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A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards☆

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ABSTRACT

As operational impacts from buildings are reduced, embodied impacts are increasing. However, the latter are seldom calculated in the UK; when they are, they tend to be calculated after the building has been constructed, or are underestimated by considering only the initial materials stage. In 2010, the UK Government recommended that a standard methodology for calculating embodied impacts of buildings be developed for early stage design decisions. This was followed in 2011–12 by the publication of the European TC350 standards defining the 'cradle to grave' impact of buildings and products through a process Life Cycle Analysis.

This paper describes a new whole life embodied carbon and energy of buildings (ECEB) tool, designed as a usable empirical-based approach for early stage design decisions for UK buildings. The tool complies where possible with the TC350 standards. Initial results for a simple masonry construction dwelling are given in terms of the percentage contribution of each life cycle stage. The main difficulty in obtaining these results is found to be the lack of data, and the paper suggests that the construction and manufacturing industries now have a responsibility to develop new data in order to support this task.

1. Introduction

The last decade has seen increasing regulations for the reduction of energy use and carbon emissions from the operation of buildings. However, the embodied energy and carbon are not currently the subject of regulation; in the UK these impacts are therefore seldom calculated. In 2010, the UK Government Low Carbon Construction Innovation and Growth Team (IGT) recommended that embodied impacts should be assessed at the feasibility stage of construction projects to inform design decisions, and that an agreed methodology needed to be developed in order to do so [1].

During 2011 and 2012, a suite of voluntary standards on Sustainability of Construction Works was developed by the European Standards Technical Committee CEN TC350. Those related to environmental performance have now been published in Europe and simultaneously as British Standards [2–4]. These define the whole life impact of construction products, including buildings, through a process life cycle analysis approach. While this method has frequently been applied to post-calculate the environmental impacts of a constructed building, its application at feasibility stage is less clear.

This paper describes the design of a whole life (cradle to grave) embodied carbon and energy tool for UK buildings (ECEB) to be used at an early design stage, designed as a response to the IGT and to comply where possible with the method described in the TC350 standards. Initial results using the tool are given for a simple masonry construction dwelling in terms of the percentage contribution of each life cycle stage.

2. Theory/background

The embodied energy and carbon of buildings are commonly measured using an adapted form of Life Cycle Assessment (LCA), a method of analysing the environmental impacts of the whole life of a product. The International Standard ISO 14044:2006 [5] defines the four key phases of LCA as 'Define goal and scope', 'Life cycle inventory analysis' (LCI), 'Impact Assessment', and 'Interpretation'.

The TC350 standards, in common with most current practice [6], uses a process based approach to the life cycle inventory stage of LCA. This method traces a range of environmental impacts of all materials, components and processes which form a building. However all life cycle analyses require a choice of boundaries, leading to inconsistencies. The method most commonly used in the UK

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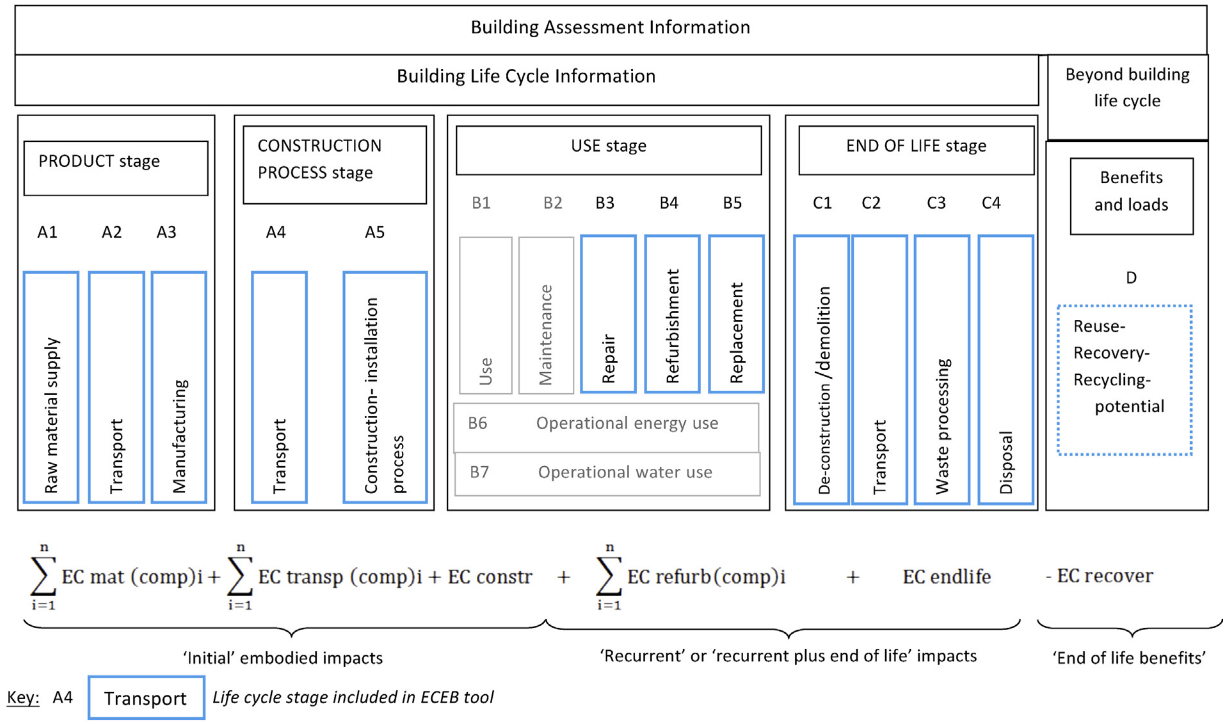


Fig. 1. Life cycle stages from BS EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method [4] mapped against the equation used by the ECEB tool. Key: A4 Life cycle stage included in ECEB tool.

considers only the greenhouse gas and energy impacts, and only from the product 'cradle to gate' stage (for example, see the RICS report [7] and tools such as Mott MacDonald's LifeCYCLE [8]). Other authors have defined 'embodied' impacts as including construction and refurbishment but not the end of life [9]. The TC350 standards measure the 'cradle to grave' impacts, defining four life stages as A1-3 Product, A4-5 Construction process, B1-7 Use, and C1-4 End of life (see Fig. 1). A further optional stage D is defined to account for the potential positive impacts of processing or re-using materials and components after the end of life. Only stage B1 (incorporating B6 and B7) describes the operational impacts which are the subject of current UK and EU regulations. All other stages form the currently unregulated impacts, and these are defined in this paper as together forming the embodied impacts. This paper, in common with most UK approaches, considers only the energy and carbon equivalent impacts, excluding the other environmental impacts which are also described in the TC350 standards.

