stainless steel, 5% Ni		29	7850	480	7·69639E-06
Stainless steel, 20% Ni		16	8000	480	4·16667E-06
Steel		45	7800	480	1·20192E-05

Source: CIBSE Guide A

Table 10: Timber material profile.

Timber						
Embodied Energy (EE) Database Statistics - MJ/Kg						
Main Material	**No. Records**	**Average EE**	**Standard Deviation**	**Minimum EE**	**Maximum EE**	**Comments on the Database Statistics:**
Timber	165	9·43	8·13	0·30	61·26	See the material profiles guide and the FAQs for guidance of these statistics and categories.
Timber, General	**55**	**7·11**	**4·80**	**0·72**	**21·30**	
Unspecified	35	6·41	3·45	0·72	14·85	
Virgin	20	8·40	6·53	1·33	21·30	
Timber, Glulam	**8**	**12·06**	**1·74**	**9·00**	**14·20**	
Unspecified	3	11·10	2·15	9·00	13·30	
Virgin	5	12·64	1·37	11·10	14·20	
Timber, Hardboard	**12**	**21·54**	**15·84**	**3·43**	**61·26**	
Predominantly Recycled	1	3·43	3·43	3·43	-	
Unspecified	8	17·85	8·78	4·00	31·70	
Virgin	3	37·42	22·68	16·12	61·26	
Timber, Hardwood	**13**	**5·38**	**5·15**	**0·33**	**16·00**	
Predominantly Recycled	1	0·33	0·33	0·33	-	
Unspecified	10	5·15	4·68	0·50	16·00	
Virgin	2	9·10	8·20	3·30	14·90	
Timber, MDF	**4**	**11·02**	**1·40**	**8·96**	**11·90**	
Unspecified	3	10·72	1·55	8·96	11·90	
Virgin	1	11·90	11·90	11·90	-	
Timber, OSB	**2**	**14·95**	**3·04**	**12·80**	**17·10**	
Unspecified	1	17·10	17·10	17·10	-	
Virgin	1	12·80	12·80	12·80	-	
Timber, Particle Board	***23***	***12·25***	***10·09***	***2·00***	***36·29***	
Unspecified	23	12·25	10·09	2·00	36·29	
Timber, Plywood	**12**	**13·58**	**6·34**	**7·58**	**27·60**	
Unspecified	7	14·33	4·92	8·30	21·40	
Virgin	5	12·53	8·48	7·58	27·60	
Timber, Softwood	**33**	**5·55**	**3·26**	**0·30**	**13·00**	
Unspecified	24	5·42	3·43	0·30	13·00	
Virgin	9	5·88	2·92	2·80	9·70	
Timber, Woodwool	**3**	**11·98**	**7·50**	**5·13**	**20·00**	
Unspecified	3	11·98	7·50	5·13	20·00	

Selected Embodied Energy and Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO_2e/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General	10·0	$0{\cdot}31_{fos}$ + $0{\cdot}41_{bio}$	Cradle-to-gate	High range for all timber products, see main comments for discussion.		Estimated from UK consumption mixture of timber products in 2007 (Timber Trade Federation statistics). Includes 4·3 MJ bio-energy. All values do not include the CV of the timber product and exclude biogenic carbon storage.
Glue Laminated timber	12	$0{\cdot}42_{fos}$ + $0{\cdot}45_{bio}$		8	14	Includes 4·9 MJ bio-energy.
Hardboard (High Density Fibreboard)	16	$0{\cdot}58_{fos}$ + $0{\cdot}51_{bio}$		15	35	Hardboard is a type of fibreboard with a density above 800 kg/m^3. Includes 5·6 MJ bio-energy.
Laminated Veneer Lumber	9·5	$0{\cdot}33_{fos}$ + $0{\cdot}32_{bio}$		-	-	Ref 150. Includes 3·5 MJ bio-energy.
Medium Density Fibreboard (MDF)	11 (?)	$0{\cdot}39_{fos}$ + $0{\cdot}35_{bio}$ (?)		Not enough data for accurate range. Likely to be high.		Wide density range (350-800 kg/m^3). Limited data to analyse. Includes 3·8 MJ bio-energy.
Oriented Strand Board (OSB)	15	$0{\cdot}45_{fos}$ + $0{\cdot}54_{bio}$		Not enough data for accurate range. Likely to be high.		Estimated from Refs. 101 and 148. Includes 5·9 MJ bio-energy.
Particle Board	14·5	$0{\cdot}54_{fos}$ + $0{\cdot}32_{bio}$		4	15	Very large data range, difficult to select appropriate values. Includes 3·4 MJ bio-energy (uncertain estimate).
Plywood	15	$0{\cdot}45_{fos}$ + $0{\cdot}65_{bio}$		10	20	Includes 7·1 MJ bio-energy.
Sawn Hardwood	10·4	$0{\cdot}24_{fos}$ + $0{\cdot}63_{bio}$		0·72	16	It was difficult to select values for hardwood, the data was estimated from the CORRIM studies (Ref. 88). Includes 6·3 MJ bio-energy.
Sawn Softwood	7·4	$0{\cdot}20_{fos}$ + $0{\cdot}39_{bio}$		0·72	13	Includes 4·2 MJ bio-energy.
Veneer Particleboard (Furniture)	23 ($_{fos}$ + $_{bio}$)	(?)		(perhaps +/- 40%)		Unknown split of fossil and bio-energy based fuels.

Comments

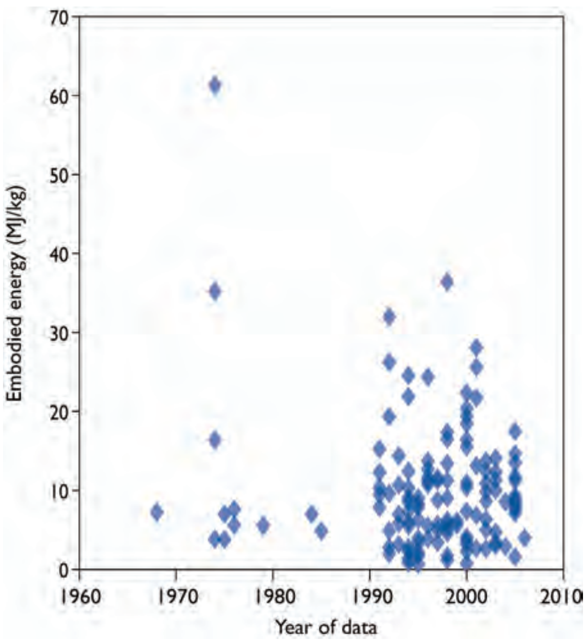
Of all the major building materials timber still presents the most difficulties to the ICE database, there are a number of reasons for this. These include a lack of high quality and detailed studies on timber within the UK and EU. The highest quality studies are possibly the CORRIM studies (see references 88, 150) but these are North American studies and the UK consumes very little timber from this region.

Other factors include a **high element of natural variation**, which may include, for example, **variations in the moisture content of the trees, variations in the consumption of total energy to manufacture the same timber product, and variations in the fuel mix.** The latter is particularly significant to timber manufacturing. Timber off-cuts are often burnt in a furnace to provide energy (normally to dry the timber in a kiln). Large variations in the proportion of embodied energy from this biomass fuel give the data a larger uncertainty than normal. This is also significant because the use of biomass as a fuel may sometimes be assumed to be carbon neutral.

The newest ICE data separates the embodied carbon emissions derived from fossil fuels and that from biomass. The two numbers together give the total carbon released if the biomass (timber) cannot be considered to be carbon neutral (i.e. if the timber is not from a sustainably managed forest). If the timber is from a sustainably managed forest it is easier to justify the carbon neutrality of burning biomass fuels. In this case the embodied carbon may be taken as the fossil fuel derived carbon only (i.e. the first carbon number).

None of the ICE data include the effects of carbon storage during the growing of the trees or the biogenic carbon storage within the timber itself. The inclusion or exclusion of sequestered carbon is a complex discussion. The present authors do not believe that this data should be included in the data for cradle-to-gate. Without including the end of life stage it is difficult to justify. See Section 8.

Material Scatter Graph	Embodied Energy and Embodied Carbon Split



Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	0·0%	0·0%
LPG	0·0%	0·0%
Oil	83·9%	86·3%
Natural gas	1·5%	1·1%
Electricity	14·6%	12·6%
Other	0·0%	0·0%
TOTAL	**100·0%**	**100·0%**

Comments:

The above fuel mix is for general sawn timber taken from the typical UK industrial fuel use. The below values are for wood boards. These two have been separated due to the large difference in fuel mix. They do not include the biomass (wood), they are for the fossil fuel only. The quantity of biomass is provided within the main data.

Energy Source	% of Embodied Energy from energy source	% of Embodied Carbon from source
Coal	0·0%	0·0%
LPG	0·0%	0·0%
Oil	5·6%	7·0%
Natural gas	39·5%	35·5%
Electricity	54·9%	57·5%
Other	0·0%	0·0%
TOTAL	**100·0%**	**100·0%**

Material Properties (CIBSE Data)					
Material	**Condition**	**Thermal Conductivity ($W\text{-}m^{-1}\ K^{-1}$)**	**Density ($kg\ m^{-3}$)**	**Specific Heat ($J\ kg^{-1}\ K^{-1}$)**	**Thermal Diffusivity ($M^2\ S^{-1}$)**
Fir, pine		0·12	510	1380	1·70503E-07
Hardwood (unspecified)		0·05	90	2810	1·97707E-07
	Dry	0·17	700	1880	1·29179E-07
		0·23	800	1880	1·52926E-07
Maple, oak and similar hardwoods		0·16	720	1260	1·76367E-07
Oak, radial		0·19	700	2390	1·13568E-07
Oak, beech, ash, walnut	Moist	0·23	650	3050	1·16015E-07
Meranti	Dry	0·17	650	2120	1·23367E-07
Pine, pitch pine	Dry	0·17	650	2120	1·23367E-07
	Moist	0·23	650	3050	1·16015E-07
Red fir, Oregon fir	Dry	0·14	520	2280	1·18084E-07
	Moist	0·17	520	3440	9·50358E-08
Resinous woods (spruce, sylvestris pine)	Dry	0·12	530	1880	1·20434E-07
Softwood		0·12	510	1380	1·70503E-07
		0·13	630	2760	7·47642E-08
		0·14	550	1880	1·35397E-07
Timber	At 50°C	0·072	480	1680	8·92857E-08
	At 50°C	0·14	720	1680	1·15741E-07
Timber flooring		0·14	650	1200	1·79487E-07
Willow, North Canadian gaboon		0·12	420	2400	1·19048E-07
Willow, birch, soft beech		0·14	520	2280	1·18084E-07
Wood derivatives:	Moist	0·17	520	3440	9·50358E-08
Cellulosic insulation, loose fill		0·042	43	1380	7·07786E-07
Chipboard	At 50°C	0·067	430	1260	1·23662E-07
Chipboard, bonded with PF	Dry	0·12	650	2340	7·88955E-08
	Moist	0·25	650	5020	7·66166E-08
Chipboard, bonded with UF	Dry	0·12	630	2260	8·42815E-08
	Moist	0·25	630	5020	7·90489E-08
Chipboard, bonded with	Dry	0·12	630	2260	8·42815E-08
Melamine	Moist	0·25	630	5020	7·90489E-08
Chipboard, perforated	At 50°C	0·066	350	1260	1·4966E-07
Flooring blocks		0·14	650	1200	1·79487E-07
Hardboard		0·08	600	2000	6·66667E-08
		0·12	880	1340	1·01764E-07
		0·29	1000	1680	1·72619E-07
Multiplex, beech	Dry	0·15	650	2300	1·00334E-07
Multiplex, North Canadian gaboon	Dry	0·12	450	2300	1·15942E-07
Multiplex, red fir	Dry	0·13	550	2300	1·02767E-07
	Moist	0·21	550	2300	1·66008E-07
Particle board		0·098	750	1300	1·00513E-07
		0·17	1000	1300	1·30769E-07
		0·12	800	1300	1·15385E-07
Plywood		0·12	540	1210	1·83655E-07
		0·15	700	1420	1·50905E-07

Source: CIBSE Guide A

4 APPLICATION – WORKED EXAMPLES AND CASE STUDIES

4.1 BASIC WORKED EXAMPLES

The data within the ICE database may be applied to real products and this allows comparative assessments to be made. Three (simple) worked examples are provided here to instruct on the use of the ICE database. These are purely hypothetical, but instructive examples.

EXAMPLE 1

A BUILDING ELEMENT: A SINGLE SKIN BRICK WALL

Background

The first example is for a single skin brick wall, which is known as a half brick thick wall. Despite the name a half brick thick wall (single skin) is only as thick as the width of a single standard brick (102·5 mm). A one brick thick wall is as thick as the length of a standard brick (215 mm) and is known as a double skinned wall.

Assumptions

Boundaries: Cradle to (building) site

Brick dimensions: length 215 mm x width 102·5 mm x height 65 mm

Brick mass: 2·3 kg per brick (note: many bricks are not solid material, they have some free space)

60 bricks per m^2 of one brick thick solid wall

5 per cent additional bricks required for cutting and waste

Mortar mix: 1:5 (Cement:Sand) mortar

10 per cent extra mortar as waste

Density of (dry) mortar mix: 1400 kg/m^3

Negligible embodied impacts of water (consumed in mortar mix)

Transport: 50 km, road

Selected data	Bricks: Embodied Energy (EE) = 6·9 MJ per brick (2·3 kg weight); Embodied Carbon (EC) = 0·55 $kgCO_2e$ per brick 1:5 Mortar: EE = 0·97 MJ/kg; EC = 0·156 $kgCO_2e$/kg Transport, road: assumed as 2·4 MJ/tkm, 0·15 $kgCO_2e$/tkm Note: The energy and carbon requirement of transport is often expressed in the units tonne kilometres, (tkm). These values represent the energy/carbon requirement to transport 1 tonne of material each kilometre, i.e. 1 kg of material (0·001 t) transported 100 km is equal to 0·1 tkm (0·001 tonnes * 100 km). See Section 5.3 for further information.
Calculations	For bricks and mortar Area of 60 bricks: 0·215 x 0·065 x 60 = 0·84 m^2 Area of mortar: 1 – 0·84 = 0·16 m^2 Mass of mortar mix: 0·16 m^2 x 0·1025 m x 1400 kg/m^3 = 23·2 kg Transport of bricks and mortar Transport, road: total tonne kilometres = [((60 x 2·3) + 23·2) x 100 km] x 1·1 (waste material) \ 1000 = 17·7 tkm Note: in this example transport of materials that will end up as waste has been added to the tonne kilometres (above).

Table 11: Total per m^2 of brick wall.

	Quantity	Unit	EE/unit	EC/unit	Waste	Total EE - MJ	Total EC - $kgCO_2e$
60 Bricks	138	Kg	3	0·24	+5%	435	34·8
Mortar (1:5)	23·2	Kg	0·97	0·156	+10%	24.8	3·98
Transport, road	17·7	tkm	2·4	0·15	-	42·5	2·66
					Total	**502**	**41·4**

Final Results	**Embodied Energy – 500 MJ per m^2 of single brick thick wall (2 significant figures)** **Embodied Carbon – 41 $kgCO_2e$ per m^2 of single brick thick wall** These results may be scaled up to the required wall area. When doing this do not forget that a brick wall has a proportion of its fabric underground to provide structural support.

EXAMPLE 2

A PRODUCT: STEEL WALL CLADDING

Background

The second example is of steel wall cladding, which is often used in non-domestic buildings.

Assumptions

Boundaries: Cradle to (factory) gate

Galvanised steel, sheet formation

Thickness: 1 mm

Flat profile cladding, i.e. a flat sheet

Steel density: 7800 kg/m^3

Two layers of paint/coating; 0·3 kg paint per m^2

Fabrication processes consume 2 kWh electricity per m^2 of cladding (illustrative assumption)

Manufacturing waste: 5 per cent by mass

Method for recycling: Market average recycled content approach. Steel within EU at 59 per cent

Transport from steel sheet manufacturer to cladding manufacturer: 100 km by road, 500 km by sea

Transport of paint to cladding manufacturer: 50 km by road

Note: this example does not include the cladding fixing system

Note: this example has excluded any additional fabrication energy of steel cladding panels.

Selected data	Sheet galvanised steel, EU average recycled content of 59 per cent: EE = 22·6 MJ/kg; EC = 1·54 $kgCO_2e/kg$ Paint, two coats: EE = 21·0 MJ/m^2; EC = 0·87 $kgCO_2e/m^2$ Transport, sea: assumed as 0·15 MJ/tkm, 0·009 $kgCO_2e/tkm$. Transport, road: assumed as 2·4 MJ/tkm, 0·15 $kgCO_2e/tkm$ Note: our calculations for UK electricity in 2007 estimate that 1 kWh of delivered electricity requires approx 3 kWh of primary energy (including upstream activities). Each kWh of delivered electricity emits roughly 0·59 $kgCO_2e$ (including all upstream emissions).
Calculations	For steel Mass of steel per m^2 cladding = 7800 kg/m^3 x 1 mm = 7·8 kg Fabrication electricity = 1 kWh = 1 x 3·6 = 3·6 MJ x 3 = 10·8 MJ primary energy per unit (kWh) For transport of steel and paint Transport, sea: total tonne kilometres = 500 km x (7800 kg/m^3 x 1 mm / 1000) tonnes of steel = 3·9 tkm Transport, road: total tonne kilometres = [(7800 kg/m^3 x 1 mm) x 100 km + (0·3 kg paint) x 50 km] \ 1000 = 0·8 tkm *Note: in this example transport of materials that will end up as waste has been added in the waste row of the table below.*

Table 12: Total per m^2 of steel cladding.

