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Geoffrey P. Hammond
Professor and Director of the Institute for Sustainable Energy & the Environment, University of Bath, UK

Craig I. Jones
Research Officer, University of Bath, UK

Embodied energy and carbon in construction materials

G. P. Hammond and C. I. Jones

The development of an open-access, reliable database for embodied energy and carbon (dioxide) emissions associated with the construction industry is described. The University of Bath's inventory of carbon and energy database lists almost 200 different materials. The data were extracted from peer-reviewed literature on the basis of a defined methodology and a set of five criteria. The database was made publicly available via an online website and has attracted significant interest from industry, academia, government departments and agencies, among others. Feedback from such professional users has played an important part in the choice of 'best values' for 'cradle-to-site' embodied energy and carbon from the range found in the literature. The variation in published data stems from differences in boundary definitions (including geographic origin), age of the data sources and rigour of the original life-cycle assessments. Although principally directed towards UK construction, the material set included in the database is of quite wide application across the industrial sector. The use of the inventory is illustrated with the aid of 14 case studies of real-world new-build dwellings. It was observed that there was little difference between embodied energy and carbon for houses and apartments until external works were taken into account (energy inputs for roads, connecting pathways, etc.).

1. INTRODUCTION

The construction industry requires the extraction of vast quantities of materials and this, in turn, results in the consumption of energy resources and the release of deleterious pollutant emissions to the biosphere. Each material has to be extracted, processed and finally transported to its place of use. The energy consumed during these activities is critically important for human development, but also puts at risk the quality and longer term viability of the biosphere as a result of unwanted or 'second' order effects.[1] Many of these side-effects of energy production and consumption give rise to resource uncertainties and potential environmental hazards on local, regional or national scales.[1] Energy and pollutant emissions such as carbon dioxide (CO_2) may be regarded as being 'embodied' within materials. Thus, embodied energy[2] can be viewed as the quantity of energy required to process, and supply to the construction site, the material under consideration. In order to determine the magnitude of this embodied energy, an accounting methodology is required that sums the energy inputs[2] over the major part of the material supply chain or life-cycle.[3] In the present context, this is taken to include raw material extraction, processing and transportation to the construction site—a 'cradle-to-site' approach. Likewise the emission of energy-related pollutants (like CO_2), which is a concern in the context of global warming and climate change, may be viewed over their life-cycle. This gives rise to the notion of 'embodied carbon'.

The aim of the present study was to develop an open-access, reliable database of both embodied energy and carbon for (principally) UK construction materials. It was initially devised to be used by various research consortia supported under the carbon vision buildings programme funded by the Carbon Trust and the Engineering and Physical Sciences Research Council (EPSRC) in the UK, specifically as part of the building market transformation project.[4] A public access version was made available by way of the internet[5] and this has attracted significant interest from academics, industry and government departments and agencies associated with the construction sector.

2. LIFE-CYCLE IDEAS IN AN ENERGY CONTEXT

2.1. The evolution of energy analysis

In order to determine the 'primary energy'[2] inputs needed to produce a given artefact or service, it is necessary to trace the flow of energy through the relevant industrial sector. This is based on the first law of thermodynamics—the principle of conservation of energy or the notion of an energy balance applied to the system.[3] The system boundary should strictly encompass the energy resource in the ground (for example, oil in wells or coal at mines). The process thus implies identification of feedback loops such as the 'embodied' energy requirements for materials and capital inputs. Different 'levels of repression' may be employed, depending on the extent to which feedback loops are accounted for, or the degree of accuracy required.[3,6,7] A study can be completed with up to four levels of analysis.[6] Undertaking a study at level 4 regression would be the most accurate, but it would necessarily be costly in time and financial terms. In a case where similar materials or devices were to be studied, it is desirable to carry out the initial study with greatest rigour (level 4 regression). Subsequently, a more practical choice of regression level could be made depending on the accuracy required, perhaps level 2 or 3. This approach can be used to determine the least energy-intensive industrial process from among a number of alternative options.

Energy analysis has been widely used since the first oil crisis of the early 1970s.[7] There are several different methods of energy analysis, the principal ones being statistical analysis, input/output table analysis and process analysis.[6,8–10]

The first method is limited by available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between different outputs from the same industry.[9]

Input/output table analysis, originally developed by economists,[3] can be utilised to determine indirect energy inputs and thereby provide a much better estimate of embodied energy. Many countries, including the UK, periodically produce inter-industry tabular datasets (one great table or matrix) depicting what each industrial category sells to and buys from other industries. Wassily Leontief (1906–1999) received the 1973 Nobel prize for economics for his work on the development of input/output methods and using them to analyse structural changes in the US economy. Such tables can be converted from monetary values to yield data on an energy basis. The sum of direct energies for a particular industry then adds up to the embodied energy in specific outputs (products) of that industry[6,8–10] presented in terms of what are commonly known as 'energy intensities' (kJ/£ of product in the case of the UK). Energy input/output table analysis is limited by the level of disaggregation (i.e. the number of rows and columns) in national input/output tables and by issues associated with allocation between multiple outputs from a particular industry (sometimes referred to as co-products).