The specified boundaries in the TC350 standards omit the auxiliary services associated with the construction of the building, including for example the impacts of the designers' and contractors' offices, and of the finance, insurance, government administration and related office buildings. An alternative LCI method, input-output (I-O) analysis, includes these services within a complete system boundary, through an assessment of the total economic or environmental inputs to and outputs from a specific industry sector or sub-sector [10]. However, the I-O method assumes homogeneity of buildings, and equates carbon emissions directly with financial cost, thus (for instance) disguising the carbon benefits of 'green' materials with relatively high costs because of reduced economies of scale. These factors limit the use of the I-O method in design decisions for individual buildings. Some authors have therefore developed hybrid approaches in an attempt to overcome these problems [11,12]. Crawford analyses four different methods and concludes that results from the process-based method are often under 50% of the results using other methods [13]. This suggests that the TC350 method may substantially underestimate the true embodied impacts.

Several authors have published analyses of one or more building case studies, and others have collated these separate results in an attempt to give a broad picture of embodied impacts [14–16]. However, Moncaster and Song [6] and others have pointed out the inconsistencies in the methods and boundary conditions applied, and in the data used.

An alternative system boundary is defined by the Strategic Forum for Construction (SFfC) and the Carbon Trust in their response to the Strategy for Sustainable Construction (SFfC) [17] (see Fig. 2). The report defines the responsibilities of the construction sector for the reduction of carbon emissions, rather than calculating the emissions of discrete construction projects and has a number of major differences from the TC350 process LCA. The first is that the 'Product' stage A1-3 in the TC350 standards is outside the scope, as reducing carbon and energy in this stage is seen as the remit of the manufacturing sector. However, other impacts which are omitted by TC350 are included by the SFfC, such as impacts from off-site offices and employee commuting. The importance of water and waste treatment, and of the impact of construction plant, is prominent, and off-site assembly is given a specific entry in the SFfC diagram. The differences between the two approaches highlight the importance of understanding not just the aggregate numbers, but also the roles and responsibilities that different actors have for reducing impacts from different stages. The authors will return to this issue in the conclusions.

This paper has followed a number of other authors [18,19] in considering both embodied carbon and embodied energy. Many others choose to focus on just energy [9,15], or just carbon [20]. While the emission of carbon and other greenhouse gases form a key environmental impact from construction, the impact of energy use has additional economic and social impacts, which are the subject of the as yet unpublished parts 3 and 4 of BS EN 15643. The TC350 standards (for example, BS EN 15804 section 7.2.4 [3]) also

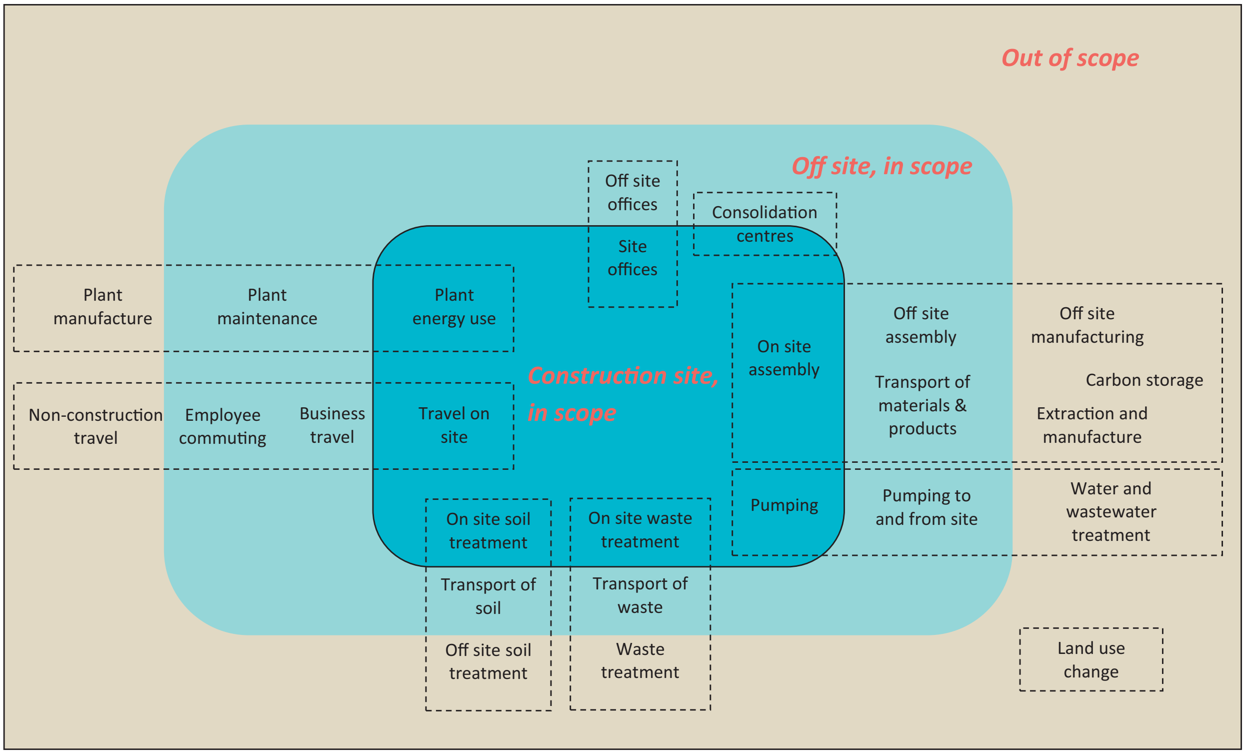


Fig. 2. 'Scope categorisation of processes across the construction project physical boundary', SFfC and Carbon Trust report p. 20 [17].

require that both carbon and energy impacts should be evaluated in an environmental LCA.

Rather than assessing the embodied impacts of individual buildings after construction [19,21], the ECEB tool proposes an adapted process LCA for use as a design-decision tool at the feasibility design stage. There are two practical problems with conducting this type of analysis for a building at such an early stage. The first of these is the individual bespoke nature of most buildings. Unlike factory-fabricated products, the materials and processes will be different for every project, and many will not be specified until much later on during design, some not until the project is on site. The ECEB tool was developed as part of the Butterfly tool [22] which generates an assumed list of building components with quantities from limited feasibility stage information; alternatively the list can be manually created.

Second is the dearth of data, for all life cycle stages. In the UK, there has been no culture of manufacturers of construction materials and components calculating and publishing the whole life environmental impacts of their products, although it is hoped that this will change with the publication of BS EN 15804 [3]. In addition many aspects of the UK construction industry, including the use of sub-contractors for different construction packages and a culture of commercial confidentiality, make data on waste and site energy use scarce. At present the database incorporated in the ECEB and Butterfly tools uses the Bath ICE database [23] for the product stage for most components, with additional information from individual manufacturers' data for a few composite components. The database is fully referenced and the authors are happy to provide a copy on request. An explanation of the approach used to develop data for subsequent stages is given in sections 4.2–4.5.