	Area - m^2	Quantity	Unit	EE/unit	EC/unit	Total EE - MJ	Total EC - $kgCO_2e$
Steel sheet, galvanised	1	7·8	kg	22·6	1·54	176·3	12·01
Paint, two coats	1	1·0	m^2	21·0	0·87	21·0	0·87
Transport, sea		3·9	tkm	0·15	0·009	0·59	0·035
Transport, road		0·8	tkm	2·40	0·15	1·92	0·12
			5 per cent waste (inc. transport)			10.0	0·65
Fabrication electricity		2	kWh	10·8	0·59	21·6	1·18
					Total	**231**	**14·9**

Final Results	**Embodied Energy – 230 MJ per m^2 of steel cladding (two significant figures)** **Embodied Carbon – 15 $kgCO_2e$ per m^2 of steel cladding** Note: this method does not consider the potential benefit of end of life recovery for reuse or recycling.

Benefits of recovery for recycling or reuse: avoided burdens
This is an extension of example 2 and gives guidance on the end of life benefit of recovery for recycling. Generally the same logic and methods may be applied to reuse.

End of Life (for Example 2)
Assumption: at the end of its lifetime 90 per cent of the steel cladding is recovered for recycling and results in new (future) steel products. There was 7·8 kg of steel per square metre of cladding, which may create approximately 7 kg (i.e. 90 per cent) of new recycled steel for use in future lifecycles. This potentially avoids the need for the same quantity of virgin steel production in future lifecycles. The benefit of avoiding this burden is equal to the difference between the impacts within the recycling production route and the primary material production route (including any differences in transportation and disposal activities). In this case the avoided burden can be estimated as:

Impact = (impact of recycling system) – (impact of virgin material product system)

It is assumed that the energy consumption within the entire recycling system is 10 MJ/kg and the virgin material production route requires 35 MJ/kg (numbers selected for ease of use). The impact may therefore be estimated as

Impact (of recovery) = (10 MJ/kg – 35 MJ/kg) x 7 kg = - 175 MJ/m^2 cladding

The total impact of -175 MJ represents a net benefit, as signified by the negative magnitude. This implies that the recovery of steel cladding panels is estimated to save (in future applications) 175 MJ per square metre of recovered panel (from the avoided need for primary steel in the future).

NOTE 1: Care must be taken when integrating this potential saving into the assessment. The 175 MJ may not be subtracted directly from the cradle-to-gate embodied energy of 230 MJ/m^2, because this would result in the double counting of recycling benefits. This is an allocation issue – the benefit exists but it must be allocated to one or more product systems. For example the benefit of recovery for recycling lies in between two product systems: the system that provided the recovered material (i.e. this cladding), and the system downstream which will consume the future recycled material. See Annex B for further guidance and notes on appropriate methodologies for recycling.

Including the benefit of recovery for recycling (for Example 2)
The selection of a methodology for allocation must be closely aligned with the goal and scope of study. The boundaries of this example may be assumed as cradle-to-grave (because there is no maintenance). Examples include (see also Annex B):

Assumptions

- 90 per cent combined recovery and recycling, therefore 10 per cent is disposed
- Burden of disposal activities (including transport) assumed negligible for the 10 per cent that is disposed
- Steel sheet, galvanised with 90 per cent (effective) recycled content for use with the substitution method: assumed EE = 13·5 MJ/kg.

Table 13 gives three different answers for the same product. The reason for this is different methodologies for recycling. The first column explains which goals and scope are the drivers and the second column explains which method would be most appropriate. There is no single (universally) correct method. For further guidance see Annex B.

Table 13: Cradle to grave energy for steel cladding under three different methods for recycling.

Appropriate goals and scope	Methodology for Recycling (Allocation)	Embodied Energy – MJ/m^2
Heavy focus on present impacts rather than future benefits.	Recycled content approach	230 (example 2) = **230 MJ/m^2**
Heavy focus on future benefits. Improving design for recovery.	Substitution method	[(13·5 x 7·8 kg + 21 (paint) + 0·59 (trans.) + 1·28 (trans.)) x 1·1 (waste)] + 21·6 (fabrication elect) = **163 MJ/m^2**
Equal valuing of present and future. Equal weighting of consumption of recycled materials and design for recovery.	50:50 method	0·5 [230 + 163] = **196·5 MJ/m^2**

4.2 CASE STUDIES FROM INDUSTRIAL USERS OF THE ICE DATABASE

The ICE database has been applied widely in industry. This section provides several examples of how select companies have been using the ICE database on real projects. The University of Bath and BSRIA are not responsible for the content, methodology or accuracy of the following external case studies.

CASE STUDY 1

FARRINGDON STATION RE-DEVELOPMENT

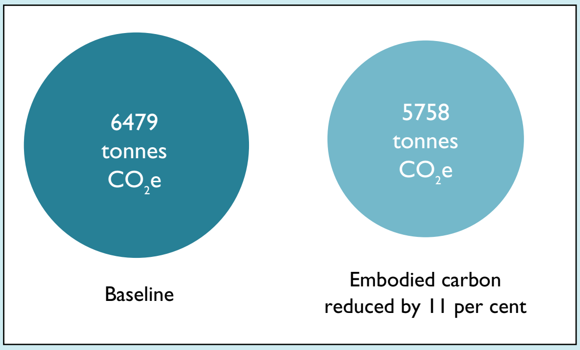
Consultant	**Atkins/Faithful+Gould**
Authors	**Sean Lockie, Piotr Berebecki**
Company information	There are increasing pressures on the construction industry to understand its carbon footprint and take action in response to climate change. Atkins/Faithful+Gould has built significant knowledge, skills and experience to conduct carbon footprints of organisations, projects, products or events. We have an established method for conducting carbon footprint calculations and substantial experience in performing operational and embodied carbon footprint assessments consistent with international best practice standards. 
Project background	Farringdon Station is being substantially improved to accommodate longer trains and more passengers. The improvements will transform Farringdon station into one of London's most important transport hubs, the only station from which passengers will be able to access Thameslink, Crossrail and London underground services, offering links to four major airports and international rail links. There will be a new ticket hall for Thameslink and Crossrail services and a new concourse and entrance to the side of the existing station building. The redeveloped station will now be able to handle 240 m (12-car) trains and lifts will offer access to all platforms for those with buggies, heavy luggage or disabilities. Atkins/Faithful+Gould provided design and sustainability advice on the project to ensure that Network Rail's sustainability strategy is followed and met. As part of the involvement Atkins/Faithful+Gould was also commissioned to assess the embodied carbon impact of the project.
Method	The cradle-to-site embodied carbon assessment was largely based on the embodied carbon factors available in the University of Bath Inventory of Carbon and Energy (ICE) database. DEFRA's guidelines have been followed to establish carbon emissions at the transportation stage. The final fit-out and furnishing of the station was almost entirely excluded and the study focused on key materials found in the building envelope and services. Therefore the primary elements included were: foundations, steel, block/brickwork, floors, insulation, windows, roofing and painting. The quantities of materials were established based on the design drawings and bill of quantities prepared by the cost consultant. The Inventory of Carbon and Energy database was then used to calculate embodied carbon associated with the key materials.

Results

The baseline totalled 6479 tonnes of CO_2e. It was possible to reduce this by 11 per cent, bringing the emissions down to 5758 tCO_2e. One of the key ways of reducing embodied carbon was to specify higher recycled content where possible. In an effort to increase the recycled content the materials specification was mapped against the WRAP (Waste Resources Action Programme) recycled content toolkit and potential quick wins were identified to improve the recycled content from 'standard' to 'good' or 'best practice'. This included: terrazzo tiling, concrete blockwork, and paving, cement replacement materials (such as GGBS - ground granulated blastfurnace slag and fly ash).

A number of low embodied carbon alternatives have been also identified and recommended to the design team. The options considered included: precast concrete beams, micro perforated aluminium panels and tiling, exposed concrete ceilings, castellated steel beams and flexible plumbing.

Figure 3: Embodied carbon of the baseline design and the actual design of Farringdon station re-development.



Additionally, a simple to use embodied carbon estimator tool was developed to enable progress-tracking during the construction stage of the project. It allows the contractor to monitor the construction stage embodied carbon performance against the design team's specifications.

Constraints and opportunities

The lack of manufacturer/product specific embodied carbon factors.

Laborious calculations of the quantities of the materials used.

The embodied carbon assessment started relatively late in the design process. Therefore the positive impact potential was limited.

Outcome

The project team's drive to improve the sustainability performance of the station has led to significant carbon savings. The design team focused on material selection as the key way of reducing embodied carbon. Network Rail and Atkins/Faithful+Gould went through a detailed process of evaluating performance of materials against: value, cost effectiveness, aesthetic characteristics and climate change. Additionally, despite the fact that the embodied carbon was not considered from the first stages of the project, a considerable carbon reduction was achieved through appropriate material selection but more could have been achieved if this was considered earlier. Another important factor was having the contractor involved on the design development early so they were able to have an input into the materials choice considerations, and the final 'carbon budget'.

Experience gained here has contributed to developing the Atkins in-house education strategy to embed a programme we call 'carbon critical' into our design process. Since then Atkins has also produced a suite on 'carbon tools' which enable our designers to design out embodied carbon based on an established and proven methodology.

CASE STUDY 2

LONDON 2012 OLYMPIC PARK AND OLYMPIC VILLAGE

Consultant	**Best Foot Forward**
Authors	**Craig Simmons**
Company information	Sustainability consultants, Best Foot Forward, were commissioned by the Department of Culture Media and Sport (DCMS) and the Olympic Delivery Authority (ODA) to assess the impact of using concrete with low embodied carbon on the overall carbon impact of construction activities in the Olympic Park and the Olympic village.
Project background	Using low-carbon concrete supports the ODA aims to use 20 per cent of construction materials from a reused or recycled source and 25 per cent of aggregate, a key material in the production of concrete, from a recycled source. The ODA has worked closely with its concrete supplier over the past 12 months to supply low-carbon concrete for use in the construction of the venues and infrastructure for the London 2012 Games. The on-site batching plant supplies the majority of ready-mix concrete used in piling and superstructure works for venues and infrastructure. Different concrete mixes with lower embodied carbon than standard concrete have been proposed by the concrete supplier in conjunction with contractors. To ensure the concrete mix meets optimum sustainability requirements, production costs and other considerations must be balanced with the required structural and high-quality finish standards. Testing and trials undertaken to date have involved substituting raw materials in cement with increasing amounts of secondary or recycled materials. For example, fly ash (a waste/by-product of producing electricity in coal-fired power stations), Ground Granulated Blast Furnace Slag (GGBS – a by-product processed from the waste associated with steel manufacture), stent (a waste product of the Cornish China Clay Industry) and recycled glass have been used. Most of the recycled materials used in the concrete are sourced from Leicestershire and Cornwall and delivered by rail directly to the concrete batching plant at the Olympic Park. At present, 94·3 per cent of materials used in concrete have been delivered to site by rail. Approximately 1·3 million tonnes of ready-mix concrete have been used for the Olympic Park and Village. By using concrete with a high recycled content and maximising the use of rail to transport raw materials to site, nearly 80 000 tonnes of carbon emissions have been avoided, which accounts for a 42 per cent reduction against the UK industry average for concrete. The actual footprint of concrete typically varies according to the concrete grade, with the main determinant of the carbon intensity being the amount and type of cement in the mix and the proportion which is replaced by substitute materials, whether PFA, GGBS, stent or recycled glass. There are limits on the proportion of PFA, GGBS and other cement substitutes that may be used in concrete without affecting one or more required (or desired) properties of that concrete.

Method and results	

The Concrete Industry Sustainable Construction Forum 2009 states that an average 18 per cent cement substitution occurs in the UK and it is performance of concrete with that percentage of cement substitution against which the London 2012 concrete is judged (calculated using University of Bath supplied carbon intensity figures).The figures below do not take account of steel reinforcement or transportation.

As the table demonstrates, the carbon footprint of the concrete used in much of the Olympic Park is greater than that of the Village concrete. This is because PFA has been used as the main cement substitute for much of the Park concrete mix, which is substituted at lower levels than GGBS. Concrete containing PFA has a higher carbon content than concrete containing GGBS. This is the case even though PFA itself substitute a small amount of cement compared with the larger amounts possible with GGBS.

A decision was made early in the design and planning phase to use PFA on the Park, where the use specification permitted, due to two main drivers: diverting waste to landfill and supporting local industry.

PFA is a waste product available in vast quantities in the UK. The quantity used in the Park would otherwise have gone to landfill as GGBS is generally more popular as a cement substitute in the UK. Some GGBS required for use in the UK must be imported and therefore may have higher carbon intensity due to the additional transportation.

The decision to create and use sustainable concrete mixes has resulted in a significant reduction in the amount of embedded carbon at the Olympic site. As the table shows, it may have been possible to reduce the carbon further, specification permitting, by using no PFA but this would have meant an additional 22 902 tonnes of material to date going to landfill in the UK.

This clearly demonstrates the complex balance needed between a number of factors, including: embodied carbon, availability and logistics, and specification.

Table 14: Embodied carbon and carbon savings of the Olympic Park and Village.

Location	**Concrete used (tonnes)**	**Carbon footprint (tCO_2)**	**Reference carbon footprint (tCO_2)**	**Carbon savings (tCO_2)**	**Carbon savings (%)**
Olympic Park	698 792	64 417	99 522	35 105	35%
Olympic Village	648 500	44 555	89 081	44 526	50%
Park and Village	1 347 292	108 972	188 603	79 631	42%

Further information

This case study is extracted, with the permission of London 2012, from the London 2012 Sustainability Plan:
http://www.london2012.com/documents/locog-publications/london-2012-sustainability-plan.pdf

CASE STUDY 3

MASDAR CITY, PROPERTY DEVELOPMENT UNIT, ABU DHABI

Consultant

Deloitte dcarbon8

Authors

Guy Battle, Tony Siantonas

Company information

dcarbon8 was founded in April 2006 by Guy Battle, and merged with Deloitte's Sustainability Services group in March 2010. dcarbon8 has won many awards for its leading edge work and has built a strong reputation globally on carbon management and sustainability consulting in the built environment. This work has focussed mainly on measuring the total carbon impact of buildings, and identifying and implementing reductions in the construction supply chain.

Project background

Masdar City is a $22 billion project which aims to be the world's first zero carbon, zero waste, car free city. The Masdar Initiative is a sustainable development being constructed 17 kilometres (11 mi) southeast of the city of Abu Dhabi. The city will cover over 6 square kilometres, house 50 000 people and 1500 businesses, and become a centre for the development of new ideas for energy production, with a new university, the Masdar Institute of Science and Technology.

The project was planned by Foster + Partners using the traditional planning principals of a walled city together with existing technologies. The key sustainability design objectives set by the client were to be zero carbon and zero waste. Once complete, the initiative will have created a city powered by solar power, with no point further than 200 m from a public transport link.

dcarbon8 was engaged as carbon consultants by Masdar City to develop the Masdar Life Cycle Assessment (LCA) policy, to conduct life cycle assessments on its supplier's products, to advise on carbon emissions reductions, the selection of choice of sustainable materials and to measure the embodied carbon of the whole development.

Constraints and opportunities

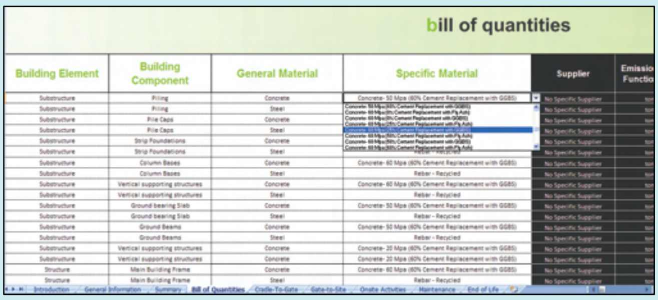
Masdar had the potential, being such a large project, to leverage its huge purchasing power throughout its supply chain to encourage material suppliers and contractors to offer sustainable products and services. By assessing the options available according to environmental and social criteria as well as economic costs, the project team were able to help engage, educate and motivate suppliers into putting sustainability at the heart of their businesses.

Method and results

As part of the work, dcarbon8 created a bespoke embodied carbon database for all of the materials used to construct Masdar City. This included evaluating the robustness of data sources and defining the operational data required from all material suppliers at the tender stage. The emissions factors were based on the original Bath ICE database and were modified, in collaboration with the University of Bath, to more accurately represent the materials that Masdar would be using.

The Bath ICE embodied carbon database was used as the basis for the creation of a Bill of Quantities Toolkit, which enabled the quick, efficient calculation of the carbon impacts of building projects, covering a full Life Cycle Assessment (LCA) from cradle-to-grave, including: onsite activities, operational energy and maintenance. It also enabled sustainability teams to design and assess carbon reductions against a baseline scenario consistent with the PAS 2050 Carbon standard.

Figure 4: dcarbon8 bill of quantities tool.



Method and results (continued)

Using the ICE database and the Bill of Quantities Toolkit, dcarbon8 carried out the carbon footprint measurement of Masdar City, covering the greenhouse gas (GHG) emissions associated with the manufacture of all building materials delivered to site, and a prediction of on-site operations during the construction processes. Measurement took place according to the Planet Positive Protocol Product Carbon Footprint Methodology, based on *ISO 14044:2006*. The assessment covered all building materials from cradle to factory gate, delivery to site, onsite construction activities, in order to reflect a capital cost of carbon for the city's delivery.