Process energy analysis is the most detailed of the methods and is usually applied to a particular process or industry. It requires process flow charting using conventions originally adopted by the International Federation of Institutes of Advanced Studies in 1974–1975.[2,6,8–10] The application domains of these various methods overlap.

2.2. Introducing ecotoxicology: environmental life-cycle assessment

It is now widely recognised that, in order to evaluate the environmental consequences of a product or activity, the impact resulting from each stage of its life-cycle must be considered.[3] This has led to the development of a range of analytical techniques that now come under the 'umbrella' of environmental life-cycle assessment (LCA). One of the antecedents of this approach was energy analysis of the type described in section 2.1. In a full LCA, 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 'from cradle-to-grave'.[11,12] The aim of LCA is to identify opportunities for environmental improvement by detecting the areas with the most significant impacts. The methodology of LCA closely follows that developed for energy analysis,[6,12] but evaluates all the environmental burdens associated with a product or process over its whole life-cycle. This requires determination of a balance or budget for the raw materials and pollutant emissions (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate energy analysis. LCA is often geographically diverse, that is, the material inputs to a product may be drawn from any continent or geo-political region of the world.

The methodology of LCA was originally codified under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) at a series of workshops in the early 1990s.[11,12] This framework subsequently formed the basis of the International Organization for Standardization (ISO) 14040 series of standards: ISO 14040–14044 (produced over the period 1997–2006). The four main stages of the ISO LCA framework are shown to follow a logical sequence of goal definition and scoping, inventory analysis, impact assessment and recommendations for improvement. There are many technical issues that need to be addressed during the conduct of a LCA,[3,7,11,12] including definition of system boundaries, quality of data available and the way the results are normalised.[3,7,12] The goal definition process is very important as part of the planning stage for a LCA. Gathering data for a life-cycle inventory (LCI) can be a time-consuming task, as many companies either view such data as confidential or simply do not have the sort of detailed records needed for a credible whole-life study. The impact assessment and interpretation stages are still undergoing refinement, although they have been codified in the ISO 14040–14044 standards (launched in 2000, but revised in 2006). Studies used to populate the inventory of carbon and energy database[5] reported here were, wherever possible, consistent with the LCA methodology recommended by ISO.

3. EMBODIED ENERGY AND CARBON

The oil crises of 1973/74 and 1979/81 heralded a great upsurge in concern for the need to conserve energy in industrialised nations. In the late 1970s, the notion of 'embodied energy' came to the fore, albeit in a variety of different guises. In mainstream energy analysis,[2,6] energy inputs to a system are aggregated from all subsidiary pathways to yield the total embodied energy or gross energy requirement (GER). It thus embraces the whole life-cycle concept subsequently utilised in LCA studies. van Gool[13] evaluated the minimum product ('process' plus 'embodied') energy required for different types of chemical process equipment, often termed 'unit operations'. A typical trade-off between process and embodied energy is illustrated in Fig. 1,[14] where a minimum total energy requirement can be observed that is somewhat greater than the thermodynamic minimum (based on the so-called Gibbs free energy (ΔG)[13]). The notion of embodied energy has subsequently been seen as a fundamental or intrinsic part of the total energy needed to construct and operate process or other equipment. Similarly, embodied energy (and carbon) is now equally viewed as being important in the context of buildings[6,15–19] and construction materials.[20]

The distinguished American systems ecologist Howard T. Odum[21,22] regarded the concept of embodied energy obtained from mainstream energy analysis as only a 'partitioned' variant of a broader property that he developed. Unusually, he took account of solar energy input into the economy, previously ignored by energy analysts. Another parameter related to the notion of embodied energy is that of 'net energy'[2]—the energy left after the energy requirements of extracting and refining the resource. It consequently represents the difference between the GER and the energy content of, for example, a fuel.[6] Many construction and consumer materials, including plastics and timber, may ultimately be burnt at the end of their product life