The collection, assessment and maintenance of accurate and transparent data is one of the key hurdles to the assessment of embodied energy and carbon of buildings, and one of the aims of the CEN TC350 is to encourage the development of this data across Europe. At present the database included in the ECEB tool includes the most comprehensive and up to date sources for the manufacture of construction products used in the UK, as described in more detail in the following paper. A few databases currently exist which are regularly updated with current data, and these are available on annual subscription [6]. These could be used as an alternative linked database for the ECEB tool. A further international collaboration is currently developing guidelines on data sources, methods and case studies as part of the International Energy Agency ECBCS programme, to inform routes to reducing embodied energy and carbon from buildings [24] and to encourage the development and open access publication of data. It is hoped that with the application of the new standards and the development of the IEA guidelines, data will become increasingly available, transparent and comprehensive.

The method used in the ECEB tool can be summarised in Eq. (1) below. Following TC 350 methodology (Annex A [4]), the building being analysed is divided into assemblies (e.g. external wall), which are further divided into elements (e.g. masonry cavity construction), which are then divided into components (e.g. bricks). For a building composed of a number n of components (comp) the equation for the whole life embodied carbon (EC whole life) used in the tool takes the following form:

$$\begin{aligned}\text{EC whole life} &= \sum_{i=1}^{n}\text{EC mat(comp)i} + \sum_{i=1}^{n}\text{EC transp(comp)i} + \text{EC constr}\\ &\quad + \sum_{i=1}^{n}\text{EC refirb(comp)i} + \text{EC endlife} - \text{EC recover}\end{aligned} \tag{1}$$

where (comp)i, is a particular component $i = 1, 2, 3$ etc., EC mat, is the carbon emitted during the material production stage, EC transp, is the carbon emitted due to transport of materials to site, EC constr, is the carbon emitted due to the processes involved in constructing the building, EC refurb, is the carbon emitted due to the repair, refurbishment and replacement of components during the life time of the building, EC endlife, is the carbon emitted due to the processes involved in demolition and waste processing, and EC recover, is the carbon credit which can be reclaimed due to certain future uses of the materials.[1]

The terms are shown mapped against the TC350 life cycle stages in Fig. 1. The embodied energy (EE) terms are similar to those for embodied carbon. Each term is discussed in further detail in the following sections.

3. Embodied energy and carbon traced back to cradle: definitions

3.1. Embodied energy

In accordance with the TC350 Standards, the embodied energy (EE) calculated by the ECEB tool is the total *primary* energy, measured in kWh, consumed from direct and indirect processes associated with a building over its lifecycle within the cradle-to-grave life cycle boundaries. This includes all activities from material extraction, manufacturing, transportation, construction, refurbishment and replacement, and disposal activities at the end of the building's life. It also includes the impacts from all material that is lost at every stage. It excludes the 'operational energy' used within the building when it is in use, for example heating, cooling, lighting and running appliances. The route tracing embodied energy back to cradle is shown in Fig. 3, and further details of the terms are given in the section below.

3.2. Primary energy

The 'primary' energy of a product is defined as the total energy consumed ('delivered' energy) at the point of production, such as the manufacturing plant, plus the additional energy that has been expended in order to extract and process the fuel and transport it to the power plant (this applies to all fuels extracted at a distance from the power plant, including for example fossil, nuclear and biomass fuels), the losses due to the efficiency of the power plant, and the losses incurred in transporting the energy to the manufacturing plant via transient energy carriers.

The energy embodied in the infrastructure, including the fuel processing and power plants and distribution systems, is not included in this analysis. It should be noted that there is an anomaly in the method when energy is produced by systems on site, such as roof-mounted photovoltaic panels. In this case the system is treated as part of the building, and the embodied energy used in its manufacture is included as it would be for any other building component, even though the energy produced is then transmitted through the national distribution system.

Energy losses in fuel extraction, production and distribution ($MJ_{expended}/MJ_{deliveredfuel}$) can vary from 0.19 for crude oil to diesel to 0.3 for natural gas piped from Western Siberia [25]. For electricity the losses at the generating and the distribution stages that are used are the UK averages in 2010 [25]. The % figures for losses at each stage shown in Fig. 3 are for typical fossil fuel energy pathways, to indicate the typical scale of losses that can occur and should not be used in any LCA analysis. Figures for a specific product will obviously depend on the fuel mix for that particular manufacturing process.

3.3. Feedstock energy

A product may also have an associated 'feedstock' energy, which may be partially released and recovered at the end of life stage of the product, usually through incineration. The TC350 standards do not specifically mention feedstock energy, but do list the renewable and non-renewable 'primary energy resources used as raw materials' (p. 34 [3]) as parameters describing resource use. The method described in this paper follows the method and reasoning of the Bath ICE (p. 4 [23]), as the main source of data for the product stage in the tool, by only including the feedstock energy derived from non-renewable resources (such as petrochemicals used in the manufacture of plastic products) within the calculation of primary embodied energy content of materials. It does not include the feedstock energy derived from renewable resources such as timber as, unlike the former example, this energy can be replaced over human timescales. An estimate of 25% material lost as waste, and therefore feedstock energy lost during the manufacturing process, is used in Fig. 3 as an example. Any feedstock energy from a building product that is recovered at the end-of-life stage and used usefully outside the building system boundary may result in an energy benefit. Benefits outside the system boundary are included in Module D of the TC350 methodology and are not considered in this paper; however it is noted that care needs to be taken to ensure feedstock energy is not double-counted.

3.4. Embodied carbon

The embodied carbon (EC) is the sum of fuel-related carbon emissions and process-related carbon emissions (i.e. non-fuel related carbon emissions which may arise for example from chemical reactions) that occur over the life cycle of a building within the boundaries of cradle-to-grave. Like embodied energy, this excludes the 'operational carbon'. The ECEB method described here, in common with others, calculates the embodied carbon equivalent (ECe), which includes the effects of emissions of all greenhouse gases normalised by their relative warming effect in the atmosphere with respect to CO_2, giving their 'global warming potential' (GWP) over a 100 year period. The most common and significant greenhouse gases emitted in the construction sector are CO_2 (GWP of 1), methane (CH4–GWP of 25) and Nitrous Oxide (N2O–GWP of 298) [26]. The total quantity is measured in kg CO_2e. This paper uses the term 'carbon' throughout to mean embodied carbon equivalent. The route tracing embodied carbon back to cradle is shown in Fig. 4, and further details of the terms are given in the section below.