Figure 5: Embodied carbon of Masdar City designs.

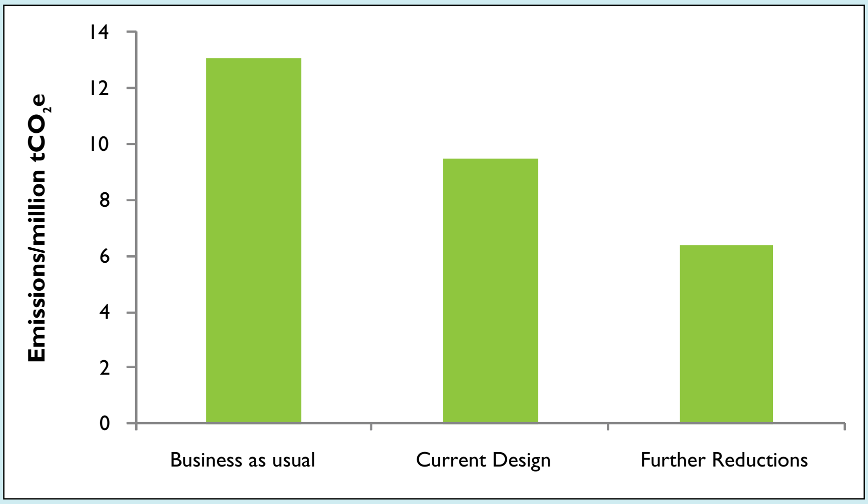
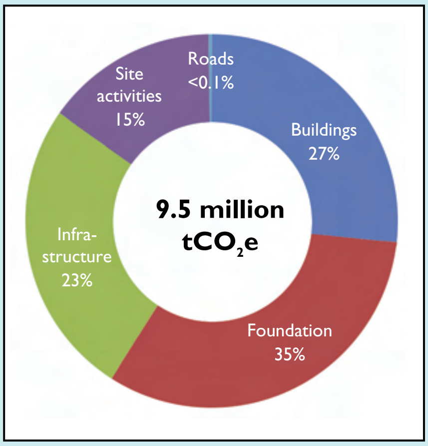


Figure 6: Carbon emissions by source.



The total carbon footprint of the city was measured to be 9·5 million tonnes CO_2e (or 3·4 tCO_2e per square metre of city space). The reductions already specified equated to a 27 per cent improvement on Business as Usual, or 3·6 million tCO_2e (the equivalent of over 650 000 average houses' annual emissions). Numerous more opportunities for carbon reductions were identified by dcarbon8 as part of the project, such as the replacement of Ordinary Portland Cement (OPC) with alternatives such as Ground Granulated Blast Furnace Slag (GGBS), Pulverised Fuel Ash (PFA), and effective on site fuel management. These measures had the potential to reduce the carbon footprint by up to 32 per cent if implemented in full across the city, potentially saving a further 3·1 million tCO_2e.

Outcome:

The Bill of Quantities toolkit has been successfully used on several projects for Masdar, including the Masdar Headquarters and Masdar Institute of Science and Technology (MIST), enabling Masdar sustainability teams to assess and reduce the carbon impacts of their new buildings from cradle to grave. dcarbon8 have continued development of the tool, using Bath ICE emissions factors as its basis, and have used it on numerous projects since then for well known clients including Lend Lease, Land Securities, Skanska, ProLogis, Haworth Inc, M&S and Sainsbury's.

CASE STUDY 4

OFFICE BUILDINGS

Consultant	**Davis Langdon, an AECOM Company**
Authors	**David Weight, Ed Brown**
Company information	Davis Langdon is a multi-disciplinary consultant with a focus on the built environment. With origins in cost management we have a deep understanding of materials use in construction. This, combined with our commitment to sustainable development, led us to develop our award winning embodied carbon calculator.

Project background

Our objective was to create an assessment tool which quickly, yet robustly, calculated the level of embodied carbon in a given design. We recognised the difficulty in linking cost plan information (which groups multiple materials together into components) with material based embodied carbon data. To close this gap we created an extensive schedule of 'recipes' that combine materials together such that we understand the embodied carbon of composite specifications in a way that reflects the structure of cost plans.

Each recipe is based on a mix of materials with an associated mass and CO_2e rate/kg. For the last, we drew from a number of sources but focused on the University of Bath's ICE database.

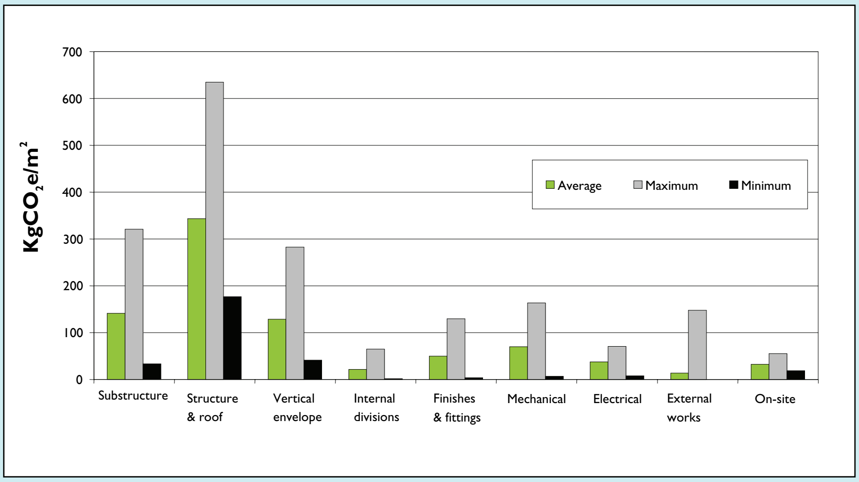
Our approach has increased the accuracy of the output by including all component parts of each composite; made the assessment process quicker and less expensive; and created an environment in which designers can test alternative design options quickly.

Methods and results

We have now run over 50 assessments through the tool – mainly offices. The original sample of buildings included both fit-outs and refurbishments, so 29 were selected as being typical new build schemes.

Before starting this work our expectation was that there would be a direct relationship between storey height and embodied carbon – driven by the increased structure/m^2 (thicker columns, increased wind bracing etc.). However, these effects don't show (Figure 7) through in the way expected, partly because many of these buildings were in London, and included a number of abnormal features (e.g. spanning above overground or underground railways, or deep basements.)

Figure 7: Embodied carbon of commercial offices.



Outcome	Our work on these buildings and others has led us to a number of CO_2e mitigation measures which we believe should be explored on all projects (where applicable). 1 – Cement Substitute Concrete and the use of cement substitutes is usually the first place to look for savings. The most popular is ground granulated blastfurnace slag (GGBS), which is often used to replace up to 40 per cent of the normal (OPC or similar) cement (but can be used at up to 80% replacement values). However, being a by-product of steel manufacture, supplies can be limited. The other alternative is Pulverised Fuel Ash (PFA) which is a waste/by-product of coal power stations and is often disposed of. The take-up of these substitutes is constrained more by time than money, as the setting times are typically longer. 2 – Achieving the same for less – dematerialisation Structural engineering is not a science of absolutes, but of judgements. Similar levels of performance can be achieved by different structural solutions – some resulting in lower levels of embodied carbon. For example: 2a – Structural efficiency Make sure that structural elements are operating to at least 90 per cent of their capacity (Reference: Chris Wise of Expedition Engineering "What if everything we did was wrong?", Building, 4th June 2010). Many structural elements use materials that are not, in fact, performing a structural role (the article referenced a concrete frame in which only 40 per cent of the concrete was working structurally). The aspiration should therefore be structural efficiency which both avoids the unnecessary use of high carbon elements such as concrete and steel, and reduces the need to support the superimposed load. 2b – Lightweight elements Voided slabs (such as Bubbledeck) or post-tensioned solutions use less material themselves, but also reduce the material required for frame and foundations. Note that there is potential for this improvement to be offset by an increase in processing energy during manufacture. 3a – Recycled and reused materials and recycled content Recycled or reused materials can save a lot of embodied energy, especially second-hand bricks, although for low-value materials like aggregates, one needs to be mindful of transport distances, which can wipe out savings (WRAP suggest a threshold of - 20 miles for transport of reprocessed aggregates). Using materials with higher levels of recycled content diverts waste away from landfill and avoids the need for primary extraction. WRAP's recommended approach is to select materials with higher levels of recycled content where all other attributes (including cost) are equal. Metals, for example, generally have high levels of recycled content because of the mature reprocessing market. See Section 7 in the document for further discussion on this. 4 – Organic materials Organic materials derive energy from the sun, soil and air, so largely avoid the need for subsequent energy in their manufacture. Further still, they actively draw down CO_2 from the atmosphere so that the growth stage at least, is a carbon negative process. However, this is subject to sustainable sourcing if a timber product is from deforestation, then its impact is completely different than if sourced from a sustainably managed forest (this relies on an equilibrium approach). Although much CO_2 will be released at end of life, it can be used as fuel, so displacing fossil fuels. 5 – Allowing time for option appraisal A bit more time during design could (for example) allow for the sourcing of recycled materials or testing the increased use of cement substitutes. Few designers have the luxury of spare time and budget to explore every issue, but a little extra space during early design to test the carbon issue might help unlock significant carbon reductions, and cost savings.
Recommendations	As with any mitigation strategy, step 1 is to understand the project baseline and find solutions that are targeted (rather than scatter-gun). Our advice to design teams is to assess the embodied carbon of a design at the start of RIBA Stage C, because at this stage there is still scope for options to be considered and evaluated. By doing so options can be considered for their level of embodied carbon, performance and cost. Beyond fundamental design choices (i.e. choice of framing material), many of the solutions centre on achieving a similar level of performance with less material – and in many cases for less cost. We would therefore encourage design teams to pursue low carbon solutions as part of good design, and not see them as imposing additional cost.

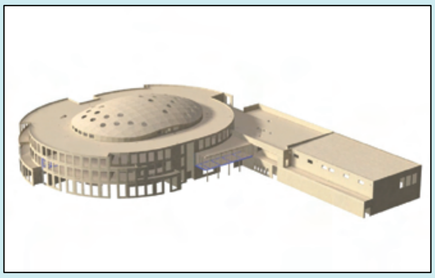
CASE STUDY 5

OPEN ACADEMY NORWICH

Consultant	Ramboll
Authors	**Oliver Neve, Gavin White**

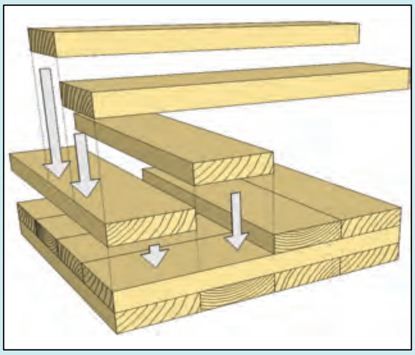
Company information

Ramboll have been looking into the field of embodied CO_2 and energy analysis of structures for some time. Through using the data available from the Inventory of Carbon and Energy and our engineering design expertise we are able to design more sustainable buildings that minimise impact on the environment.



Project background

Figure 8: Cross laminated timber construction.



The Open Academy Norwich is a new build cross laminated timber school located north-east of Norwich city centre. The three storey building has a total floor area of approximately 9500 m^2 and houses classrooms, a theatre and a sports hall. Ramboll performed the engineering design for the timber structure that is presently the largest timber building in the UK.

The project uses cross laminated timber in the form of solid timber panels ranging in thicknesses from approximately 50 mm to 300 mm and constructed from planks of softwood that are stacked and glued together under high pressure in perpendicular layers.

Methods and results

When referencing either embodied CO_2 or energy, we present figures in terms of embodied CO_2 as this can be considered to be the currency in which the construction industry trades in. Embodied CO_2 data has a huge opportunity to influence building design through estimating and comparing the embodied CO_2 of various building solutions. This is best done at an early scheme design stage before form and material choices are finalised to gain a high level understanding of the associated embodied CO_2 impacts of design.

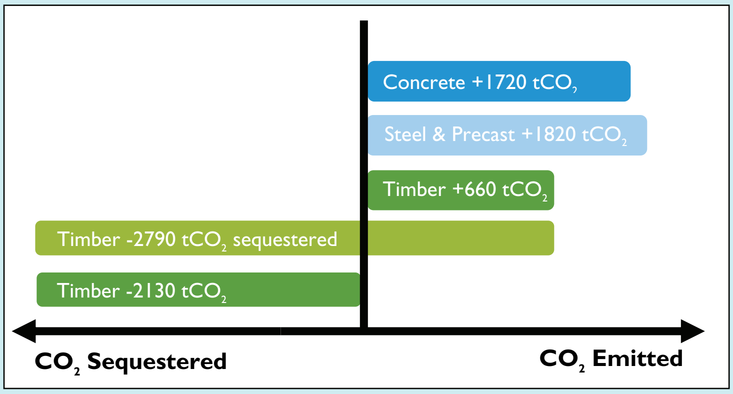
For Open Academy, a concrete frame, steel-precast plank and timber building were compared. High level analysis was conducted that estimated the typical structural arrangement for each of the solutions. From this process material quantities were gathered and converted into an equivalent embodied CO_2 value as described in the chart below.

Although cross laminated timber is currently not provided in the ICE database it can be considered appropriate to use glue laminated timber figures since parallels can be drawn between the sourcing of timber and production methods employed.

The ICE database does not include carbon sequestration though figures are presented in a manner that can allow sequestration to be calculated. As described in *PAS 2050* it can be argued that sequestration can be included so that as trees grow they extract CO_2 from the atmosphere and store it as carbon. Provided that the timber is sourced from a sustainable forest that re-plants trees at the same rate at which they are removed, and the timber which is then used in construction does not decompose or is burnt, then arguably carbon sequestration is taking place in a short term cycle and can be accounted for. Furthermore, if at the end of the timber's life as a construction product it is burnt in a biomass boiler, it can be argued that it is offsetting the consumption of fossil fuels and the corresponding CO_2 savings can be counted too. 0·8 tCO_2 is sequestered per m^3 of timber (*Wood for Good - The role of wood in reducing climate change*) enabling carbon sequestration calculations to be performed as illustrated in Figure 9.

Method and results (continued)

Figure 9: Summary of embodied CO_2 for different structural solutions.



Outcome

As described in the chart above, the concrete and steel-precast solutions are similar with an embodied carbon of approximately 1800 tCO_2 that is equivalent to approximately seven million miles in a modern family car. Conversely the timber solution has an embodied CO_2 value that is near to a third of these values at 660 tCO_2 when discounting sequestration. However if sequestration is accounted for then it can be argued that the structure is carbon negative with a value of approximately -2100 tCO_2. Therefore it can be contended that savings of approximately 1800 + 2100 = 3900 tCO_2 have been made compared to a concrete or steel-precast solution. These figures are always presented in an open transparent manner that allows the client and design team to evaluate the structural solution and make an informed decision for the final building form.

Although embodied CO_2 analysis plays an integral role to the sustainability of a building, the interface with other design elements needs to be carefully considered to ensure a holistic approach to design. For example some of the other benefits of cross laminated timber evaluated during the design process at Open Academy included cost, construction time, foundation design and air tightness amongst others. Issues that needed particular attention during design included reduced thermal mass, dependence on the Euro exchange rate and acoustics. However, in this case it was considered that cross laminated timber construction, compared to concrete and steel construction, offered an overall advantage. As with more conventional forms of construction, such as steel and concrete, the cross laminated timber solution also needs to comply with current regulations such as thermal and acoustic standards.

With this information the client and design team adopted a cross laminated timber structure that challenges ideas of conventional design allowing a creative and sustainable solution to be achieved. The Open Academy has been a successful project delivered on time and is approaching practical completion for September 2010.

As legislation and future decarbonisation of the grid reduces the operational CO_2 of buildings, the embodied CO_2 of the structure plays an ever increasing role in providing sustainable buildings, (*RICS Research Report – Redefining Zero*). Consequently there is significant merit to be offered through undertaking an embodied CO_2 assessment. Quantifying embodied CO_2 values is an extremely important part of good design and one that Ramboll sees as a significant area for future development.

Figure 10: Aerial view of the Open Academy during construction.