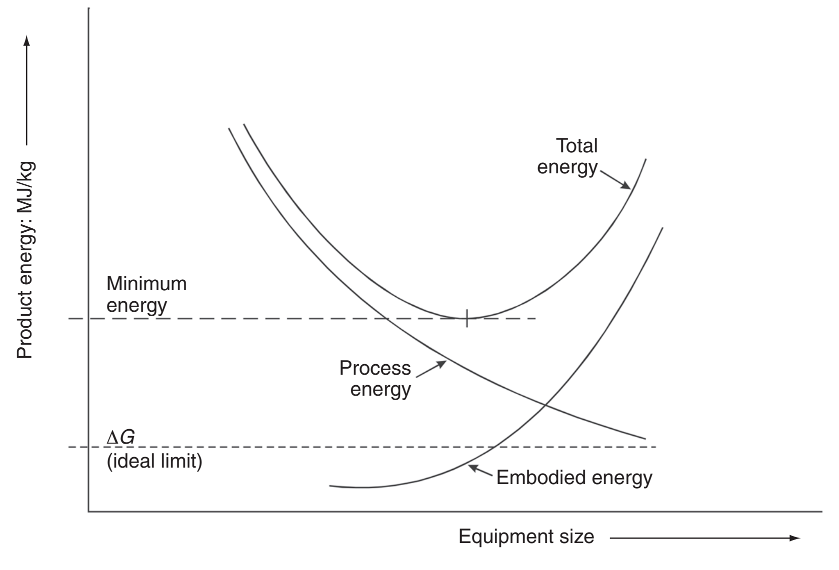

Fig. 1. Product (process + embodied) energy requirements associated with process equipment (Source: Hammond[14] adapted from van Gool[13])

and thereby yield useful heat. Net energy analysis can be viewed as a variant of mainstream energy analysis. Slesser[6] is sceptical about the use of this approach, except in the vitally important case of fuels and, perhaps, some other materials (such as those derived from biomass).

4. INVENTORY OF CARBON AND ENERGY

4.1. Methodology

The University of Bath's inventory of carbon and energy database[5] was developed to provide an open-access, reliable database for embodied energy and carbon associated with construction materials. The majority of the input data originated from secondary data resources. Indeed, the database was originally populated with materials stipulated in the CIBSE guide[23] with initial embodied energy values extracted from Boustead and Hancock's handbook.[10] The number of materials in the inventory was subsequently extended and it now contains over four hundred values of embodied energy and carbon, making it ideal for the analysis of embodied energy or carbon in whole buildings, products and systems. Given that the database contains a wide range of materials, it can also be used for many applications well beyond those just related to construction. Extension of the original database was based on embodied energy and carbon values obtained from published energy analysis and LCA studies. These were selected from the peer-reviewed literature on the basis of a defined methodology and a set of five criteria (outlined in section 4.2). A flow chart depicting the iterative process of refining the input data for the database is shown in Fig. 2. LCI and LCA inputs were extracted, as far as possible, from peer-reviewed quality journal papers, technical reports and monographs. An assessment was then made as to where the embodied energy coefficients fell on the spectrum from high to low quality. The embodied carbon in construction materials comes from two sources: fossil fuel inputs (directly related to the embodied energy) and that released, for example, from converting limestone to cement.[19]

The database was made publicly available via the internet and has attracted significant interest (Fig. 3). Subsequent feedback from professional users has played an important part in the choice of 'best values' for 'cradle-to-site' embodied energy and carbon from the range found in the literature. The variation in published data stems from differences in boundary definitions (including geographic origin), age of the data sources and rigour of the original LCAs. This type of professional feedback constituted a novel form of peer review in its own right. Methodological discussions took place with representatives of the materials sector (e.g. metals, particularly steel) industries regarding methods for allowing for the impact of recycling. Menzies *et al.*[20] used the database[5] in connection with their study on the embodied energy implications of steel as a building material. The present inventory[5] has also been employed by various developers of carbon and environmental footprint calculators,[24,25] including the Environment Agency's carbon calculator for construction. Discussions have taken place with a diverse range of construction organisations in the UK on the implication of the data[5] for their activities. In addition, Calkins[26] has incorporated (with the permission of the authors) several tables of values of embodied and carbon extracted from the inventory[5] into her recent book on materials for 'sustainable' construction sites.