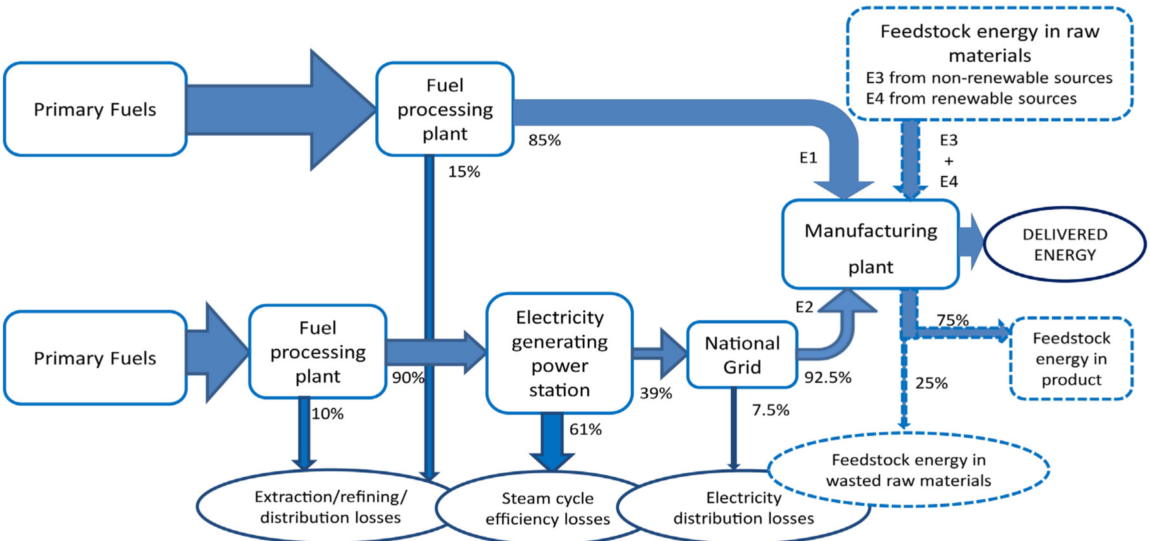
3.5. Direct and indirect carbon emissions

Direct carbon emissions of a particular product are equivalent to the annual emissions of greenhouse gases from the manufacturing plant, normalised for their global warming potential, and divided by the annual mass output of product, to get a value in kg CO2e/kg of product. These emissions are largely a result of fuel combustion at the manufacturing plant, but also include the effects of any chemical reactions that result in emissions of greenhouse gases, for example, the emission of CO_2 in the production of cement when limestone ($CaCO_3$) is converted to lime (CaO).

In order to trace these impacts back to cradle, the indirect emissions must also be included. These result from extracting, processing and delivering the energy and fuels used, both renewable and non-renewable, similar to the losses included in the calculation of primary energy. As for primary energy calculations, the carbon emissions embodied in the infrastructure are not included in the analysis. The carbon emissions from the delivered energy will include the carbon impacts from the upstream processes and losses that occur from the primary energy as in 3.2 above.

Raw materials used in the manufacture of a product may also have a carbon content that has the potential to be emitted as CO_2 but is not released during the manufacturing process. This can be

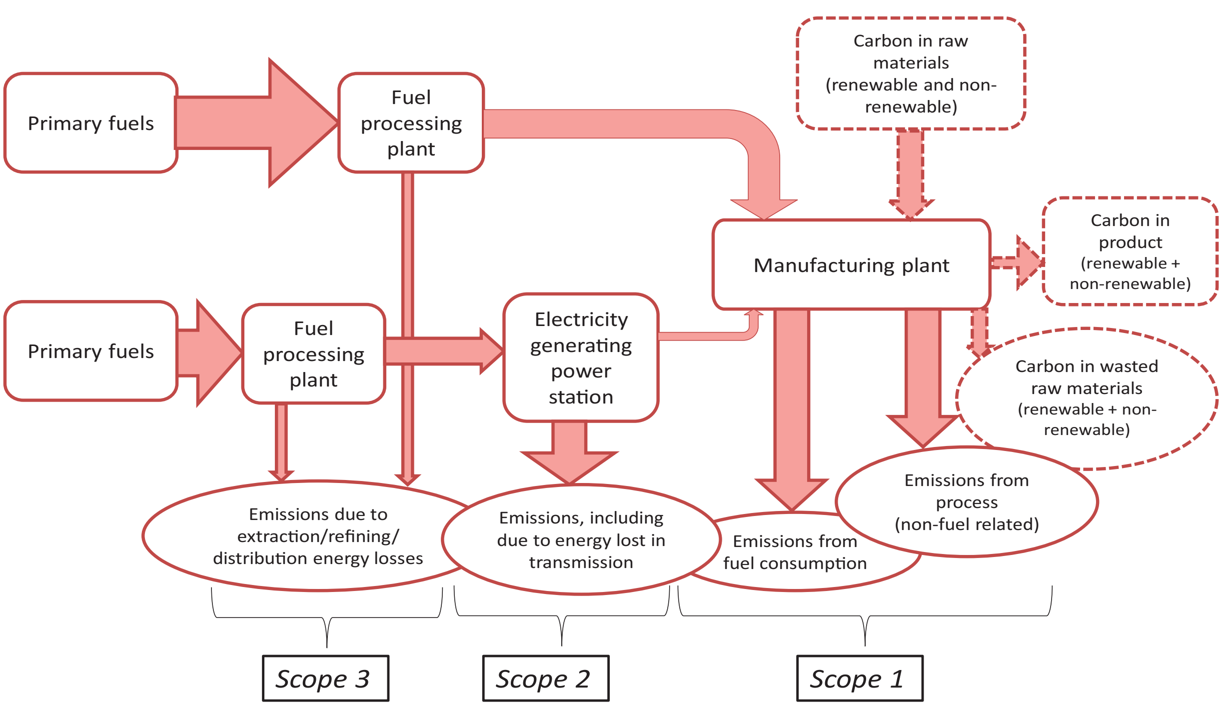
[1] The issue of the impact of choices after the end of life of the building is complex and contested, and although the ECEB tool includes this stage as optional in common with the TC350 advice, it is not discussed further in this paper.



Inputs to Manufacturing Plant:	**Delivered Energy Density** (MJ/kg)
E_1 MJ fuel (eg gas, oil, or renewables such as hydropower)	$= [E_1 + E_2]$/ mass of product
E_2 MJ electricity	
Raw Materials:	**Primary Embodied Energy Density** (MJ/kg)
Feedstock – non-renewable: E_3 MJ	$= [E_1/0.85 + E_2/(0.9 \times 0.39 \times 0.925) + E_3/0.75]$ / mass of product
Feedstock – renewable: E_4 MJ	$= [\mathbf{1.2} \times E_1 + \mathbf{3.25} \times E_2 + \mathbf{1.3} \times E_3]$ / mass of product

Fig. 3. Total primary energy (traced back to cradle) embodied in manufactured product – see sections 3.2–3, coefficients taken from [25].

non-renewable carbon (such as the carbon content of plastics from petroleum products) or renewable carbon, which can be replaced in the environment over human time scales. An important example of the latter is the carbon in timber harvested from a sustainably managed source where the felled timber is replaced by at least an equal amount of timber. This carbon stored in the timber used in construction can be calculated as a negative carbon emission, and is often referred to as 'sequestered' carbon. It is equal to about 1.8 kg CO_2e/kg timber [27,28] and so can often negate the positive carbon emissions of timber products across all the life cycle stages. The database incorporated in ECEB at present includes the sequestered carbon in timber in the optional stage D, as it is considered to be



Total Embodied Carbon Density (direct and indirect emissions) (kg CO_2e/kg product)
= [Scope 1 + Scope 2 + Scope 3 (- renewable carbon in product in some cases)] / mass of product

Fig. 4. Embodied Carbon, direct and indirect emissions traced back to cradle – see sections 3.4–5.

a benefit outside the system boundary. Consideration of this stage is outside the scope of this paper and so sequestration of carbon in timber products is not included in the results presented here. Users of different databases and tools should be aware of whether sequestration is included or not, and of the arguments around this complex issue.