CASE STUDY 6

PROJECT REFORM

Consultant	**Buro Happold**
Authors	**Ed Sauven, Phil Hampshire**
Company information	Buro Happold work in all areas of the built environment including structural engineering, building services, master planning and a wide range of specialist disciplines. We have over 30 years of experience providing high quality, innovative solutions, which help to minimise the impact on the planet.
Project background	The Inventory of Carbon and Energy was utilised in two studies that were completed during the concept design of a large scale high spec office development within the City of London for one of the major financial Institutions. The requirement for open trading floors resulted in an architectural desire for very long span floor plates with minimal obstructing columns. The initial study evaluated the carbon impact of varying the structural grid size (distance between columns). The second study identified the carbon savings that could be achieved from reusing the existing basement and avoiding the need for its replacement with a new one of similar proportions. The project statistics were as follows: Number of storeys: 15 Levels of basement: 2 Gross area: 158 115 m^2 Net area: 96 000 m^2 Location: City of London
Constraints and opportunities	The Inventory of Carbon and Energy offered open source, reliable and referenced information to enable an estimate of the embodied carbon for the different building options to be estimated. Without this, expensive specialist software packages would have been required to undertake the work. This would have meant that the embodied carbon analysis would not have been able to be completed in the project timeline. The information from the Inventory of Carbon and Energy was integrated within the Buro Happold Structures Carbon Tool: a tool developed to support structural engineers in the pursuit of sustainable design during the selection of structural systems for multi storey frames. Using the tool and the information from the Inventory of Carbon and Energy the process was highly auditable, with the referenced data, calculations and assumptions clear for all parties to critique.
Method	The methodology used was a streamlined version of the approach described in *ISO14040* using the following steps: goal and scope definition, inventory analysis, and life cycle impact assessment. <u>Goal and scope definition</u> The purpose of the study was to assess the embodied carbon of four options which varied the size of the structural grid and the impact of reusing the existing basement or constructing a new one. The four options considered were as follows: Option 1: 18 x 9 trading floor grid with existing basement reused Option 2: 18 x 9 trading floor grid with new basement constructed Option 3: 18 x 18 trading floor grid with existing basement reused Option 4: 18 x 18 trading floor grid with new basement constructed The functional unit to compare across the options was defined as "sub and super structure of the building in isolation from any other aspects." The façade has been included in the analysis to enable the assessment of the different depth structural zones. The systems boundary for the project included: the energy required for construction, demolition and the embodied energy and carbon of the materials.

Method (continued)

Inventory analysis

The data used to analyse the embodied carbon of the materials was taken from the Inventory of Carbon and Energy. The construction impacts ('factory gate to commission') were assessed using data taken from other sources. The embodied energy and carbon was then calculated depending on the mass of different elements of the structure.

Life cycle impact assessment

The four solutions were compared to assess the best option. The results of the analysis are shown in Figure 11 which clearly identifies the best structural option in terms of embodied carbon to be the 18 x 9 structural grid and the reuse of the existing basement.

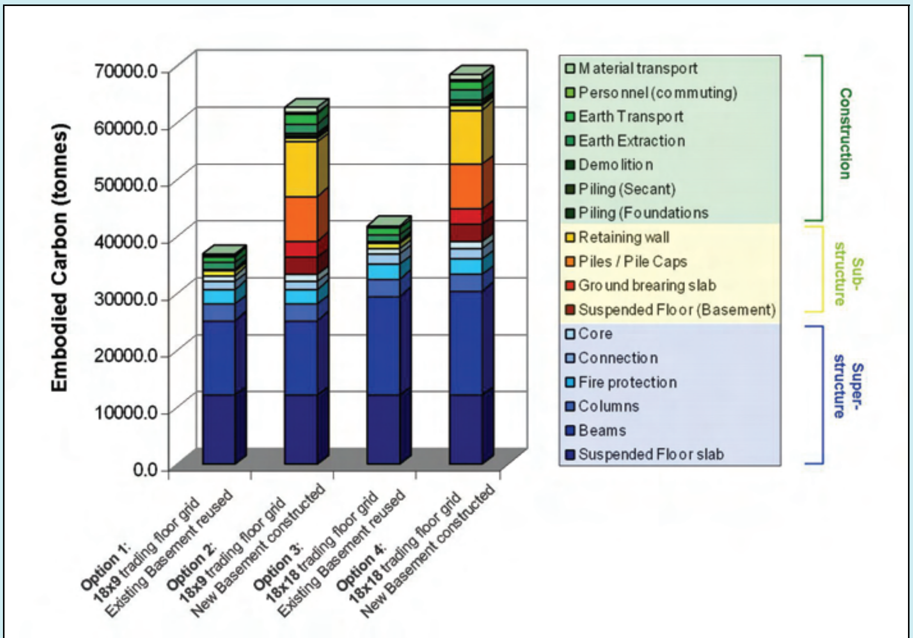
Results

The comparison across the structural grid arrangement showed that the 18 x 18 grid has 13 per cent more embodied carbon than 18 x 9 grid. The outcome being that the 18 x 9 grid saved 4900 tonnes of CO_2 . To put this in perspective for the client this was identified as the equivalent of 13 000 individual return flights from London to Berlin. This saving came from the reduced embodied CO_2 in the floor structure as a result of less steel and concrete being required to support the shorter spans.

Additionally, reusing the existing basement saves a significant 40 per cent carbon compared to new construction. This was calculated as equivalent to 26 000 tonnes CO_2 or 70 000 individual return flights from London to Berlin. The avoidance of new pile caps and retaining walls formed the majority of the savings.

The study showed that the basement is the substantial component in the scheme and the emissions associated with 'cradle to factory gate' were substantially more than from 'gate to commissioning'.

Figure 11: The embodied carbon from 'cradle-to-commission' for the four options.



Outcome

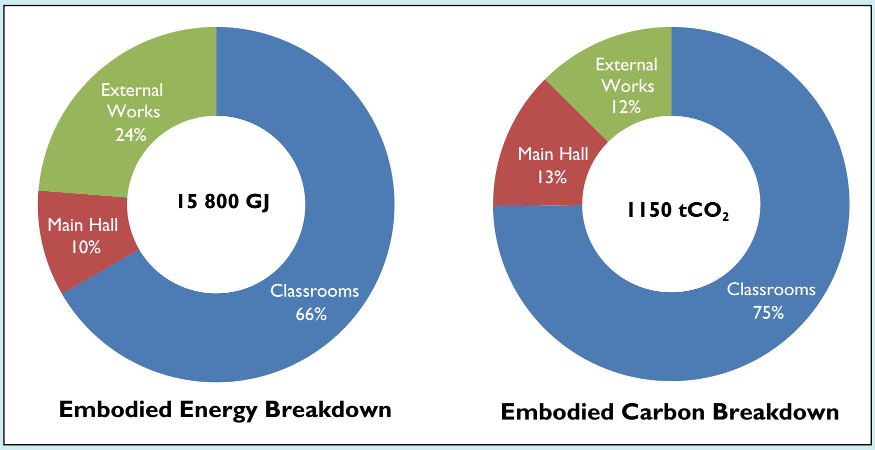
This study was completed by applying a bespoke tool that utilised the Inventory of Carbon and Energy data. It enabled the relative merits of different frame options to be assessed and highlighted the carbon hotspots within a building frame. This allowed the embodied carbon of the different options to be explicitly considered in the design process and resulting in significant carbon savings in construction.

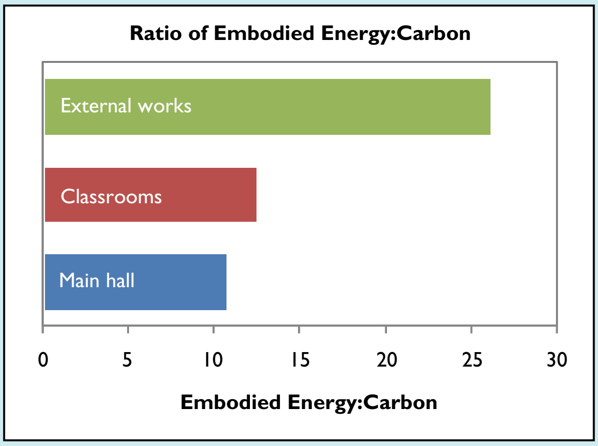
CASE STUDY 7

NEW BUILD PRIMARY SCHOOL

Consultant	**Sustain Ltd**
Authors	**Matthew Fishwick, Craig Jones**
Company information	Sustain is a leading carbon reduction company. By reducing carbon we build organisational resilience in our clients. The Environmental Accounting team specialises in the areas of embodied carbon, carbon footprinting and LCA. Sustain have been undertaking these assessments for over 11 years and have been working with a number of client groups including many in the construction, food, agricultural and retail sectors. In addition, Sustain were part of the pilot phase of the development of the *PAS 2050* and are also contributing to the development of the upcoming GHG Protocol – Product Carbon Footprints, which will be published by the WRI and WBCSD in 2011, and are a member of the technical committee for the development of the *ISO 14067* (Product Carbon Footprints), due in 2012.
Project background	The embodied energy and carbon of a new build primary school in England was assessed. The building had a classroom area of almost 1400 m^2, which included a small amount of space for administration, and a main hall with a further area of 200 m^2. In addition to the buildings the primary school had 770 m^2 of playground area, 680 m^2 of car parks, 1500 m^2 of sports courts and 450 m^2 of general paving. The baseline embodied energy and carbon was assessed as a benchmarking activity which can be used for improvement purposes. The fabric of the building included traditional brickwork, concrete roof tiles, timber doors and a mixture of timber and uPVC windows.
Method	The ICE database was used, along with our own in house database called Sustaindex which contains emissions factors for a broad range of product sectors (including energy factors, materials, consumer products, and food, amongst others). The cradle-to-site embodied energy and carbon was assessed. It was considered important to assess both the embodied energy and the embodied carbon. We've found that more recently the attention is switching towards carbon, i.e. product carbon footprinting. However, a lower embodied energy would be beneficial to reduce the strain on our limited fossil fuel resources. The method did not take into account carbon storage for timber products because the study was cradle-to-site, which excludes the important end of life stage of timber, and also because timber was not used in significant quantities for this construction.
Results	The embodied energy and carbon results are shown in Figure 11. The total embodied energy for the primary school was estimated to be 15 800 GJ in total and the embodied carbon 1150 tonnes CO_2. An estimate of waste was included in the calculations.

Figure 12: Embodied energy and carbon breakdown of a new build primary school.



Results (continued)	The project was split into an estimate for the classroom areas, the main hall and the external works. The external works included all other areas such as the playground, car parks, sports court and general paving areas. An interesting relationship was observed in the results for external works. This calculation provided 24 per cent towards the embodied energy but only 12 per cent to the embodied carbon. This is a large difference in contribution. This result was examined further and it was discovered that the embodied energy was high due to the use of asphalt surfaces. These surfaces contain bitumen, which is a by-product from oil manufacturing and with a high energy content itself. However, the energy to manufacture bitumen is much smaller, which gives it a very high embodied energy in comparison to its embodied carbon. The results in Figure 13 show the relationship between embodied carbon (kg CO_2) and embodied energy (MJ) for the main parts of the primary school. The results show a large difference in how many units of energy were consumed for each unit of carbon released into the atmosphere. **Figure 13:** The relationship between embodied energy and embodied carbon. 
Constraints and opportunities	An 80:20 rule had to be applied to an analysis of the elements and materials, which was significant in number. A building contains a large number of items but it would be unnecessarily time consuming to analyse all of these for energy and carbon. Therefore the analysis focused on the items that from experience were estimated to provide a notable contribution to the final result. Sustain are confident that we have captured the vast majority of energy and carbon in an ideal compromise between time and efficiency.
Outcome	The embodied energy and carbon of a new build primary school was calculated to offer a benchmark for future improvements. The building areas (classroom + main hall) themselves had an embodied energy per unit floor area of 7·6 GJ/m^2 and an embodied carbon of 640 kg CO_2/m^2. These were in line with the expected range from previous analysis of other buildings and studies. This case study shows the benefit of considering embodied energy alongside embodied carbon. It demonstrates that the external works had a comparatively low embodied carbon but a high embodied energy. This should be examined in the future to reduce the strain on valuable fossil fuel resources as well as managing the release of greenhouse gases.

5 USING THE ICE DATA

The methodology used to obtain and validate the data in the Inventory has been outlined in Section 2. In addition to the method of data compilation there are wider issues to consider when using the Inventory. Contextual knowledge of the building project is vital if the results obtained are to be of the highest quality. This is especially important for studies that consider the full lifecycle. This section provides guidance on common pitfalls in order to avoid misusing data from the Inventory. It also highlights some of the wider issues and gives suggestions as to how these issues can be accommodated in an embodied carbon study.

5.1 THE IMPORTANCE OF FUNCTIONAL UNITS

In a comparative assessment the functional unit is one of the most important parameters. It defines the system for comparison and provides a fair basis between results for products or systems. There is a considerable temptation for inexperienced users of the ICE database to examine the embodied energy and carbon values as printed in the summary tables to instantly 'determine' the 'best' materials. This type of analysis must not be completed. The data within the ICE database is typically in the units MJ or $kgCO_2$ per kilogram of material, which is not a fair functional unit for material comparisons.

Simply because a material has a lower embodied energy or carbon value per kg does not mean it will be the best choice for product performance. In addition, there are a whole range of other issues that must be considered, for example the lifetime, maintenance requirements, material density or durability. Once these have been considered, a fair unit for comparison should become more apparent and the mass of material required to provide a set function can be determined.

An example of a set function is the examination of wall cladding systems. There are competing cladding systems and materials and each set will have different material quantity requirements. For example, aluminium has a lower density than steel and so aluminium cladding would typically require a smaller mass of material than if the cladding were made from steel. A fair comparison would be the impact of 'a square metre of installed wall cladding over a building lifetime of 60 years'; this is in contrast to the comparison of 'a square metre of wall cladding' which would exclude the lifetime, maintenance, disposal, and does not specify if installation is considered in the assessment. Only once all these factors have been considered can the best option be determined.

5.2 CONTEXTUAL KNOWLEDGE

An example of how the wrong comparison can be made is the analysis of the embodied carbon and energy of different types of buildings in the UK. Table 15 shows the results of a study of typical buildings, ranked from best to worst embodied carbon burden for whole properties. From these results it would initially appear that apartments are the solution to minimising embodied carbon and detached houses should be avoided. However, when the results are normalised with respect to floor area, which might be more relevant in determining the embodied carbon per capita of resident, the ranking is changed (Table 15) now apartments appear profligate, whereas detached houses are ranked in position 2, second only to terraced houses. This does not suggest that detached houses are the way forward because clearly they are not. It highlights that there are economies of scale for larger properties (i.e. larger rooms). For example, if the specified detached house was terraced there would naturally be an even lower embodied carbon figure.

In reality, housing policy will also need to take many additional factors into account, such as occupancy and requirements of external works such as connecting roads and pathways (where apartments will benefit). This example illustrates the importance of selecting the functional unit and also the contextual knowledge of the study (see Hammond and Jones, 2009).

Table 15: The embodied energy and carbon of UK new build dwellings.

Building type	Percentage of new properties	Average floor area, m^2	Rank order (best to worst), embodied carbon per property	Rank order (best to worst), embodied carbon per unit floor area
Apartment (4 storey building)	24	50	1	4
Apartment (3 storey building)	24	50	2	5
Terraced	20	68	3	1
Semi-detached	15	73	4	3
Bungalow (detached)	11	76	5	6
Detached	31	125	6	2

All buildings in this example are assumed to meet 2006 UK *Building Regulations*.

5.3 PARETO PRINCIPLE – THE 80:20 RULE

Completing a full embodied energy and carbon assessment of a building can be time-consuming. Often a compromise must be reached between the required accuracy of the result and available resources. The first step is to obtain an inventory of items, including approximate quantities of each type of material. This is likely to cover a large number of items and it is unlikely that data for all the items will be readily available. However, applying the Pareto Principle suggests that roughly 80 per cent of the embodied energy and carbon will come from roughly 20 per cent of the products. Therefore the processes and products that will be most significant should be identified and focused on first. Many of the remaining items may have a negligible impact. They could possibly be omitted from the assessment, especially if past experience justifies their omission. Examples would be the wall ties in worked Example 1 (Section 4.1), door handles, hinges and other small items. This works well when assessing a whole building. However it should be noted that when completing an assessment to a defined standard, such as the *PAS 2050* or any of the new upcoming international standards, there will be cut-off rules for an acceptable level of omission.

5.4 TRANSPORT

The ideal boundaries of the ICE database are cradle-to-gate. This encourages case specific data on transport to be included in individual studies. It also provides an extra check to determine whether long range transport does not use more energy and release more carbon than a local alternative. However, despite receiving much attention transport is often a relatively minor contributor to embodied carbon, often less than 7 per cent or so of the total cradle-to-site embodied carbon. Notable exceptions to this (crude) rule of thumb include aggregates and sand. These materials have a relatively high contribution from transport because they require a low amount of processing energy. However, they are typically locally sourced. The Mineral Products Association (MPA) give an average transport distance for an aggregate of 38 km.

It is not difficult to include transport in an assessment. Resources such as online route planners are useful to estimate the distance travelled by road. For road transport it is important to consider if the vehicle will have an empty return trip. For shipping routes, websites such as Port World (www.portworld.com) are a valuable resource.

The impacts of transport are typically represented by the units of tonne kilometres (tkm). The impact of 1 tkm is defined as being that which is derived by transporting a tonne of the product over one kilometre. Consequently to include transport impact in the calculation the total mass of material transported (data must be included in tonnes – not kilograms) is multiplied by the transport distance in kilometres and further multiplied by the impact per tkm. The total gives the impact of transport. As a general rule the impact of road transport is much greater than sea or rail. Consequently, a product could travel a large distance by sea but only a short further distance by road and have a lower transport impact than a product transported a much shorter total journey distance only by road.

To estimate the embodied energy and carbon impact of transport it is recommended that users start with the following resources (in no particular order):

- Department for Environment Food and Rural Affairs (DEFRA). "Guidelines to DEFRA's/DECC's GHG conversion factors for company reporting". www.defra.gov.uk/environment/business/reporting/conversion-factors.htm
- European Commission's information hub on life cycle data, tools and services http://lca.jrc.ec.europa.eu/lcainfohub/index.vm
- U.S. Life Cycle Inventory Database, National Renewable Energy Laboratory (NREL). www.nrel.gov/lci/database/
- Data in LCA software and databases such as SimaPro, ecoinvent or GaBi.