4.2. Selection criteria

Values of embodied energy and carbon are clearly not precise when applied to a general category of material (such as aluminium, steel or timber). Each material will experience a variation in material form and specific type (especially true for timber). However, they can be considered to provide good benchmarks for use in determining the life-cycle performance of buildings and manufactured products. Researchers in the field will inevitably disagree about the selection of 'best' values. The choice of a single number, representative of a typical product, requires careful analysis of the available data sources, and is dependent upon the system boundaries for each particular study. It is not always possible to determine the boundary conditions employed by secondary data sources and, even with well-defined boundary conditions, a professional examination of all the data points must be undertaken. In many cases, data must be adjusted against predefined selection criteria (although typically leading to only minor revisions) in order to fit within a coherent framework.

Five criteria were applied for the selection of embodied energy and carbon values for the individual materials incorporated into the database. This ensured consistency of data within the inventory. The criteria were as follows

(*a*) *Compliance with approved methodologies/standards.* Preference was given to data sources that complied with

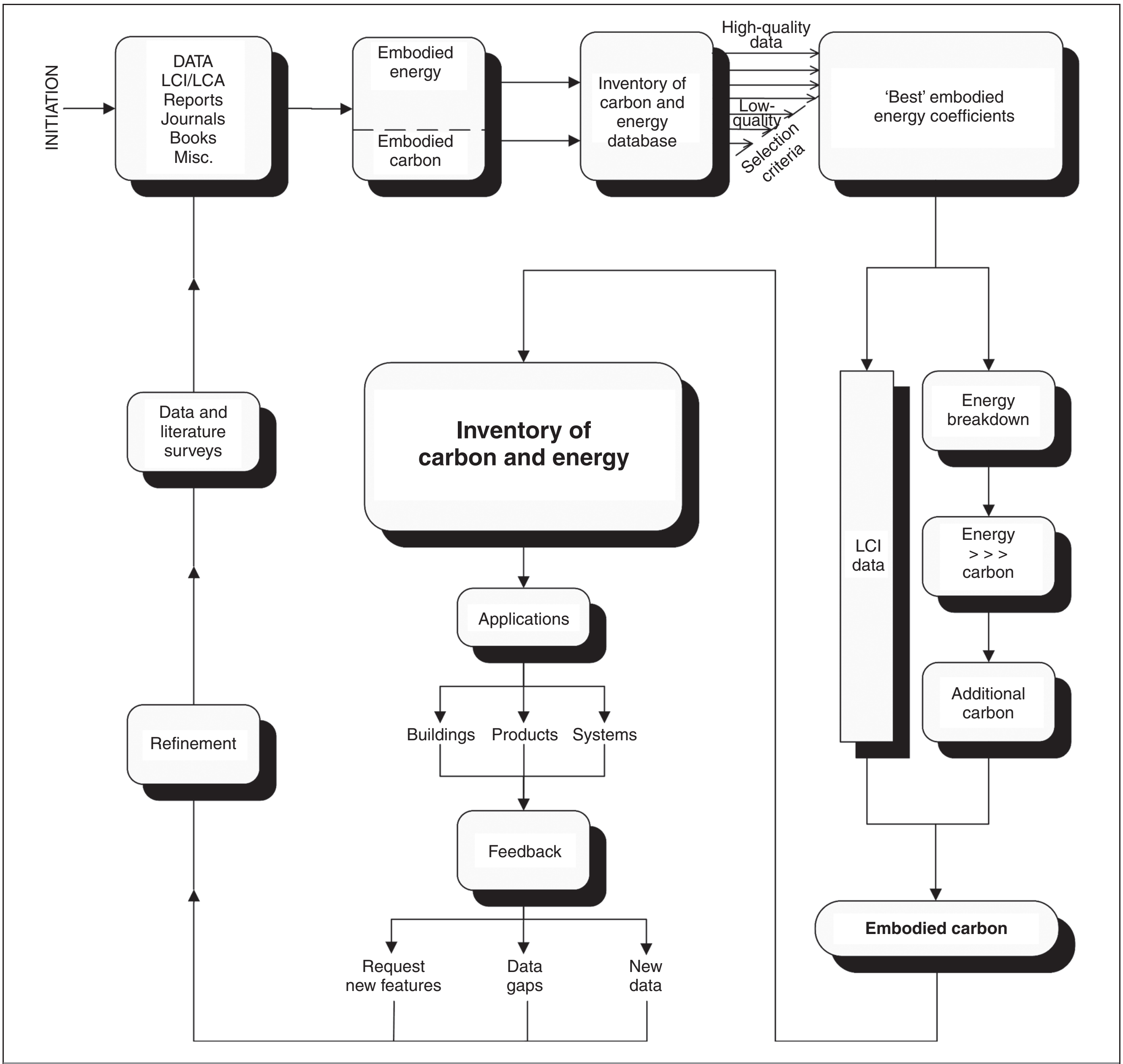

Fig. 2. Flow chart illustrating development of the inventory of carbon and energy[5]