The ECEB tool uses data published by the Departments of Energy and Climate Change (DECC) and of the Environment, Food and Rural Affairs (Defra) for direct and indirect UK carbon emission factors for fuels, electricity and transport modes [29]. This defines three 'scopes' of emissions as follows [29]:

- **Scope 1 - Direct emissions**
  Direct GHG emissions emitted at the point of combustion of fuels.
- **Scope 2 - Indirect emissions: electricity and heat**
  Indirect GHG emissions from consumption of purchased electricity, heat or steam.
- **Scope 3 - Indirect emissions: other**
  Indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g. transmission & distribution losses) not covered in Scope 2, outsourced activities, waste disposal, etc.

The embodied carbon traced back to the 'cradle' is the sum of emissions in all scopes. The Scope 3 (indirect) emissions for diesel are around 17% of the total emissions from all scopes, and 9% for natural gas. Note that these ratios are analogous to the 'energy cost of delivered fuel' as discussed in section 2.1, but the values are not directly proportional.

4. Calculations of impacts at each life cycle stage in ECEB

4.1. Product stage: TC350 modules A1-3

The first life cycle stage, the product stage, calculates the 'cradle to factory gate' emissions for all components in the modelled building.

The ECEB tool defines two types of building component. 'M' type components are those which are made up of a single material. This type includes therefore the high mass structural components such as concrete foundations, and timber, steel, concrete or masonry structural elements in the walls, floors and roof; an initial analysis shows that about 90% of a typical building by weight is made up of these component types. The process of calculation for these in ECEB is as follows:

i. A list of components and their number and size can be derived by one of two methods; either these can be input direct by a user, or they can be generated by a tool 'Butterfly' [22], which develops a default list of components from limited information at the feasibility stage.
ii. ECEB then determines the mass of material from volume and density data stored in the material database.
iii. Embodied energy and carbon for the component is calculated by multiplying the mass by the embodied energy and carbon coefficients, also stored in the database.

The equation for the first term in Eq. (1) is therefore:

$$\sum_{i=1}^{n} \mathrm{EC\,mat(comp)i} = \sum_{i=1}^{n} [\mathrm{Volume} \times \mathrm{density} \times \mathrm{coefficient}]\mathrm{(comp)i} \tag{2}$$

Table 1
Table of 'C' type components and their defining metric.

'C' type component	Windows PV panels SHW panels radiators	HW cylinders	Boilers, inc. biomass Pumps, incl. GSHP, ASHP CHP Wind turbines
Defining metric	Area (m^2)	Volume (m^3)	Power output (kW)

Table 2
Coefficients for embodied impacts in module A5 construction based on ten housing projects.

	Construction stage Module A5
Embodied energy (MJ)	151 MJ/m^2 GIFA
Embodied carbon (kg CO_2e)	9 kg CO_2e/m^2 GIFA

The second type of component is the 'Composite' or 'C' type, formed from multiple materials, such as windows, fixtures and fittings and services components. A similar process is followed. However, the relevant metric for calculating the embodied energy and carbon is no longer simply the mass of the component. For some of these composite components, the embodied impacts have been calculated by the manufacturer, and all that is needed to calculate the total embodied impact is the number of components in the building. For others there is currently only data for similar products ('base components'), and for these components one of three representative metrics has been identified (see Table 1). For each component type a defining coefficient is then calculated from the base component. For example for windows the representative metric is area. The materials database includes the embodied carbon of a specific $2\,m^2$ window (the 'base component') as 66 kg CO_2e, and so the coefficient for this type of window becomes: $66\,kg\ CO_2e \div 2\,m^2 = 33\,kg\ CO_2e/m^2$. The ECEB method then calculates the embodied carbon of a similar $4\,m^2$ window as: $4\,m^2 \times 33\,kg\ CO_2e/m^2 = 132\,kg\ CO_2e$. Similarly for a specific non-condensing gas boiler of power output 12 kW, the embodied carbon is given in the database as 216 kg CO2e. Therefore, the coefficient is divided by the power output to give a coefficient of: 216 kg CO2e ÷ 12 kW = 18 kg CO2e/kW. For a similar non-condensing gas boiler of 24 kW, the embodied carbon is then calculated as: 24 kW × 18 kg CO2e/kW = 432 kg CO2e. While this approach is clearly of limited accuracy, it is simple to implement, provides a useful estimate at an early stage in the design before components have been fully specified, and provides a necessarily pragmatic approach to address the problem of lack of specific manufacturer's data for many components (Table 2).

The expanded equation for the first term of Eq. (1) for this material type becomes:

$$\sum_{i=1}^{n} \mathrm{EC\,mat(comp)i} = \sum_{i=1}^{n} [\mathrm{Nr} \times \mathrm{metric(comp)} \times \{\mathrm{coefficient/metric}\}\mathrm{(base\,comp)}]\mathrm{(comp)i} \tag{3}$$

This stage contributes 50 and 54% of the total for embodied carbon and energy, respectively, for the modelled masonry residential unit.

4.2. Transport: TC350 module A4

BS EN 15978:2011 clause 7.4.3.2 defines the boundaries for transport of materials and components from the factory gate to site, specifically including all materials lost or damaged during transportation and assuming the inclusion of all materials subsequently lost or damaged on site. This latter wastage, of materials on site, is estimated as a percentage increase against each material type in the database, is included in the calculations of mass in stages A1-3 and is carried through to the calculations for A4. This percentage is derived from contractors' site waste data and so does not include specific allowance for loss during transport which will be returned directly to the manufacturer, which is therefore currently omitted from the model.

BS EN 15978 also requires the inclusion of impacts from the transportation of construction equipment and plant to and from the site, but the ECEB method does not include these impacts due to the difficulties of allocating particular equipment or plant to individual components.

The calculation for this phase multiplies the total mass including site waste by distance travelled, and then by a Transport Mode Factor in MJ/tonne-km for embodied energy or kg CO_2e/tonne-km for embodied carbon, as follows:

$$\sum_{i=1}^{n} \mathrm{EC\,transp(comp)i} = \sum_{i=1}^{n} [\mathrm{mass} \times \mathrm{distance} \times \mathrm{transport\,factor}](\mathrm{comp})\mathrm{i} \quad (4)$$

The distance that each component travels is calculated in one of three ways depending on the component. The first is for a specific product, usually a composite 'C' type component with one manufacturer, for which a UK postcode, or a country of origin if non-UK, is included in the material database. The distance between this location and a site location, entered as a post code by the user, is calculated by converting the postcodes into coordinates, and multiplying the straight line distance between the two by a factor of 1.25 to allow for real distances by road. For international sources ECEB includes a table of distances between the UK and all other countries. The tool is capable of calculating multiple journeys for these components, with default ports of entry specified as Dover for road freight and Felixstowe for all shipping imports. The secondary transport distance is then calculated between this point and the site location. The tool can also accept a user-defined third distance of the manufacturer's location to the export port in the country of origin.