Each of these data sources should be examined for the basic assumptions. For example, some of the data will be calculated with default assumptions about return trips while other sources will leave this to the users.

5.5 WASTE

Waste is generated at many stages in the life cycle of a product. The manufacture of a product weighing 1 kg at the point of sale requires more than 1 kg of initial feedstock material. Examples of where the additional material is consumed include manufacturing, fabrication and assembly. This must not be neglected from the embodied energy and carbon study. Further waste materials are generated when a building is constructed, for example, due to over-ordering of materials or products or as a result of breakages or off-cuts.

The waste resulting from the construction process can be significant but relevant data is available for UK buildings. The BRE Smart Waste programme (http://www.smartwaste.co.uk/) has some good 'benchmarking data' that is freely available on request (at the time of publication enquirers can email the Smart Waste team for the most detailed and up to date information). The data includes a material breakdown of the quantity of waste created for each square metre of constructed floor area. It is also separated by construction type (residential, industrial, offices, etc). By mid-2010 Smart Waste data had been created from a total of 569 real projects. These included 260 residential, 116 education, 47 commercial retail, 46 commercial offices, 41 healthcare, 22 leisure, 15 public buildings, 13 industrial buildings, and 9 other commercial buildings. A detailed assessment would also consider the end point for these materials, such as landfill, incineration, or recycling.

The Smart Waste data suggests that large volumes of waste are created during the construction process (up to 22 m^3 of waste per 100 m^2 of constructed floor area). Thus it is vital that an estimate of waste is included in the calculation of embodied energy and carbon for construction projects.

5.6 COMPLETING THE LIFECYCLE

As stated in Section 1, the total carbon and energy cost of a building must include both embodied and operational burdens. This will ensure that every aspect, including refurbishment, maintenance and replacement of products is accounted for. Ideally a study would be performed across the full life cycle of the building. Assumptions will need to be made and they should be clearly stated and sensitivity analysis should be completed to determine their influence. Some of the factors that need to be considered are:

Additional processing energy
Highly fabricated and intricate items require manufacturing operations that are beyond the boundaries of the ICE database. In the analysis of an individual product this energy may need to be investigated.

Maintenance schedule
All buildings require regular maintenance. Naturally there is a financial cost to this, but there is also an embodied carbon requirement. Questions should be asked regarding the maintenance requirements of the selected material and how these impact on the lifetime (including operational) energy and material consumption. Furthermore, issues including whether or not the product requires periodic attention, such as repainting, should be considered. Paint is a high embodied carbon material and a regular recoating schedule will have a high embodied carbon requirement.

Operation
Certain products may have an effect on operational energy requirements, for example in the case of a building the U-Value of insulation, or the thermal mass of the building fabric will have an effect on the operational energy and carbon. How these products are incorporated into the design of a building and how the building is operated will determine the extent of this positive or negative impact.

End of life
The recycling of metals offers significant recovery benefits but who takes these benefits (recycled material user, or scrap material producer) is debatable. See Annex B for detailed guidance on the end of life benefits of recovery for recycling, as applicable for metals.

The end of life of timber products is also important and must be included if carbon storage benefits have been included in the assessment.

Re-carbonation of cement, concrete and lime
During the life cycle (including demolition) of concrete, cement and lime based products a process of re-carbonation takes place. Cement and lime release significant quantities of carbon dioxide into the atmosphere during production which is released through de-carbonation in the kiln. The main ingredient in cement is typically clinker, which releases 0·52 $kgCO_2$ per kilogram of clinker. This is a significant fraction of the embodied carbon of cement. Likewise the production of lime, such as quick lime or hydrated lime, releases 0·48 $kgCO_2$ per kilogram.

The re-carbonation of CO_2 from the atmosphere depends upon a number of factors. For cement based concrete this includes the amount of cement in the concrete, the amount of GGBS or fly ash, which is considered to increase the rate of carbonation (see Pade and Guimaraes, 2007), and especially the amount of concrete exposed to air. For concrete masonry the value is higher but for structural concrete, not exposed to air, it is zero. The crushing of concrete at end of life (for use as aggregate) increases the lifecycle carbonation. The UK Concrete Centre suggests that 15-20 per cent of embodied carbon will be re-absorbed over its service life. However, it is difficult to use such values in a generic fashion due to the wide range of factors affecting re-carbonation. BRE (2007) and Pade and Guimaraes (2007) provide more detailed guidance.

ICE database users should consider re-carbonation of cement and lime based products when extending the boundary conditions of their study.

6 STANDARDS AND METHODS

The highest quality data has normally been obtained by following a process that conforms to approved standards and methods. Those of greatest influence are the international standards on environmental lifecycle assessment (LCA), in particular *ISO 14040:2006* (ISO 2006a) and *ISO 14044:2006* (ISO 2006b). These standards also have an accompanying technical report *ISO/TR 14049:2000* (ISO 2000). It is important to bear in mind that the standards are not tightly prescriptive in their criteria for compliance. They govern what is considered acceptable methodological practice rather than defining the actual single method that should be applied. Instead they define the appropriate options. These options often come with a recommended ranking order of selection. For example, the methodology for recycling (which is called allocation in the ISO standards) has preferential ranking options. This gives rise to a great deal of variability between studies and can make it difficult to compare studies. For this reason more defined methods have been developed.

One such method is the Carbon Trust carbon label methodology, known as *PAS 2050* (BSI, 2008). This standard is more defined, and aspires to conform to the ISO standards on LCA. This takes the credibility of accepted methods but uses a more prescriptive approach which enables direct product comparisons to be made. Another example of a defined method is the BRE methodology for environmental profiles, available from the BRE website. This is the method that the BRE use in their calculations of the environmental impacts of products.

The reader is advised to keep track of upcoming international standards. Standards under development which at the time of writing include:

- The *CEN TC 350* series of standards (intended to be released from spring-2011 onwards) on the "sustainability of construction works"
- The World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) joint developed product and supply chain standards. This includes two standards, a *Product Accounting and Reporting Standard* and the *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*. Expected in spring 2011
- A new French environmental labelling scheme which will be a national initiative (mid 2011) to inform consumers of the environmental impacts of mass products through environmental labelling
- *PAS 2050*, on product carbon footprinting, is due to be revised for a second release in 2011
- The *ISO/CD 14067* on the "carbon footprint of products", which is currently under development. Expected 2012.

7 RECYCLING OF METALS

Embodied energy, embodied carbon and LCA studies consider many factors. One of the more influential factors is recycling, particularly for products that have a large quantity of metallic components. Primary metals (also known as virgin metals) are first extracted from the ground in the form of an ore. The ore then undergoes several processing operations until it becomes a usable metal product. The product is then used until it reaches the end of its life, where it's likely to be recovered for recycling.

Recycling is beneficial for several reasons. For example, metal recycling operations require far less energy (and carbon) than primary (virgin) production processes. For example, when a metal is extracted for the first time it is taken from the ore, which has a low metallic concentration. Energy needs to be invested to refine this ore into a purer, more useful, form. This is an energy intensive process. But at the same time when scrap metal is recovered and used for recycling the ore processing operations are not necessary. This is one of the main reasons that recycled metals have a lower embodied energy and carbon than primary metals.

There is clearly a benefit from recycling. It is also clear that primary metals have a larger embodied carbon than recycled metals. But when analysing a product there are a range of options to account for the benefit of recycling in the numbers. At first, the logical method would seem to be allowing for the benefits of recycling by looking at how much recycled material has been used in the product. This is often used and is known as the recycled content approach. But this type of assessment fails to consider the end of life benefits from recovering scrap metals.

When a building reaches the end of its life the metals are typically recovered and sent for recycling, which will generate an environmental saving. But now we have two environmental benefits to consider for our building. We have used recycled material to produce the building (recycled content) and we have created an environmental benefit at the end of life of a building (recyclability). However, in the study of a single building we cannot take both of these benefits at once and in full. This would be known as double counting the benefits. Double counting occurs because we have claimed environmental savings from using recycled material and also creating recycled material. But in reality these two benefits are firmly linked. For example, a (hypothetical) building saves 1 tonne of CO_2 at the end of life by the recovery of metals for recycling. If we reduce the embodied carbon of our building by this amount it leaves no benefit for the actual user of this recycled metal in their assessment. This also implies that we could no longer also take the benefit from using recycled material in our building, because that would cause double counting. Such double counting must be avoided.

There are several different methods to account for recycling in an assessment. Three important methods are:

- **Recycled Content Approach**: This method considers the benefit from using recycled material in full. This leaves no room in the analysis for recyclability benefits
- **Substitution Method**: This method is the complete opposite to the recycled content approach. The method gives a full benefit to benefits of recyclability which leaves no room for consideration of the benefit of using recycled material
- **50:50 Method**: This methods falls in between method 1 and 2. It gives half of the benefit of using recycled material and half to recyclability. The consideration of both of these factors, which method 1 and 2 cannot satisfy, is most practical for assessment of a whole building.

Further discussion of these methods is found in Annex B. It is important to remember that each of the above methods has different strengths and weaknesses. There is no universally acceptable method. The method for recycling should be selected based on the goal and scope of study and the results must be reported in a transparent way. If the goal and scope of study is to complete an assessment to a fixed method (such as *PAS 2050*, the *CEN TC 350* series of standards, or any of the other future upcoming international standards) then they will define the acceptable method for recycling.

However, regardless of the method chosen, the most important recommendations in regards to recycling are:

a) The chosen method must be in line with the goal and scope of study

b) The reporting must include a transparent display of assumptions and results. The results for the cradle-to-gate, operation and end-of-life stages should each be reported separately.

Finally, it's sometimes important to consider the bigger picture. For several metal applications, specifying 100 per cent recycled content should be discouraged. When a metal has a high recovery rate with little to no room for improvement, i.e. construction steel, the scrap resource cannot be increased anymore. This implies that ordering 100 per cent recycled steel simply takes away the option from other purchasers on the market place, who are then forced to purchase virgin steel. In this case there is no net, global benefit. This only applies when the recycling rate cannot be increased, (for further analysis see Annex B).

8 CARBON STORAGE IN TIMBER PRODUCTS

There has been much debate surrounding the carbon storage benefits of timber products. The science of carbon pools, the carbon cycle and carbon storage are still developing and there are many scientific uncertainties. The issues are complex and leading studies offer contrasting results. In addition, the arguments are different for sustainably sourced timber and non-sustainably sourced timber. Because of the high level of overall uncertainty and because the ICE database is a cradle-to-gate study, estimates of carbon storage benefits have not been included in the Inventory. Specific reasons for this decision are given below.

Firstly, the ICE database is a cradle-to-gate study. These boundaries do not consider the product lifecycle beyond the factory gate. The inclusion of carbon storage benefits within these boundaries would likely result in negative embodied carbon factors. This was considered a problem for two reasons. Firstly, the cradle-to-gate data is incomplete, so what happens during operation and eventual end of life treatment could push the embodied carbon back into positive values. This is very much dependent upon the end of life scenario and there are many options for timber, e.g. incineration, landfill with and without landfill gas capture, and reuse. The actual end of life scenario cannot be known for sure, but the probability of each option will be influenced by actual use of the timber product. For example, certain timber coatings may remove the option of normal incineration but if incineration is still an option they may require specialist incineration plants. However, when carbon storage benefits are included in an assessment, the end of life scenario must also be included. Due to the influence of the timber application on end of life options the responsibility must fall on the users to modify the data in an appropriate manner.

Secondly, there is a real risk of the negative embodied carbon coefficients being applied inappropriately. A superficial, and inaccurate, understanding would suggest that increasing the amount of timber will give a lower (more negative) carbon footprint of the product. This could lead to inappropriate overuse of the material and goes against general sustainability concepts. Clearly the ICE authors cannot guarantee that such data would be used appropriately.

Generally the absence of carbon storage in the data doesn't penalise timber products. The low density of timber means that timber can still compare well to other materials if compared with a fair functional unit. Although naturally this should not be taken as a rule of thumb, an options appraisal should be completed for any specific application.

Readers wishing to modify the base ICE data to include carbon storage effects and end of life scenarios may wish to start with the following resources:

- *PAS 2050* (from the BSI), specification of the greenhouse gas emissions of goods and services

  This methodology, from the Carbon Trust, contains a relatively simple method for including the carbon storage benefit of timber products. This method includes a time weighted carbon storage benefit for sustainably sourced timber products
- European Commission's information hub on life cycle thinking based data, tools and services
- U.S. Life Cycle Inventory Database, National Renewable Energy Laboratory (NREL)
- Data in LCA software and databases such as SimaPro, ecoinvent or GaBi
- Intergovernmental Panel on Climate Change (IPCC) assessment reports.

For statistics on UK waste wood end of life recovery rates see:

- Wood waste market in the UK, Summary report, Waste & Resources Action Programme (WRAP), project code MKN022, August 2009
- Reference document on the status of wood waste arisings and management in the UK, Waste & Resources Action Programme (WRAP), ISBN: 1-84405-200-1, June 2005.

9 SUMMARY

The ICE database contains embodied energy and embodied carbon values for many different building materials calculated between the boundaries of cradle-to-gate.

The data has been structured in a way that can be quickly used for calculations, perhaps to determine the best material option of a simple product. However, to get the best out of the data there are several topics that must be understood. These include the handling of recycled materials, especially when the end of life stage is included, and carbon storage of timber products. Both of these have great influence on the results.

Detailed guidance on the former is provided here (Annex B). In summary recycled metals are used as an input to a building, which is beneficial. But at the end of life of a building a high fraction of the metal is typically recovered and sent for recycling, which also saves energy. This means that metals are offering benefits at the start of a building's life (recycled content) and also at the end of a building's lifetime (recyclability). It is important not to double count the benefit of metals, therefore recognised methods exist to determine the impact of the building being studied on a whole life cycle basis (cradle-to-grave).

The topic of carbon storage for timber products is equally important. The science is less certain and it would be difficult for the ICE database to assume the usage scenario for the ICE database users. Such data would also need to be used with genuine care. For example the publication of negative embodied carbon factors for timber could lead to misuse of the data and over ordering of timber products. This would increase environmental burdens and place a greater strain on natural timber resources. It must also be considered that the ICE data for timber is only within the boundaries of cradle-to-gate, which does not cover the important end of life stage. The only way to ensure that the inclusion of carbon storage benefits of timber has been completed with a robust method the user must modify the data accordingly.

Timber and recycling may be difficult but overall the ICE database can be used with relative ease, (there are thousands of users from around the world). The ICE database authors invited companies to provide case studies, as presented in Section 4. The lessons to be learnt include how carbon savings can still be made late in the design process through appropriate material selection (Case Study 1). Case Study 2 demonstrated the benefit of using cement substitutes in concrete, which is a particularly powerful way of reducing the embodied carbon in construction, in the context of the London 2012 Olympics. Case Study 3 shows the carbon footprint of Masdar City and how the potential to reduce the carbon footprint was significant. Case Study 4 provides a useful breakdown of the embodied carbon of office buildings and some outline measures to save carbon. Case Study 5 provided an example of how the effect of carbon storage in timber products can be included in the assessment. The ICE database authors encourage users to separate out the data as was done in this case study, i.e. the embodied carbon to produce the building was separated from the estimate of carbon storage benefit. Even without the benefit of carbon storage, the timber frame building was estimated to be an attractive option in this case. Case Study 6 demonstrates that structural engineers can make large carbon savings. The study demonstrates a significant benefit from retaining some of the existing structure (basement) and selecting the optimum structural grid size. Finally, Case Study 7 shows the merit of examining both embodied energy and embodied carbon side by side. All the studies offer data that may be used for comparison with future studies and offer some useful insights.

The ICE database is well applied in industry and offers an assessable tool for embodied carbon and carbon footprint assessment. This field of work comes with a degree of uncertainty that will always remain. But the readers should not let this distract them from the real benefits of completing an embodied carbon assessment. Large carbon savings can be made, which will help mitigate greenhouse gas emissions and meet international emission targets.

10 FREQUENTLY ASKED QUESTIONS

Q – Is the ICE database applicable to countries other than the UK?
A – The ICE database can be used as 'proxy data' in the absence of country specific data. This is also a common approach in life cycle assessment (LCA) where the driver is as much to make a comparison as to arrive at an absolute number. The ICE database has drawn on data from around the globe. For many materials there is a strong influence from international data, for example steel, plastics, and aluminium. This data has been tailored as much as possible for a UK perspective, for example by including the specific material type consumption mixture (sheets, extrusions, etc) within the UK. This is used to estimate the values for the 'General' category (see the FAQ on 'General'). Additionally, for many materials, the ICE database has used a UK perspective to convert from embodied energy to embodied carbon.

Embodied energy normally relates to an international context better than embodied carbon. Two products may have a similar embodied energy but a different national fuel preference and electricity mixture can result in an entirely different embodied carbon. It is standard practice in this research field to use the best available information as proxy data for other countries. It is not perfect but it can still provide useful analysis and conclusions.

Q – Why would building services engineers worry about embodied carbon and not just operational carbon?
A - Building services engineers have always understood the trade off between operational and embodied carbon, though they have not necessarily expressed it in these terms. They know that the options for services depend on the fabric solution, and vice versa. Embodied carbon brings this into sharper focus. Complex items of building services equipment generally have more influence on operational carbon than embodied carbon, but it is the balance between embodied and operational in the whole life assessment that makes this important to the services engineer.