The second case is where components are commonly provided by a discrete number of manufacturers, for which an average location is estimated. The calculation of distance travelled is then the same as above.

The third case is for components which are generally available within a small distance of most sites, including aggregates and readymix concrete, for which a default distance is used.

The transport mode factors are taken from the Guidelines for Greenhouse Gas Reporting published by the UK Government [29] where they are provided in the form of kg carbon per tonne of material transported per km travelled (kg CO_2e/tonne-km) for each transport mode. Direct and indirect carbon emissions are defined in this document as follows:

- **Scope 1 - Direct emissions**
  Direct emissions of CO_2, CH_4 and N_2O from the combustion of fuel from owned/controlled transport.
- **Scope 2 - Indirect emissions: electricity and heat**
  Not relevant for transport emissions therefore not used.
- **Scope 3 - Indirect emissions: other**
  Indirect emissions associated with the extraction and transport of primary fuels as well as the refining, distribution, storage and retail of finished fuels.

Transport mode factors for energy impacts are not provided in these guidelines, but information provided in the European Commission Well-to-Wheels study [30] on the carbon emissions per energy content of each fuel type is used to calculate transport energy mode.

In accordance with the CEN/TC 350 process analysis methodology, the energy and carbon impacts are only evaluated for the fuel, and do not include the embodied impacts associated with transport infrastructure or manufacture of vehicles. Complex logistics and distribution networks are not accounted for in the ECEB model, but return journeys made by empty HGVs once materials have been delivered are included in the transport mode factors.

This stage contributes 9 and 10% of the total for embodied carbon and energy respectively for the modelled masonry residential unit.

4.3. Construction: TC350 module A5

The system boundary for the construction phase is set out in BSEN 15978:2011, section 7.4.3.3. It includes all processes carried out on site from start to end of construction works, as well as the production, transportation and management of site and construction waste.

The impact of production and transportation of materials that are subsequently wasted during construction (i.e. the 'upstream' impacts) are already included in ECEB by incorporating a material waste factor in the initial quantity calculations. The energy and carbon impacts of dealing with this wasted material 'downstream' from construction is difficult to evaluate, given the uncertainty surrounding final destination of waste, and potential for recycling, and these impacts are not currently included. The transport impacts of construction plant and equipment to and around site are also excluded at present as again there is currently a lack of data available to make robust estimations of this impact.

The calculation in ECEB for this life cycle stage is currently estimated using data of total energy used on site during construction from case study projects of eleven multi-residence buildings provided by Willmott Dixon, part of the project Butterfly research consortium. Energy use data was recorded by reading electricity and gas metres, and keeping records of diesel consumption, including all main contractor and subcontractor use for all construction processes. Outlying data from one of the projects was excluded from the analysis as a large and non-typical amount of extra energy was consumed when drying out a timber frame following severe wet weather. The site energy consumption was converted into primary energy and CO2 emissions, traced back to cradle using the conversion guidelines for direct and indirect carbon emissions and data for energy losses in fuel pathways. These were converted into benchmark figures for energy and carbon per m^2 gross internal floor area (GIFA).

The equation for this term of Eq (1) is:

$$\mathrm{EC\,constr} = [\mathrm{building\,area} \times \mathrm{construction\,factor}] \quad (5)$$

The accuracy of the coefficients can be improved through the collection of more data for different building typologies and sizes, different site waste and energy management scenarios, and different site conditions.

For the modelled residential unit this phase contributes 3 and 5% of the total embodied carbon and energy impacts, but the figures should be treated with considerable caution due to the very limited data for developing the construction factors.

4.4. Repair, replacement & refurbishment: TC350 modules B3-5

The use stage of BS EN 15978:2011 incorporates modules B1-B7, covering the period from the practical completion of the construction work to the point of time when the building is deconstructed or demolished.

Module B1 encompasses the impacts and aspects arising from the normal conditions of use of the building, and the majority is included in energy use and resultant carbon emissions within the building during occupation (module B6) and the energy and carbon impacts of water use (module B7). These impacts form the regulated operational energy and carbon impacts, which are modelled separately as part of the UK Building Regulation requirements; they do not therefore form part of the embodied energy and carbon calculations of ECEB.

Module B2 covers maintenance, and examples are given in the standard such as painting windows and annual inspection of boilers. ECEB is currently based on domestic dwellings, for which maintenance is heavily dependent on the residents and their lifestyle choices. Therefore, these impacts have been excluded from the ECEB model. This approach may need to be reassessed using longitudinal case study data for non-residential buildings.

The remaining modules in the 'Use' stage of the CEN/TC350 standards, B3 Repair, B4 Replacement and B5 Refurbishment, are calculated in ECEB. The boundary conditions are set out in BSEN 15978:2011, section 7.4.4.4–6.

For each component that is replaced, module 4 impacts will include the energy and carbon from the production and transportation of that component, taken from modules A1-3 and A4. As for the original materials, the database is constructed to include an allowance for waste materials.

An allowance for the energy and carbon associated with the construction processes of installing the replaced components is also added. This is calculated as a percentage of the total impact of the construction stage, which is considered to be equal to the percentage contribution of the replaced components to the product stage modules A1-3.

The equation is then of the form:

Table 3
Coefficients for embodied impacts in module C1 demolition based on ten housing projects.

	Excavation and demolition Module C1
Embodied Energy (MJ)	77 MJ/m^2 GIFA
Embodied Carbon (kg CO_2e)	5 kg CO_2e/m^2 GIFA

Further uncertainties in this calculation are due to the likely reduction of carbon intensity of the UK fuel mix in the future [34] (calculations for this phase are currently based on the 2010 UK fuel mix), the replacement of components with future innovations for which the impacts may be quite different, and the unpredictable nature of major refurbishment works. However, the uncertainty in the actual figures should not prevent their calculation and use in comparing design choices, as the impact of this stage is potentially high.

4.5. End of life: TC350 modules C1-4

The boundary conditions for assessment in this phase are set out in BS EN 15978:2011, sections 7.4.5 & 7.4.6, and further guidance on quantifying impacts is found in section 8.7 & 8.8.