Within services alone there are some more minor decisions to make but this may change. In the future it is possible that all products covered by European Directives, such as *Energy Related Products* or *Waste Electrical and Electronic Equipment*, will have embodied carbon (or similar environmental) labels. Currently we do not see such labels on these products, although consumer labelling in the food sector is increasing. Relatively large material consumption goes into pipework, radiators and ducting and cable. But rather like whole life costing, where the exercises may be undertaken as a two way choice, the carbon could be calculated for the differing radiator materials, and the resulting answer fed into the overall whole life carbon calculation, to aid the decision making process.

Q - Can I use the ICE database to sectors outside of construction?
A – Yes. The range of materials consumed within a building is vast. Hence many of the materials in the ICE database are relevant to a diverse range of sectors. An exception would be for electrical items. These specialist items are likely to have a large number of intricate components that are not covered by the ICE database. Electronic goods also tend to have high additional manufacturing energy (a brief analysis suggests that the embodied energy and carbon of electrical items is wide ranging and comparatively high). If electrical items are of interest, Environmental Product Declarations (EPDs) are becoming a valuable resource. EPDs are often available for download on manufacturers' websites. See Section 11.3 on EPDs.

Q - Why does timber have two embodied carbon coefficients?
A – The newest ICE data separates the embodied carbon emissions into those derived from burning of fossil fuels and those from burning of biomass. Thus the user can choose to make biomass combustion CO_2 neutral if required, e.g. this could be done in specific conditions under Intergovernmental Panel on Climate Change (IPCC) methods. The two numbers summed together give the total carbon released cradle-to-gate. The total would be used in the case where the biomass combustion cannot be considered as carbon neutral (i.e. if the timber is not from a sustainably managed forest). However, under sustainable forestry conditions the embodied carbon may be taken as simply the carbon released from fossil fuels (i.e. the first carbon number). For further discussion please see Section 8.

Q - Can I use the ICE data in a carbon (footprint) calculator?
A – Yes, so long as you clearly reference the ICE database for providing some of the background data for the tool. The ICE database is widely used in calculators, some of which are freely available, and its format is ideal for integration into such tools.

This publication has been produced by the developers of one such project Interoperable Carbon Assessment Toolkit (iCAT), to encourage the understanding of the ICE data. The project iCAT will produce a fully interoperable tool to enable early inclusion of embodied carbon in design decisions. It can take added degrees of detail as the project develops and eventually be used by facilities managers in maintenance and refurbishment decisions.

Q – What was the effect of the conversion of the embodied carbon data from CO_2 only to CO_2e?
A – The CO_2e values are higher than the CO_2 only values. The main reason for this increase is typically methane emissions, but for some materials other greenhouse gases are significant. For example, PFCs for Aluminuim and dinotrogen monoxide for nylon. When looking at the difference please bear in mind that the data has been traced back to the cradle. For the greenhouse gas protocol (scopes 1, 2 and 3) the data considers all three scopes. For example methane emissions from coal mining and gas leakages from natural gas pipelines are considered. These are only captured when the data is traced back to the cradle.

Q – I tried to replicate the ICE values of embodied carbon using the embodied energy fuel breakdown. I cannot achieve similar values. Why?

A – Embodied energy is a measure of primary energy (see Glossary). Primary energy is taken here as energy that is traced back to the cradle (earth). It includes the energy required to extract, refine and transport fuels and not just the energy directly contained in, for example, a barrel of oil. The main error in your calculation is likely to be from the embodied energy and carbon associated with electricity. The breakdown in the ICE database (see material profiles) includes the fraction of energy from electricity. This fraction is measured in primary energy. This means that the standard carbon emission factors for each unit of electricity do not apply. Electricity in the UK comes from a centralised network, which undergoes large losses in generation. As a general rule of thumb three units of primary energy are required to provide a single unit of electrical energy to UK consumers, i.e. 3 units of fossil fuel in the ground are required for 1 unit of electricity out of a plug socket. This ratio varies widely for each country. If you do not consider the relationship in the ICE embodied energy breakdown you will get a factor three error to the electricity contribution of embodied carbon.

A final point to make for this question is that several key building materials have a non-fuel related release of carbon emissions in manufacturing processes. These materials include, for example, cement and concrete, clay, bricks, ceramics, glass and a small quantity from steel. The most notable example is certainly cement. This non-fuel related release is in the embodied carbon figure but naturally it is not included in the embodied energy calculation.

Q – What do the sub categories mean in the 'Embodied Energy Database Statistics' of the material profiles?

A – As discussed in the material profile guide, these statistics have come from all the data that was collected to create the publically available ICE database. The sub categories come from how the data was stored. The unspecified category is for data that did not specify a recycled content. It is not recommended to use the average embodied energy from any of these statistics; they are presented here as supplementary information. The full data range and standard deviation may be useful to see how difficult it was for us to select the best values. Not all of the data that was collected is appropriate to use. The recommended data is the main values that have been selected.

Q – What is the difference between embodied carbon and a carbon footprint?

A – They are very similar. In fact the main difference between the two is that the term carbon footprint can also be used to discuss operational carbon requirements, for example heating and lighting of a building, or operation of a power tool. Embodied carbon can only be used in the context of materials, for example all activities related to the construction of a building or production of a power tool, including the production of materials.

Q - Do the values for embodied carbon measure carbon dioxide (CO_2) only, or a broader range of greenhouse gasses (GHG), i.e. in carbon dioxide equivalents (CO_2e)?
A – The previous versions of the ICE database captured carbon dioxide only. This is the first version of the ICE database that has also estimated the full greenhouse gas emissions associated with materials. Version 2.0 contains both the CO_2 and GHG emissions measured in CO_2e. If you are not sure which values are presented take a look at the units. GHG emissions are measured in kg CO_2e.

Q - What does the category 'General' include, for example 'General Aluminium'?
A – 'General' serves as a typical category and a 'fall back' option. For example, the values in this category have been calculated to represent the average material purchased in this market. Considering the case of aluminium, the data was calculated with a world average recycled content (see Annex B), but also with the UK consumption mixture, i.e. per cent of extrusion, rolled and cast. This category may be selected if further details of the specific material type are unknown.

Q – How significant is embodied carbon versus operational carbon?
A – The relationship between operational carbon and embodied carbon varies widely. This is mainly as a result in large differences in the operational performance of buildings. However, the thermal standards of new buildings are increasing and the UK Government is still aspiring to bring 2016 zero carbon homes and 2019 zero carbon buildings (non-domestic) into legislation. 'Zero carbon' has not yet been defined but it is almost certainly not going to include the embodied carbon of construction. This implies that when zero carbon homes and buildings are introduced the embodied carbon will be the only carbon burden remaining.

The embodied carbon was estimated to be equivalent to 12-19 years of operational carbon for an average UK domestic new build dwelling (see Hammond and Jones, 2009). This was estimated to the 2006 UK *Building Regulations*. However, non-domestic buildings have a greater diversity of types, sizes, applications and lifetimes. The embodied carbon versus operational carbon results are therefore usually expressed as a percentage of the whole life carbon emissions. A new report from the South West Regional Development Agency (SWRDA) on sustainable offices (SWRDA, 2010) summarised that the embodied carbon impacts (construction, plus demolition) accounted for approximately one third of the whole life carbon. Likewise the RICS redefining zero report (Sturgis and Roberts, 2010) estimated the contribution of embodied carbon to be 20 per cent for supermarkets, 30 per cent for houses, 45 per cent for offices and an incredible 60 per cent for warehouses. These are significant proportion and ones that are not currently given the deserved attention for reduction. As thermal standards reduce, embodied carbon is becoming an ever important fraction of the whole life carbon burden. However, these figures clearly show that embodied carbon from construction is already a significant burden and one that needs attention.

11 FURTHER RESOURCES AND REFERENCES

11.1 GENERAL RESOURCES

From the University of Bath

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Embodied Impact Assessment: The Methodological Challenge of Recycling at the End of Building Lifetime, Jones, C.I, Construction Information Quarterly, The Chartered Institute of Building, 11 (3), 2009.

Wider Resources

Athena Institute: The Athena Institute undertakes research on the LCA of North American buildings, offering tools and databases that may be of use.

BES 6001: Responsibility for Construction Products.

Best Available Techniques Reference Documents (BREFs): Large documents are available about the best performance currently achievable in key industrial sectors. Some data may be useful. For further details see http://eippcb.jrc.es/reference/.

BRE Environmental Profiles Database: The BRE carry out environmental product declarations for many manufacturers. Some of the final results may be downloaded from their web site. The accompanying methodology report is recommended reading.

BRE Environmental Profiles of Construction Materials, Components and Buildings, Report BR370, Howard, N. S. Edwards and J. Anderson, 1999, CRC, London.
Note: The BRE have a new revised methodology (below reference), but the above report is still a good read from an educational point of view and the newest method report has been labelled a 'draft' report.

BRE Methodology for Environmental Profiles of Construction Products, Product Category Rules for Type III environmental product declaration of construction products, Draft, August 2007.

Economic Input-Output Life Cycle Assessment (EIO-LCA): You can use this tool to perform Input-Output based analysis (of the US), available from www.eiolca.net/.

European Reference Life Cycle Database (ELCD): The European Commission's information hub on life cycle thinking based data, tools and services. http://lca.jrc.ec.europa.eu/lcainfohub/index.vm

GaBi: Another one of the most respected LCA software tools and databases. It's the main competitor to SimaPro (see www.gabi-software.com/). It's generally agreed that both GaBi and SimaPro are equally good tools, only in different ways.

Guidelines to DEFRA's/DECC's GHG Conversion Factors for Company Reporting, available from www.defra.gov.uk/environment/business/reporting/conversion-factors.htm.

The LCA Forum: Post your LCA questions, methodological discussions and requests for help here (http://lists.lyris.net/cgi-bin/lyris.pl?enter=lca). This forum is regularly used by some of the well respected LCA experts.

The LCA Search Tool: Search for LCA reports with this website www.pre.nl/LCAsearch/default.htm.

Product Ecology Consultants (PRé): PRé have several useful resources, including free and subscription based resources.

SimaPro: One of the most respected LCA software packages (normally comes with ecoinvent, which is a well used LCA database). Read more at www.pre.nl/simapro/default.htm.

U.S. Environmental Protection Agency (EPA): The EPA have a fairly extensive list of key LCA resources, which is well worth a visit (www.epa.gov/ORD/NRMRL/lcaccess/resources.html).

11.2 TOOLS

This list is by no means exhaustive and no claims are made about the accuracy of the listed tools.

AggRegain: A WRAP tool for aggregates (www.aggregain.org.uk/about_aggregain.html).

Asphalt Pavement Embodied Carbon Tool (ASPECT): A UK based asphalt embodied carbon tool. (www.sustainabilityofhighways.org.uk/).

Athena - Impact Estimator for Buildings North American building LCA tool (www.athenasmi.org/tools/impactEstimator/index.html).

Carbon Calculated Construction Calculator, an online tool that uses the ICE data and DEFRA data to calculate the embodied emissions of construction builds, re-fits and refurbishments (www.carboncalculated.com).

Economic Input-Output Life Cycle Assessment (EIO-LCA), a tool that estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the US economy (www.eiolca.net/).

Environment Agency Carbon Calculator for Construction**,** an excel tool that utilises the ICE V1.5 data, available from the Environment Agency (www.environment-agency.gov.uk/).

Footprinter, currently 3 versions which estimate the ecological and carbon footprints; construction, furniture and office. Created by Best Foot Forward (www.footprinter.com/).

GaBi, another powerful environmental LCA tool (www.gabi-software.com/)

LCA in Sustainable Architecture (LISA) Free streamlined LCA decision support tool for construction, case studies available (www.lisa.au.com/index.html)

Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PALATE), an Excel-based tool for life-cycle assessment (LCA) of environmental and economic effects of pavements and roads. (www.ce.berkeley.edu/~horvath/palate.html)

SimaPro, Powerful environmental LCA software (www.pre.nl/simapro/)

11.3 ENVIRONMENTAL PRODUCT DECLARATIONS

Environmental product declarations (EPDs) are becoming a valuable source of information. However, with so many different products it is not possible to integrate them into the ICE database. It is also important to try and understand the methodology behind an EPD. The direct comparison of two EPDs may not be possible without first understanding the method.

Questions that should be asked before using EPDs within a study include:

Is there a standardised (and open) method?

- **Yes** – Make sure you understand the method and how it differs from your study.
- **No –** If it doesn't conform to an accepted method (for example PAS 2050, BRE, CEN TC350) is there a clear and well defined method? If there is no clear method it may be difficult to use the EPD in a study.

What materials database has been used to assemble the data?
EPD's are often created for products made from several materials, i.e. x per cent steel, y per cent plastic. To calculate the results the study will use a materials impact database (such as the ICE database, ecoinvent, GaBi, ELCD). Each database will contain differences in its base data.

Can I use an EPD for a similar product?
There is a wide variation in product designs, especially electronics. However if the only EPD available is not from the same manufacturer it is common to use the best available data as a proxy.

11.4 GENERAL EPD RESOURCES AND DATABASES

The International EPD system: www.environdec.com. This website contains an EPD database, which may be viewed for free. In addition manufacturers can register their EPD's and there is a verification system in place.

BRE Environmental Profiles: www.greenbooklive.com. The BRE complete environmental product declarations for manufacturers and many of these are contained in the online database. The results cover a lifespan of 60 years. This makes the data easy to use for studies of whole buildings with a lifetime of 60 years but it also makes it difficult to compare with other non-BRE data, or to dissect the data. There is a well documented BRE method for constructing environmental profiles. www.greenbooklive.com/

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Climate Change Act 2008, Office of Public Sector Information (OPSI): www.opsi.gov.uk/acts/acts2008/pdf/ukpga_20080027_en.pdf

European Commission's information hub on life cycle thinking based data, tools and services: http://lca.jrc.ec.europa.eu/lcainfohub/index.vm

The International EPD system: www.environdec.com

University of Bath, Sustainable Energy Research Team, Inventory of Carbon and Energy: www.bath.ac.uk/mech-eng/sert/embodied/

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U.S. Life Cycle Inventory Database, National Renewable Energy Laboratory (NREL): www.nrel.gov/lci/database/

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World Steel Association: www.worldsteel.org

Standards

BSI, 2008 Specification of the Greenhouse Gas Emissions of Goods and Services.

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ANNEX A – ICE BOUNDARY CONDITIONS

The boundaries within the ICE database are cradle-to-gate. However even within these boundaries there are many possible variations that affect the absolute boundaries of study. One of the main problems of utilising secondary data resources is variable boundaries since this issue can be responsible for large differences in results. The ICE database has its ideal boundaries, which it aspires to conform to in a consistent manner. However, with the problems of secondary data resources there may be some instances where modification to these boundaries was not possible. The ideal boundaries are listed in Table 16 below.

Table 16: The ideal boundaries used in ICE.

Item	Boundaries treatment
Delivered energy	All delivered energy is converted into primary energy equivalent, see below.
Primary energy	Default method, traced back to the 'cradle'.
Primary electricity	Included, counted as energy content of the electricity (rather than the opportunity cost of energy).
Renewable energy (inc. electricity)	Included.
Calorific value (CV)/Heating value of fossil fuel energy	Default values are higher heating values (HHV) or gross calorific values (GCV), both are equivalent metrics.
Calorific value of organic fuels	Included when used as a fuel, excluded when used as a feedstock, e.g. timber offcuts burnt as a fuel include the calorific value of the wood, but timber used in a table excludes the calorific value of the wooden product.
Feedstock energy	Fossil fuel derived feedstocks are included in the assessment, but identified separately. For example, petrochemicals used as feedstocks in the manufacture of plastics are included. See above category for organic feedstock treatment.
Carbon sequestration and biogenic carbon storage	Excluded, but ICE users may wish to modify the data themselves to include these effects.
Fuel related carbon dioxide emissions	All fuel related carbon dioxide emissions which are attributable to the product are included.
Process carbon dioxide emissions	Included; for example CO_2 emissions from the calcination of limestone in cement clinker manufacture are counted.
Other greenhouse gas emissions	The newest version of the ICE database (2.0) has been expanded to include data for GHGs. The main summary table shows the data in CO_2 only and for the GHGs in CO_2e.
Transport	Included within specified boundaries, i.e. typically cradle-to-gate.

In the creation and maintenance of the ICE database the authors have tried to avoid using data that has been estimated with avoided burdens. From an LCA perspective the database is considered attributional in nature rather than consequential.

ANNEX B – HOW TO ACCOUNT FOR METAL RECYCLING

This is a technical annex to the ICE database. The method selected for recycling is an influential factor in embodied energy and carbon assessments. A detailed assessment should consider the content of this annex.

The ICE database is a cradle-to-gate database. However, it is likely that when picking up the data and applying it to real products, such as a building, the boundaries (scope) of study will be extended. A well rounded study would consider extending the boundaries to consider the full lifecycle of the product (production, operation, and end of life). The inclusion of end of life stages, which may include the burdens of disposal and benefits of recycling or reuse, requires important methodological choices. When considering the benefits for recycling a method must be chosen and this may differ from the default method within the ICE database. It is therefore vital that the pros and cons of each method for recycling are well understood so that an informed choice can be made. This will ensure that the method is consistent with the specific goals and scope of study. The aim of this annex is to discuss suitable methods for including end of life recycling benefits.

However, if the goal and scope of study is to comply with international standards, such as the *PAS 2050*, the upcoming *CEN TC 350* series of standards, or any other upcoming international standard, then the acceptable method for recycling will be defined by the standard. It is still encouraged to document the results in a transparent manner for these studies (as discussed in this annex).

B.1 - METHODOLOGIES FOR (METAL) RECYCLING

Introduction

The method for recycling is an important component of an embodied impact assessment and the related subject of environmental lifecycle assessment (LCA). There is no single universally acceptable method which is, in part, why the subject is so widely debated and methods regularly contested.

This part of the annex offers a basic guide to the selection of an appropriate and robust methodology for recycling in embodied impact and LCA studies. Some of the simpler methodologies are discussed in the context of embodied impact assessment, the ICE database and with particular focus on highly recyclable materials, such as metals, in buildings and construction. Interested readers may also wish to read the paper "*Embodied Impact Assessment: The Methodological Challenge of Recycling at the End of Building Lifetime*" (Jones, 2009). Three relatively simple methods are discussed here:

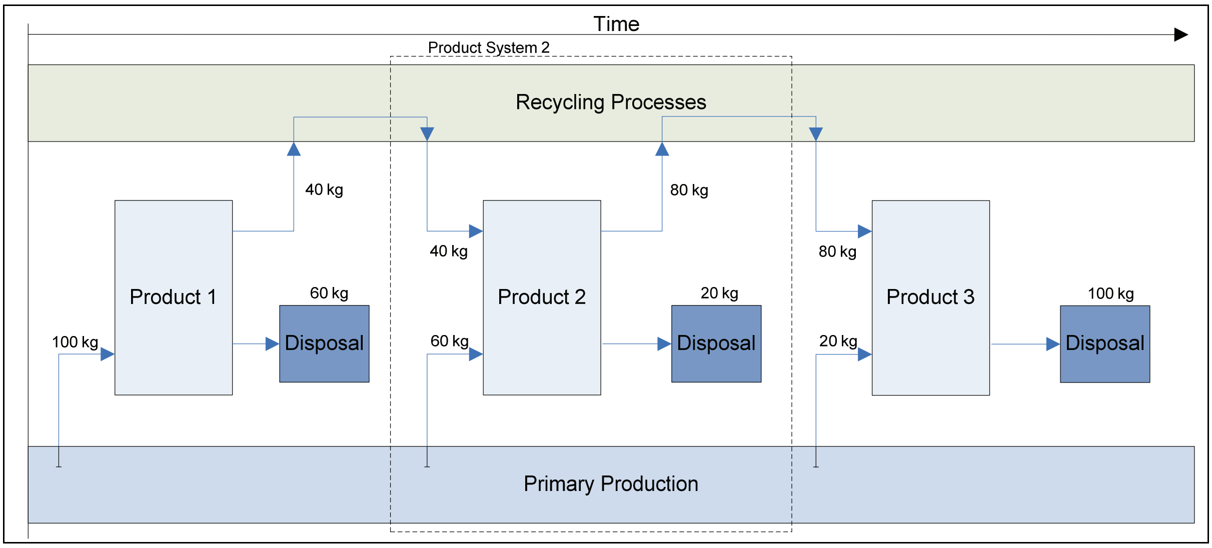
1. Recycled content approach (100:0 method)
2. Substitution method (also known as closed loop system expansion, or 0:100 method)
3. 50:50 method (50:50)

These three choices each offer unique advantages and disadvantages. It must be appreciated that boundaries of study (e.g. cradle-to-gate, cradle-to-grave) are important to the selection of an appropriate method. This annex is therefore split into two different sections. This is justified because alternative boundaries have different methodological needs. The document is split into appropriate methodologies for cradle-to-gate and appropriate methodologies that include the end of life stage (i.e. cradle-to-grave). Before separating into these divisions the methods are briefly described.

THE METHODS EXPLAINED

To aid the explanation of each method a base case scenario has been created. The base case assumes that a highly recyclable material, e.g. a metal, undergoes several different lifetimes. The first lifetime of a material must naturally be obtained from primary feedstock (i.e. virgin ore in the ground). At the end of this life a fraction of the material is recovered and recycled into a new product with no loss in material quality. This material feeds into the second lifetime, which requires further primary material to make up the mass of the product. The material undergoes 3 different lifecycles before all of the material is finally lost to waste (in the last lifecycle). This scenario is represented by Figure 14.

Figure 14: Base case scenario.



Product 1 requires 100 kg of primary material in its production. At the end of life it creates 40 kg of new recyclable material, which is fed into Product System 2 at the start of its lifetime. At the end of its lifetime Product System 2 creates 80 kg of recyclable material, which feeds into Product System 3. This whole scenario assumes that material losses from the recycling processes are negligible. This is a simplifying assumption that does not change the meaning of the analysis. Product System 2 is the base case scenario for analysis and is reliant on both Product System 1 (upstream) and Product System 3 (downstream).

The creation and use of recycled material represents a net benefit to the environment. This arises from the avoided burdens of primary material production (i.e. a reduced requirement for virgin material in the future) and the lower environmental impact of recycling processes. The benefit lies across any two adjoining product systems, for example system 1, which creates the recyclable material, and system 2, which consumes the material. The benefit would not exist without both systems. This raises a fundamental question – which system should claim the benefit of recycling? This is a methodological difficulty and the benefit must be allocated (divided) between the adjoining systems.

Product System 2 (the base case system) is an interesting situation. It receives incoming recycled materials but it also creates recyclable materials at the end of its lifetime. There are environmental benefits at the start of life and end of life of Product System 2. Consequently this system must consider the shared benefit with Product System 1 (for the incoming materials) and the shared benefit with Product System 3 (of the outgoing recyclable materials from Product System 2). Methodology for recycling is a way of allocating these benefits between one or more product systems whilst maintaining consistency. The three methods are described below.

The equations within this section are slightly simplified representations of the full situation. The equations allow the concepts to be illustrated to aid comprehension. A full detailed model of metal recycling would consider the points at which scrap outputs leave the system (i.e. early metal production stages versus later conversion, for example of slab or billet into sheets or sections, and fabrication stages) and their final destination. Furthermore, the metal conversion energy, such as rolling or extrusions (for which the impacts are uncoupled from the primary and recycled routes), should (if possible) be removed from the calculations of benefits of recycled content and recyclability and added back into the assessment at a later stage.

All of the methods described maintain accountability of environmental impacts and benefits, and environmental credits (benefits) to system 1 become burdens to downstream systems (i.e. Product System 2).

Recycled content approach (100:0 method)

The recycled content approach allocates the full benefits of material recycling to the input side of a product system. This leaves no benefit for end of life recyclability, which is effectively neglected in this method. Under this method the lower environmental impact of recycled material production may be considered as a naturally occurring environmental benefit, i.e. the use of recycled materials in a product naturally lowers the environmental burden of material production due to the recycled content.

This method requires knowledge of the fraction of primary and recycled materials entering the product system. Such inputs to Product System 2 are also outputs from Product System 1. Likewise, these outputs from Product System 2 are also inputs to Product System 3. The recycled content approach gives the full benefit of recycling to incoming materials. Consequently (end of life) recycling benefits from Product System 2 are allocated (given) to Product System 3 (which is the system that receives the recycled materials as an input). Including a further benefit to Product System 2 of the outgoing materials would double count the environmental benefit.

The recycled content approach is the methodology that was adopted in the Carbon Trust's carbon labelling methodology, which is known as PAS *2050*. The method may be represented by Equation 1 (adapted from *PAS 2005*):

$$E = (1-R)E_V + (R * E_R) + (1-r)E_d \quad \text{– Equation 1}$$

Where:
R = Recycled content
r = Recyclability (combined recovery and recycling rate and recycling material yield)
E = embodied impacts, per unit of material
E_R = embodied impacts arising from recycled material input, per unit of material
E_V = embodied impacts arising from virgin material input, per unit of material
E_d = embodied impacts arising from disposal of waste material, per unit of material

This equation (slightly amended from the *PAS 2050*) includes the end of life disposal. In this method there is a small benefit at end of lifetime from recycling. This occurs as a result of the avoided need for disposal. Recovered material avoids the burden of disposal activities and a benefit can be expected (often small for metals).

Substitution method (closed loop system expansion, or 0:100 method)
The substitution method is an opposite to the recycled content method. In the substitution method the creation of recyclable material is allocated the full benefit of recycling at end of life (called recyclability). This leaves no benefit for incoming recycled materials, which are effectively neglected. The substitution method may be represented by Equation 2 for materials such as metals that have no loss in inherent properties, (also see Eurofer, 2007).

$$E = rE_R + (1-r)(E_V + E_d) \quad \text{– Equation 2}$$

In its simplest form the substitution method may be modelled as an effective recycled content, with the "effective recycled content" defined by the fraction of new recycled material that arises from the end of life recovery processes (i.e. a measure of its recyclability). This should not be confused with a real recycled content and recycling material yield should be considered in this definition. For example in a system that creates 100 kg of recovered aluminium scrap it could be assumed that the material loss from recycling processes is 5 per cent. This results in 95 kg of new recycled material for use in the next lifecycle(s).

With this method Product System 2 (base case example) may be modelled with an "effective recycled content" of 80 per cent (i.e. a measure of its recyclability). This is in contrast to its real recycled content of 40 per cent.

50:50 method
The present authors have chosen an implementation of the 50:50 method that is more practical in its implementation than its traditional definition. For materials with a comparatively small disposal impact, such as metals, the traditional approach was unnecessarily confusing is its implementation. This approach allocates the impacts of disposal in full to the quantity of material lost to waste, as in the equation below.

This version of the 50:50 method falls exactly half way in between the recycled content approach and the substitution method. The 50:50 method allocates half of the benefits of using recycled materials (start of life) and half of the benefits of creating recycled materials (end of life recyclability). The impacts of disposal are allocated in full to the loss of material to waste streams. It may be modelled with Equation 3.

$$E = \tfrac{1}{2}(1-R)E_V + \tfrac{1}{2}R * E_R + \tfrac{1}{2}r * E_R + \tfrac{1}{2}(1-r)E_V + (1-r)E_d \quad \text{– Equation 3}$$

The first two clusters of terms are taken from the recycled content approach (Equation 1), the third and fourth clusters of terms are taken from the substitution method (Equation 2), and the last cluster represents the handling of disposal.

METHODOLOGY FOR CRADLE-TO-GATE

The ICE database falls in the category of having boundaries of cradle-to-gate. By definition the boundaries of cradle-to-gate exclude all activities beyond the factory gate. End of life disposal and reuse scenarios are beyond the scope of such studies. Of the three considered methodologies only a recycled content approach can operate effectively within these boundaries.

The remaining two methods allocate end of life credits for the creation of recyclable materials, which happens beyond the factory gate. Consequently they are (by definition) incompatible with the boundaries cradle-to-gate. The minimum boundaries that the remaining two methods can satisfy are 'cradle-to-gate + end of life' (see 'Appropriate methodology for studies that include the end of life').

What should cradle-to-gate data represent?

The boundaries of cradle-to-gate should reflect the impacts of producing and supplying a product (i.e. material extraction, processing, transport, and fabrication). Consequently these studies are particularly useful for the impacts of materials (such as those found in the ICE database). Material production is an activity that occurs very much in the present (in contrast to end of life recycling benefits that occur in the future) and the methodology must reflect this. The recycled content approach is ideal because the parameters in the equation are firmly attached to the present circumstances (i.e. the actual recycled content). This is in contrast to the other two methods, which allocate some or all of the benefits of recycling to the creation of recyclable materials (in the future). In construction this may be in the order of 60-100 years and assumptions must be made.

A single material has the potential for different applications and each alternative application will affect the lifetime, maintenance requirements and potential recovery rates at end of life. These factors can have profound implications on the lifecycle impact of the product. It is the responsibility of the ICE database user to determine these factors for the specific application of the material. In doing so the ICE user may wish to take and modify the boundaries for studies that include end of life, as covered by the content below.

APPROPRIATE METHODOLOGY FOR STUDIES THAT INCLUDE THE END OF LIFE

The end of life is an important lifecycle stage. All three methods are suitable for studies that include the end of life (e.g. cradle-to-grave, cradle-to-gate + end of life).

The boundaries of cradle-to-grave consider the impacts of producing, supplying, using and disposing of the material. The first two methods are traditionally popular choices and will be analysed and discussed below.

Recycled content approach and substitution method

The two methods will be compared with the use of a basic example. The following assumes Product System 2 (from the base case scenario) with the use of steel. Energy has been used for the case studies, rather than carbon. However, embodied carbon coefficients may be substituted for the energy data in these examples.

Example 1

All values are embodied energy per kg material

Primary Steel = 30 MJ
Secondary Steel = 10 MJ

Recycled content = 40%
Resulting new recycled material = 80%

Recycled content method
Embodied Energy = 30 * 60 + 10 * 40 = *22 MJ*

Substitution method
Embodied Energy = 30 * 20 + 10 * 80 = *14 MJ*

The energy required to produce primary steel is somewhat arbitrarily assumed to be 30 MJ/kg and that for recycled steel 10 MJ/kg. The recycled content of incoming materials is 40 per cent and there is a recycling and recovery rate of 80 per cent (that is 80 per cent of new recycled material will be created for future lifecycles). The energy required to produce the steel comes from the cradle-to-gate recycled content method, which is calculated to be 22 MJ. However at the end of the product lifetime scrap materials are recovered and recycled into new products. It was therefore estimated that 8 MJ of energy is avoided because of the end of life recyclability (from the avoided future impacts of primary material production, i.e. 22 MJ – 14 MJ). Under a recycled content method this energy saving is not considered because it is passed on to the next user of steel. Therefore the lifecycle energy remains at 22 MJ (neglecting impacts of operation and disposal for simplicity - this has no effect on the results but simplifies the analysis).

A substitution method gives the energy saving (8 MJ) in full to this product (system). A lifecycle energy requirement of 14 MJ (22-8) is assigned to Product System 2. The difference of 8 MJ represents a real energy consumption that was required to produce the steel, but where does this energy go? The energy doesn't physically move anywhere, it was consumed. However, under this method it is assumed to be given to (allocated to) the future use of steel, i.e. the next product (product 3) takes it in its equations.

Present versus future

The substitution method represents the sum of the impacts to produce and supply the material (cradle-to-gate) plus the benefit of recyclability (end-of-life). The former occurs in the present whereas the latter occurs in the future. However under this method, which presents a single number result, it is not possible to determine the impact on the present climate alone (cradle-to-gate). For example under a substitution method the results are typically much lower than the cradle-to-gate burden. This is because the product system is given a recycling credit for future recyclability. It is perfectly fair to estimate the future benefit of recycling but the results should also make clear the cradle-to-gate burdens somewhere in the reporting. This is necessary so that the impacts on our present climate can be considered as well as the scale and timescale of future benefits. For products with a short lifetime this is less of a problem; the future benefit is reclaimed within a short lifetime, such as a metal food can. However, a building is a large and complex product and its lifetime is often long (circa 60 years).

On the other hand the recycled content approach has its disadvantages. With a recycled content method, future benefits are always passed on to the next user and are not considered within the studied lifecycle. These differences must be considered when selecting the most appropriate method. The selection must always be in line with the goal and scope of study. The ICE database has a primary focus on construction, where product lifetimes are large (albeit there are a wide range of other applications for ICE). The current authors believe that the present impacts and future benefits are important and that neither can be ignored in an assessment. However, it is important to take early action on climate change and sustainable development. There is a balance between present impacts and future benefits. The current authors believe that the future benefits and present impacts should both be considered in an assessment – this is something that neither the recycled content approach nor the substitution method can accommodate in isolation. It is possible to resolve these shortcomings without seeking alternative methods, but this requires additional quality based or numerical based assessments.

If the goals and scope of a study justify the selection of a recycled content approach then the shortcomings of this method must be overcome with qualitative assessments. The main disadvantage of this method is that at the end of product lifetime there is no consideration of the benefits of recyclability and recovery potential of materials. The numerical assessment of a recycled content approach will only help to minimise the environmental impacts of material production (cradle-to-gate). This must be complemented with 'design for recovery and reuse' and a conscious selection of materials with a strong end of life benefit and potential for recovery.

On the other hand if the goals and scope of study justify the selection of a substitution method then the shortcomings must be overcome with a further numerical assessment to make clear the cradle-to-gate burden. This is because a substitution method can only help to maximise the end of life benefit. Therefore, to ensure that the impacts in the present are minimised, this requires the use of a recycled content method in parallel. This can be done with a transparent display of assumptions and results where the cradle-to-gate and end of life stages are clearly identified separately in the reporting. The advantage of such transparency is that regardless of the method chosen for recycling the situation is clearly open for all to see. The stage of cradle-to-site (or cradle-to-gate) should be clearly separated from the operational stage and both separated from the end of life stage. The results should be split into:

1. **Cradle-to-site (or gate):** The first transparent result should be the cradle-to-site (or cradle-to-gate) burden. This gives a better indicator for the energy and carbon burden on the present climate
2. **Operation:** The energy/carbon to operate the product system should be clearly reported
3. **End of life:** The last transparent result should estimate the end of life benefit - i.e. the substitution method can be applied to estimate the future benefits of recyclability (taking care not to double count recycling benefits). This should also include an estimate of when the benefit would be expected (in how many years time).

The transparent reporting of results will give a greater insight into the environmental burdens and issues than either single method presented alone as a single number. It will open up the data to reveal the impacts on the present and the potential benefits to the future. Both of which are important parameters.

Example

The application of this approach to Example 1 (above) would provide the following results to report.