BS EN 15978:2011 breaks the end of life phase into four sub-phases, C1 Deconstruction/demolition, C2 Transport, C3 Waste processing and C4 Disposal. C1 includes all energy used and carbon emitted on site during the process of demolishing a building, including erecting site infrastructure, operating the plant to carry out the demolition work and sorting of materials arising from the demolition operations. As for the construction phase, the ECEB tool estimates all these activities pro-rata to the size of the building based on case study data, as shown in Table 3.

$$\sum_{i=1}^{n} \mathrm{EC\,refurb(comp)i} = \sum_{i=1}^{n} \Big[(\mathrm{EC\,mat} + \mathrm{EC\,transp} + \mathrm{EC\,constr}\,\frac{\mathrm{EC\,mat(comp)i}}{\sum_{i=1}^{n}\mathrm{EC\,mat(comp)i}} \times (\{\mathrm{design\,life}/\mathrm{expected\,comp\,life}\} - 1) \Big]\,\mathrm{(comp)i} \tag{6}$$

The expected life in years of each component is derived from the extensive database 'CACTUS' provided by BLP Insurance [31], which is based on real data from component failures in buildings. This is incorporated into the ECEB materials database, and used to calculate number of replacements for each component over the life of the building.

The impact of this stage, as a proportion of the whole life cycle embodied impacts, has been measured by other authors to be between 15% [32] and 30% [33] of the total for a domestic dwelling. The impact will depend on the components used, with services and finishes providing the highest impacts for this stage; therefore for a building type such as a laboratory which is heavily serviced, including the calculation of the impact of this life cycle stage will make more difference than for a building type with lower servicing requirements such as a domestic dwelling. It will also be determined by the design life of the building used in the calculation; as the building life increases, more replacements will be needed, and both the actual and proportionate embodied carbon and energy due to this stage will therefore increase [32].

For calculation of modules C2-4, ECEB currently makes a conservative estimation of the proportion of waste (P1) reused on site (mainly as hardcore), reprocessed off site (P2) and land filled (P3) based on a report by Craighill and Powell [35]. The demolition waste at the end of the building's life is assumed to be equal to the mass of material in the constructed building, not including the waste factor, and to have a similar breakdown by type. A preliminary study of the ECEB results confirmed that the great majority of the waste by mass is hardcore or aggregate.

The second phase, C2, models the transportation of waste materials from site. ECEB assumes all waste which is removed off site travels 30 km to landfill or reprocessing plant by road on rigid HGVs, and the energy and carbon transport factors are taken from the main DECC/DEFRA GHG conversion document [3] as for the transport of materials to site. The mass of waste removed from the site is calculated from the total mass of the building materials multiplied by the proportion removed (P2 + P3).

Phases C3 and C4 include the impacts from waste processing and disposal. ECEB has used data from two detailed reports from BRE [36] and Craighill and Powell [35] to assess the energy and carbon impacts of these phases through a waste factor.

The resultant equation for this term in Eq. (1) is:

$$\mathrm{EC\,endilife} \quad [\mathrm{building\,area} \times \mathrm{demolition\,coefficient}] + [(\mathrm{P2} + \mathrm{P3})\mathrm{mass} \times \mathrm{distance} \times \mathrm{transport\,factor}] + [(\mathrm{P2} + \mathrm{P3}]\mathrm{mass} \times \mathrm{waste\,factor} \tag{7}$$

For the modelled residential unit, which has a design life of 50 years, this phase contributes 17 and 26% of the total embodied carbon and energy impacts.

For the modelled residential unit this phase contributes 21 and 5% of the total embodied carbon and energy impacts, respectively. The variation between carbon and energy is explained by the end

Table 4
Preliminary ECEB results for masonry construction dwelling unit.

TC350 stage	Embodied carbon (%)	Embodied energy (%)
A1-3 Product	50	54
A4 Transport	9	10
A5 Construction	3	5
B2-5 Refurb and replace	17	26
C1-4 End of life	21	5
Total A-C	100	100

of life treatment of different waste materials including greenhouse gas emissions from landfill. The ECEB model assumes current UK fuel mix and current practices for the end-of-life treatment of construction materials. However, both the future decarbonisation of the UK electricity supply through the gradual replacement of fossil fuels, and the land filling of organic materials producing greenhouse gas emissions, are likely to end. It is recommended that the energy and carbon for this life cycle phase should therefore be quoted separately from the previous phases.

5. Discussion and conclusions

The paper has described the detailed method used by a new design decision tool, ECEB, to calculate the whole life embodied energy and carbon of buildings, as recommended by the UK Government IGT report [1]. The IGT report called for a method which could be used as a design decision tool at feasibility design stage, and this is what the ECEB tool aims to fulfil, while also aiming to follow where possible the analysis set out by the European TC350 standards, published in 2011 and 12 [2–4].

Preliminary calculations using the tool for a modelled basic masonry construction dwelling unit with a design life of 50 years have demonstrated the proportion of total embodied carbon and energy attributable to each life cycle stage, as shown in Table 4.

The method described in this paper provides an estimate of the whole life, 'cradle to grave' embodied energy and carbon impacts, calculated at the early stages of design. It therefore offers a more comprehensive comparison of design options than methods which look only at the impacts of the initial 'cradle to gate' materials stage; ECEB includes also the carbon and energy impacts of the material transport to site, the construction method, the component durability and the end of life options. The preliminary results shown in Table 4 suggest that calculating the expected emissions from all life cycle stages rather than focusing only on the product stage can increase the embodied carbon by a factor of two. This is an important finding because it demonstrates the importance of calculating, and reducing, embodied carbon and energy from buildings, and challenges the widespread belief that embodied impacts are negligible compared with operational impacts. The results were for a basic masonry construction dwelling; for other buildings the relative impact of different life cycle stages will be different, as has been indicated through this paper. For example, the use of different primary construction materials, such as timber, will have a considerable effect on the embodied carbon in the product and end of life stages. A different building type, such as a heavily serviced laboratory, is likely to have a different proportion of whole life energy and carbon for the replacement stage.

'Cradle to gate' methods [7] and tools [8] still have an important role to play in offering a simpler and quicker comparison between design options, but the potential impact of the different life cycle stages and their relevance to different building materials and types should be considered while using these simpler methods.

The paper concludes that for case studies of constructed buildings, the TC350 process-based LCA approach can provide a relatively accurate analysis of impacts for the initial life stages up to the end of construction (modules A1-5) through collection of real data, and an approximation of the impacts during and after the use lifetime of the building (modules B3-5 and C1-4). However, there are some difficulties in using this approach for early stage calculations to inform design decisions. Not only does choice of components need to be estimated, so does their location of manufacture and the likely construction processes, energy and waste. The approximation of impacts during and after the lifetime of the building then becomes even more uncertain.

The paper has further shown that analysis of whole life embodied energy and carbon of buildings within the UK is considerably restricted by the lack of data. The main gaps are in the manufacturers' data for cradle-to-gate (modules A1-3) impacts of specific products such as services components, in the assessment of energy use and carbon emissions during construction (module A5), and also that used at the end of life and in transport and processing of demolition waste (modules C1-4). In the theory section an alternative system boundary proposed by the Strategic Forum for Construction [17] was discussed. Many of the areas highlighted above as having the least existing data also form the main responsibilities of the construction industry as identified by this report and as shown in Fig. 2. The construction and manufacturing sectors must therefore now take the initiative to develop this missing data.

As recommended in the IGT Report [1], embodied carbon and energy should be calculated as part of the design information necessary to make the right design decisions for buildings, as part of a comprehensive energy and carbon reduction strategy. However, calculations should not just be carried out at the early stages, but should continue throughout the design and construction stages, and through refurbishment and end of life, in order to optimise the reduction of energy and carbon. Decisions taken at each stage will depend on more accurate knowledge of the impacts of different life cycle stages and of their potential for reduction; decisions will also be made by a variety of stakeholders who hold responsibility for different activities, including clients, designers, contractors and facility managers. The Strategic Forum for Construction, for example, has identified the reduction of carbon from the commuting of site staff as an important issue for contractors, although this is not an issue of such concern for designers and is not specifically included in the TC350 method. These varying responsibilities should be clarified.

Until more accurate knowledge has been developed, it will be difficult to determine which aspects have the highest potential for the reduction of carbon emissions and energy use. It is now therefore essential to develop this further knowledge. Work at Cambridge will continue on refining the method and approach of the ECEB tool, and it is hoped that industry will support this initiative.

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References

[1] HM Government, Low Carbon Construction Innovation & Growth Team Final Report, 2010.
[2] British Standards Institution, BS EN 15643 Sustainability of Construction Works – Assessment of Buildings in Part 2: Framework for the Assessment of Environmental Performance, British Standards Institution, London, 2011.

[3] British Standards Institution, BS EN 15804 Sustainability of Construction Works in Environmental Product Declarations. Core rules for the Product Category of Construction Products, British Standards Institution, London, 2012.
[4] British Standards Institution, BS EN 15978 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method, British Standards Institution, London, 2011.
[5] International Organization for Standardization, ISO 14044, in Environmental Management – Life cycle assessment – Requirements and Guidelines, International Organization for Standardization, Geneva, Switzerland, 2006.
[6] A.M. Moncaster, J.-Y. Song, A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings, International Journal of Sustainable Building Technology and Urban Development 3 (2.) (2012).
[7] RICS, Methodology to calculate embodied carbon of materials RICS information paper IP 32/2012, RICS: Park Communications Limited, London, 2012.
[8] Mott MacDonald, LifeCycle. Available from: http://www.eru.mottmac.com/registrationsubscription/lifecycle/
[9] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: an overview, Energy and Buildings 42 (10) (2010) 1592–1600.
[10] G.J. Treloar, A Comprehensive Embodied Energy Analysis Framework, in Faculty of Science and Technology, Deakin University, 1998.
[11] A.A. Acquaye, A.P. Duffy, B. Basu, Stochastic hybrid embodied CO2-eq analysis: an application to the Irish apartment building sector, Energy and Buildings 43 (2011) 1295–1303.
[12] Y. Chang, R.J. Ries, S. Lei, The embodied energy and emissions of a high-rise education building: a quantification using process-based hybrid life cycle inventory model, Energy and Buildings 55 (0) (2012) 790–798.
[13] R.H. Crawford, Validation of a hybrid life-cycle inventory analysis method, Journal of Environmental Management 88 (2008) 496–506.
[14] M.K. Dixit, et al., Identification of parameters for embodied energy measurement: a literature review, Energy and Buildings 42 (2010) 1238–1247.
[15] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy and Buildings 39 (2007) 249–257.
[16] A. Stephan, R.H. Crawford, K. de Myttenaere, Towards a comprehensive life cycle energy analysis framework for residential buildings, Energy and Buildings 55 (0) (2012) 592–600.
[17] Strategic Forum for Construction & Carbon Trust, Construction carbon 15% target by 2012 Scoping paper Rev A, Ove Arup and Partners Ltd, London, 2010.
[18] G.P. Hammond, C.I. Jones, Embodied energy and carbon in construction materials, Engineering Sustainability: Proceedings of the Institution of Civil Engineers 161 (2008) 87–98.
[19] J. Monahan, J.C. Powell, An embodied carbon and energy analysis of modern methods of construction in housing: a case study using a lifecycle assessment framework, Energy and Buildings 43 (2011) 179–188.
[20] D. Knight, B. Addis, Embodied carbon dioxide as a design tool – a case study, Proceedings of ICE Civil Engineering 164 (3) (2011) 171–176.
[21] C. Thormark, A low energy building in a life cycle – its embodied energy, energy need for operation and recycling potential, Building and Environment 3737 (2002) 429–435.
[22] BLP Insurance, Butterfly. Available from: http://www.blpinsurance.com/added-services/butterfly/
[23] G.P. Hammond, C.I. Jones, Inventory of (Embodied) Carbon & Energy (ICE), Department of Mechanical Engineering, University of Bath, 2006.
[24] International Energy Agency Annex 57. Evaluation of embodied energy & carbon dioxide emissions for building construction. Available from: http://www.ecbcs.org/annexes/annex57.htm#p
[25] Department of Energy and Climate Change, Digest of United Kingdom energy statistics (DUKES), The Stationery Office, London, 2011.
[26] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: The Physical Science Basis, 2007.
[27] Darby, H. A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross-laminated timber multi-storey residential building in SB13. 2013. Munich, Germany.
[28] K. Symons, A. Moncaster, D. Symons, An application of the CEN/TC350 standards to an energy and carbon LCA of timber used in construction, and the effect of end-of-life scenarios, in: in ALCAS, Sydney, Australia, 2013.
[29] AEA, Guidelines to DEFRA/DECC GHG Conversion Factors for Company Reporting, version 1.2, updated 19/08/2011, F.a.R.A.D. Department of Energy and Climate Change (DECC) and the Department for Environment, Editor, The Stationery Office, London, 2011.
[30] R. Edwards, J.-F. Larivé, J.-C. Beziat, Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context WTT APPENDIX 2 Description and Detailed Energy and Ghg Balance of Individual Pathways, E.C.J.R.C.I.f.E.a. Transport, Editor, Publications Office of the European Union Luxembourg, 2008.
[31] BLP Insurance CACTUS database. Available from: http://www.blpinsurance.com/blp-consult/
[32] Nygaard Rasmussen, F. and Certification of Sustainable Buildings in a Life Cycle Assessment Perspective, in Environmental Engineering, Technical University of Denmark, 2012.
[33] S. Citherlet, T. Defaux, Energy and environmental comparison of three variants of a family house during its whole life span, Building and Environment 42 (2007) 591–598.
[34] Jones, C. Embodied Carbon a Look Forward Sustain Insight Article: Volume I, 2011, Sustain: Bristol.
[35] Craighill, A. Powell, J.C. A lifecycle assessment and evaluation of construction and demolition waste, CSERGE Working Paper, 1999, CSERGE, University of East Anglia: Norwich.
[36] BRE, Developing a Strategic Approach to Construction Waste – 20 Year Strategy, BRE, Watford, 2006.