1. **Cradle-to-gate:** Impact on the present climate: 22 MJ (recycled content approach)
2. **Operation:** Zero operational requirements in this case (material, assumed no maintenance requirement). In the case of a building this stage will naturally be significant
3. **End of life:** Potential benefit in the future: estimated to be 8 MJ, approximately 60 years in the future (i.e. substitution method – [minus] recycled content approach, i.e. 22 – 14 = 8 MJ).

These stages should be clearly reported regardless of the cradle-to-grave method for recycling (which would integrate them into a single number). For example this transparent display of results offers far more insight than the recycled content alone, which would yield 22 MJ but completely neglect the potential for this product to create 8 MJ of future benefit. It also offers far more insight than the substitution method alone, which would yield 14 MJ, but doesn't represent the full burden of energy consumption in the present.

Nevertheless, it is appreciated that in many cases a single number result will be required. For a complex product such as a building a 50:50 method is recommended as a starting point.

50:50 Method

In an attempt to resolve the differences of the two methods there was an immediately obvious candidate, the 50:50 method. Example 1 was extended to include the 50:50 method.

Example 1.1

All values are Embodied Energy per kg material

50:50 Method
Embodied Energy =
(30*60*½) + (10*40*½) + (30*20*½) + (10*80*½) = *18 MJ*

In this example the results of the 50:50 method fall exactly halfway in between the recycled content (22 MJ) and the substitution method (14 MJ) at 18 MJ. This is because the method has given half of the benefit for recycled content (input side) and half of the benefit for recyclability (output side). This has a practical advantage. When the option is between either the recycled content or the substitution method then either recyclability or recycled content will be neglected at the expense of the other. But the 50:50 method may consider both (in fact half of the benefits of both). The implications of this go beyond purely methodological ideals and have practical advantages. The needs of the ICE database users must be considered. A manufacturer, designer or purchaser of highly recycled products will always be drawn to the recycled content method. For example, if an architect has gone to great length to design a house with large quantities of recycled and reused materials they will wish the environmental assessment to reflect this with an advantage. These efforts would not be appreciated in a substitution method but they would be reflected in a recycled content approach.

Conversely, if the designer has gone to great lengths to improve the recovery rate and design for reuse then they would also want the data to reflect this. For example, if lime mortar was used construct a brick wall. At the end of life it will be easier to deconstruct (rather than demolish) than if a cement based mortar was used. There is no guarantee that the wall will be deconstructed rather than demolished but the potential recovery rate would be higher and the bricks could be reused in a second lifetime. These efforts from the designer would go unnoticed in a recycled content method but they would be considered in a substitution method.

The most interesting case is the situation where a designer has gone to great efforts to accommodate reused and recycled materials in the design and gone to great length to design for reuse and recovery. A truly sustainable building would aspire to both of these goals and this situation should not be considered uncommon, especially if we hope for real sustainable development. Neither the recycled content method nor the substitution method can accommodate this situation. Regardless of the method chosen to present a single number result there should be a transparent display of reporting, as previously outlined. For a single number result the 50:50 method is a robust choice, it can accommodate complex needs of this situation which includes both recycled content and recyclability.

Discussion – Why 50 per cent?

A 50:50 method is at times viewed as a 'compromise' method. This is particularly unfair to the strengths of the method, especially in the context of a building. In the first instance the 'arbitrary' selection of a 50 per cent allocation factor is often questioned. Whilst it is true that a 50 per cent allocation is arbitrary, it must be appreciated that a recycled content approach and a substitution method are also founded on equally arbitrary assumptions. For example, if we consider there to be two allocation factors, the first is the percentage allocation to the start of life benefit of recycling, i.e. incoming materials. The second is the percentage allocation to end of life benefits, i.e. outgoing materials (see Jones 2009). Note that the total of these two allocation factors must equal 100 per cent for the same product system. A 50:50 method sets 50 per cent and 50 per cent as its two allocation factors, hence the 50:50 method. A recycled content approach sets 100 per cent and 0 per cent, which may be considered a 100:0 (see C Jones, 2009) method. A substitution method (without value correction) selects 0 per cent and 100 per cent, which may be considered 0:100. From this perspective the recycled content approach and the substitution method should also be questioned for the arbitrary choice of a 0 per cent allocation factor, which effectively neglects one side of the system. 100 per cent and 0 per cent are also arbitrary selections which have no scientific justification. 100:0 and 0:100 methods neglect one proportion of the life cycle, however a 50:50 method does not. In an ideal world there would be a scientific time value weighting by which the future (benefits and burdens) can be valued against the present. However, this does not yet exist and the current University of Bath authors believe that the 50:50 method is a sensible starting point.

Naturally there are disadvantages to the 50:50 method (there are in all methods). Similar to the substitution method, the benefit to the future is estimated with present technology. On the 60 year (or so) time scale of a building this is likely to overestimate the future benefit due to technological improvement over time. This gives a level of uncertainty to the data and a level of risk that environmental impacts will be under accounted for. Despite this disadvantage the 50:50 method only credits the system for half of the future benefit. This reduces the level of risk and uncertainty associated with the method. A detailed estimate of energy and carbon requirements for future technologies would be desirable, but the long timescale (circa 60 years) presents real and practical problems. Finally, it must be remembered that the future cannot be estimated with any level of certainty. Any method that attempts to estimate future benefits naturally carries a level of uncertainty, but this is not justification enough to neglect the impacts on the future.

To summarise the most important recommendations that can be made in regards to a method for recycling are:

a) The chosen method must be in line with the goal and scope of study
b) The reporting must include a transparent display of results. This includes a transparent display of assumptions and results. The results for the cradle-to-gate, operation and end-of-life stages should each be identifiable.

Examples of ICE data with these three methods

Two sets of examples are applied. The difference between the two examples is because of alternative assumptions between UK (EU) and worldwide practices.

UK (EU) Assumptions

Steel:
Recovery rate in UK construction = 94 per cent (Sustainable Steel Construction, 2006)
Recycling yield = 95 per cent (Eurofer, 2007)
r = 94 per cent * 95 per cent = 89 per cent
Recycled content = 59 per cent
E_d = negligible

Aluminium:
Recovery rate in UK construction = 85-96 per cent (The Global Aluminium Recycling Committee (GARC), 2006) = assumed 90 per cent
Recycling yield = 98 per cent
r = 90 per cent x 98 per cent = 88 per cent
Recycled content = 33 per cent
E_d = negligible

Table 17: UK (EU) cradle-to-grave ICE aluminium and steel data under three different methods for recycling.

Material	Recycled Content Approach		Substitution Method		50:50 Method	
	EE MJ/kg	EC $kgCO_2/kg$	EE MJ/kg	EC $kgCO_2e/kg$	EE MJ/kg	EC $kgCO_2e/kg$
Aluminium						
General	155	9·16	49·7	3·00	102·3	6·08
Cast	159	9·22	47·4	2·75	103·2	5·98
Extruded	154	9·08	53·2	3·22	103·6	6·15
Rolled	155	9·18	48·7	2·99	101·9	6·08
Steel						
General	20·1	1·46	12·3	0·76	16·2	1·11
Bar and rod	17·4	1·40	11·0	0·74	14·2	1·07
Coil (sheet)	18·8	1·38	12·9	0·70	15·8	1·04
Coil (sheet), galvanised	22·6	1·54	14·9	0·78	18·8	1·16
Pipe	19·8	1·45	13·4	0·74	16·6	1·10
Plate	25·1	1·66	16·6	0·86	21·8	1·26
Section	21·5	1·53	13·1	0·75	17·3	1·14

Worldwide Assumptions
Unless listed below the assumptions are the same as the UK (EU) example.

Steel: Recovery rate in worldwide construction = 85 per cent (Worldsteel)
R = 85 per cent x 95 per cent = 81 per cent
Recycled content = 39 per cent

Aluminium: Recovery rate in worldwide construction = 85 per cent
r = 85 per cent x 98 per cent = 83 per cent
Recycled content = 33 per cent

Table 18: Worldwide cradle to grave ICE aluminium and steel data under three different methods for recycling.

Material	Recycled Content Approach		Substitution Method		50:50 Method	
	EE MJ/kg	EC $kgCO_2/kg$	EE MJ/kg	EC $kgCO_2e/kg$	EE MJ/kg	EC $kgCO_2e/kg$
Aluminium						
General	155	9·16	60·6	3·64	107·8	6·40
Cast	159	9·22	58·7	3·40	108·8	6·31
Extruded	154	9·08	63·9	3·84	109·0	6·46
Rolled	155	9·18	59·6	3·63	107·3	6·40
Steel						
General	25·3	1·95	14·3	0·95	19·8	1·45
Bar and rod	21·6	1·86	12·7	0·92	17·1	1·39
Coil (sheet)	23·5	1·85	14·7	0·89	19·1	1·37
Coil (sheet), galvanised	28·5	2·03	17·2	0·98	22·8	1·50
Pipe	24·9	1·94	15·3	0·93	20·1	1·44
Plate	32·0	2·21	19·2	1·07	25·6	1·64
Section	27·1	2·03	15·3	0·96	21·2	1·49

B.2 - GUIDE TO THE EFFECTIVE USE OF THE RECYCLED CONTENT APPROACH

A recycled content approach needs to be done with care in its implementation. This section discusses appropriate use.

AVOIDING MARKET DISTORTIONS

Introduction

To use the recycled content approach effectively the fraction of primary and secondary material inputs are required. Despite appearing as a single method there are several different implementations. The most common recycled content approach draws the system boundaries of the recycled material tightly around the specific product in question. Thus, the recycled material is cut off from the global material production and recycling system. This implies that the benefits of recycled content are given to the individual product in question. For example if the global average recycled content is 40 per cent but the recycled content of the product under investigation is 60 per cent then the latter value will be assigned to the investigated product system. This often appears to be the most logical method (and will be called the traditional approach from here on) but there are special cases when this implementation should be avoided.

It can be argued that in certain material markets the traditional recycled content approach may facilitate 'market distortions' (see Atherton, 2007; EAA, 2007). Such arguments are particularly valid to highly recyclable materials with high recovery rates, i.e. metals. It's well documented that the impacts of recycled metals are lower than for primary metal production. Consequently, a high recycled content would result in a lower environmental burden. Under a traditional recycled content approach the manufacturer of highly recycled material benefit with a lower environmental impact for the product. However, any work that is completed in the name of environmental gain must ensure that its methodology is robust and ethical in its implementation. It is vital that global additionality of the benefits is ensured. Individual efforts may appear to offer environmental gain but when the system boundaries are expanded to encompass the entire global system it may be determined that there is no net benefit to society. To avoid these false 'benefits' the recycled content method must be applied with care and attention (as will be explained below).

Steel is a good example of an important building material where the traditional approach is often inappropriate. In the case of steel, scrap material may be recovered at the end of a product's lifetime. The availability of recycled steel is related to the total quantity of iron ore extracted from the earth and the average lifetime of steel products on the marketplace. These parameters define the upper threshold of steel scrap availability (and therefore recycled steel) at any single point in time. The present recovery rate of scrap steel is high, particularly in construction, and often with little room for improvement. As a consequence an increase in demand for scrap steel would not be enough to drive up the global average recycled content. In this case the increased consumer demand for steel scrap is uncoupled from the supply due to the limiting factor of scrap feedstock availability. Likewise, the same logic can be applied to specifying a high recycled content.

The conditions within the steel market imply that the consumption of 100 per cent recycled steel merely takes away this option from others in the marketplace. For example, if a single consumer purchases all of the recycled steel in the market place then the remaining consumers are forced to purchase primary steel. These consumers may also desire recycled steel but the supply of scrap steel has been depleted (at that point in time) and there is no feasible way to increase the availability of scrap materials. The consumer who purchased all the recycled steel may try to claim an environmental benefit, but in reality this is only at the expense of the remaining consumers who were 'burdened' with primary steel. From a global perspective the 'benefit' of the 100 per cent recycled steel is somewhat reduced by the lower recycled content steel remaining on the market place.

Therefore, under a traditional recycled content approach the benefits of recycling can become distorted across the marketplace where some consumers gain at the expense of the remaining consumers. This is a view that is shared across the metals sector. However the criticism of the recycled content approach usually refers to the methodology in its traditional sense – where the individual products recycled content is assessed and as described above. For example the metals sector sate *"…application of the recycled content approach may create market distortions and environmental inefficiencies. If a designer specifies high recycled content in a well meaning effort to reduce environmental impacts, it may stimulate the market to direct recycled feedstock towards designated products and away from production where recycling is most economical…and may result in efficient processing and unnecessary transportation*" (Atherton, 2007). Likewise the aluminium sector has similar opposition to the recycled content method and the European Aluminium Association state "*…recycled aluminium is used where it is deemed most efficient in economical and ecological terms. Directing the scrap flow towards designated products, in order to obtain high-recycled content in those products, would* *inevitably mean lower recycled content in other products. It would also result in inefficiency in the global optimisation of the scrap market, as well as transportation energy.*" (EAA, 2007). The present authors share these views about a traditional recycled content approach for metals but have worked to resolve them within the ICE database.

The default ICE database method

It is apparent that under certain conditions a traditional recycled content approach is inappropriate. This may be assessed for highly recyclable materials with a single condition:

- Where the availability of scrap materials (in a in a closed-loop market) for use as a feedstock input in recycling processes is uncoupled from increases in consumer demand.

  For example, where worldwide recovery rates are high with little or no room for improvement. This implies that an increased demand for recycled products will not increase the average recycled content in the marketplace.

When this condition is satisfied a traditional approach cannot be applied. Alternative implementations must be considered. The ICE database has therefore taken geographic market averages as its default method. Each steel product of a specific type (e.g. sheet, rod or section) is modelled with the same recycled content. This implies that the benefits of recycling are shared across the entire material sector. The method represents the benefit of using recycled materials in a global context. It cannot be exploited and does not facilitate market distortions on any level. In the broadest context the recycled content may be defined on a global level, i.e. the world average recycled content (which always gives the most complete picture). Alternatively, if the market satisfies certain conditions (closed loop markets - see section below) smaller geographic markets can be applied. In the case of steel an EU 27 market average was determined to be a feasible option. [See 'A closed loop market average recycled content']

To implement this method effectively the same recycled content must be modelled for all different forms of (carbon) steel (e.g. rebar, sheet or section). Technological and economic factors often dictate where scrap materials are directed. The fact that a certain type of steel is almost exclusively manufactured from primary feedstock (iron ore) or secondary feedstock (scrap steel) becomes irrelevant. For example, steel rebar is often manufactured in an electric arc furnace (EAF) and therefore often has a recycled content of 100 per cent. Conversely steel sheet is typically derived from a primary production route. An increase in the demand and production of steel rebar will not result in an increase in the global average recycled content for worldwide steel. Likewise, an increase in the demand and production of steel sheet will not reduce the global average recycled content. Scrap steel remains a valuable commodity and will be consumed regardless of the demand for certain types of steel. Consequently, changes in the demand of certain forms of steel (rebar, sheet or section) have no capacity to increase the global average recycled content. The consequences of this are that although rebar is normally made from recycled steel and sheet is typically made from virgin steel both materials are given an 'effective market average recycled content' within the ICE database.

In markets where the above condition is not satisfied then a traditional recycled content approach can be applied. An example of this would be materials which have low recovery and recycling rates with a large potential for improvement.

A CLOSED LOOP MARKET AVERAGE RECYCLED CONTENT

The effective implementation of a market average recycled content requires that the market is able to operate in a closed loop capacity. It must prove that the market sector is not distorting the recycled content in the other market places. For example, if a market imported more scrap than it exported then the high recycled content within this market should be considered artificial. This market is taking away scrap materials from other markets and consequently the above arguments about market distortions become relevant. A closed loop market must prove to be self sufficient so that it could (theoretically) operate in a standalone capacity.

The present authors have analysed the aluminium, copper and steel markets. For aluminium and copper it was determined that UK and EU metals were heavily reliant on external markets. They do not have the capabilities to operate in self sufficiency. Therefore the world average recycled content for aluminium and copper will remain as the default ICE database method. The same was discovered for the UK steel market. The UK does not have the technical capacity to process a large proportion of its scrap materials. As a consequence the UK exports large amount of scrap materials into the EU. The majority of UK produced steel is through a primary production route, but this is a technical constraint of production and does not represent the recycled content of the average steel consumed within the UK.

On the other hand, the EU 27 steel market was determined to be self sufficient (except for the purchase of iron ore, which was considered to be acceptable). The EU 27 could therefore be considered as a closed loop market and an EU 27 average recycled content may be applied. The EU 27 was determined to not rely on external markets for the provision of scrap steel. Furthermore, imports and exports of steel were similarly balanced. As a consequence ICE version 2.0 contains an EU 27 average recycled steel content (59 per cent) alongside a world average recycled content (39 per cent). [Note: the ICE database supports the use of a 3 year market average recycled content - where data allows.]

Which market average recycled content should I apply?
The most recent ICE database contains a choice of market average recycled contents for steel. The 'UK typical' values for steel have adopted the EU 27 market average recycled content as their proxy. Only steel produced and consumed within the EU 27 countries may apply the EU 27 three-year average recycled content of 59 per cent. Furthermore, the use of this value requires that to maintain consistency within the same project (or single methodological framework) a rest-of-the-world (ROTW) recycled content should be applied to production of steel outside the EU 27. The three-year average ROTW recycled content was estimated to be 35·5 per cent. Alternatively, a three-year world average recycled content of 39 per cent may be applied for all steel products; however this cannot be mixed with the EU 27 average, or ROTW average within the same project.

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