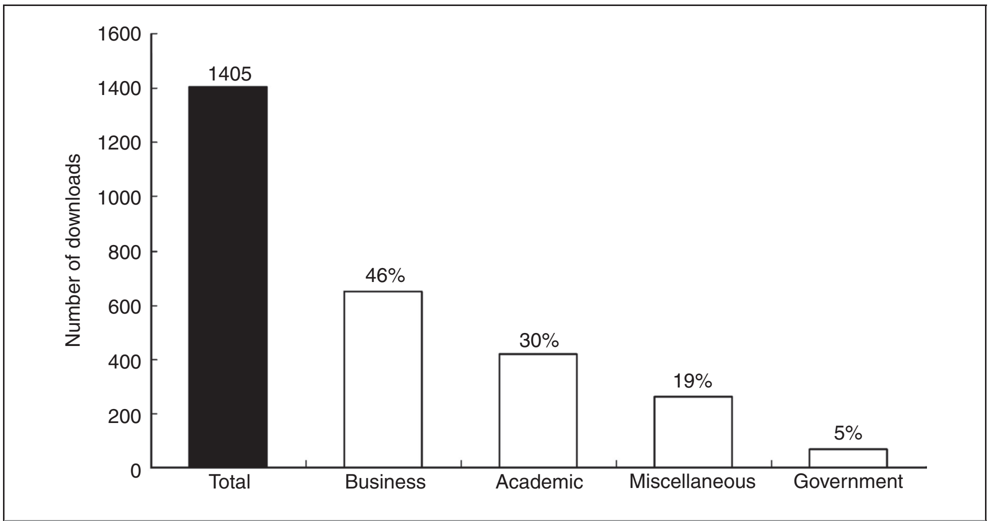

Fig. 3. Downloads from database[5] during 2007

accepted methodologies. In the case of modern data, an ideal study would be ISO 14040/44 compliant. However, even studies that comply with ISO standards can have wide ranging and significant differences in methodology; further selection criteria were therefore necessary to ensure data consistency. A recycled content, or cut-off approach, was preferred for the handling of (metals) recycling.

(*b*) *System boundaries.* System boundaries were adopted as appropriate for cradle-to-site embodiment. Feedstock energy was included only if it represented a permanent loss of valuable resources, such as fossil fuel use. For example, fossil fuels utilised as feedstocks, such as the petrochemicals used in the production of plastics, were included (although identified separately). However, the calorific value of timber was excluded. This approach is consistent with a number of published studies and methodologies, including the Building Research Establishment (BRE) methodology for environmental profiles of construction materials.[17] The effects of carbon sequestration (for example carbon sequestered during the growing of organic materials, i.e. timber) were considered but not integrated into the data (for justification of this decision see section 6). Non-fuel-related carbon emissions were accounted for (process-related emissions).

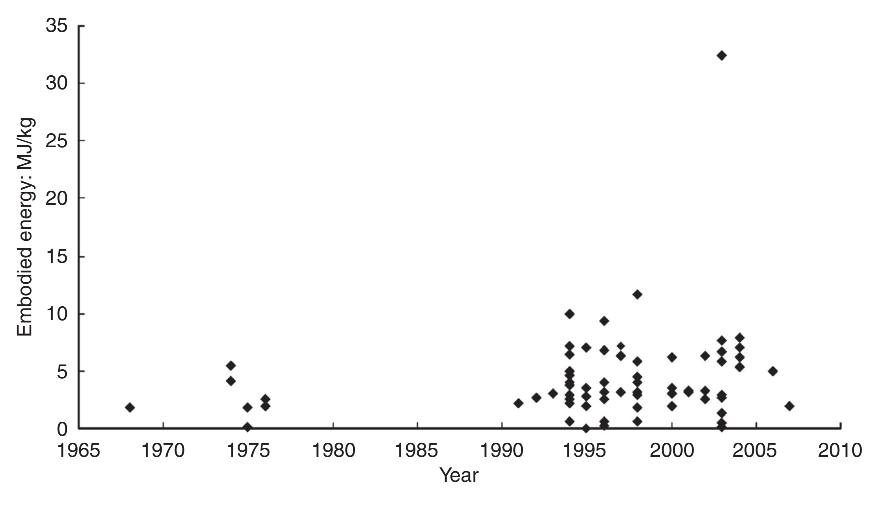

Fig. 4. Variation in embodied energy of clay and bricks over time

(*c*) *Origin (country) of data*. Ideally, the data incorporated in the database would have been restricted to that emanating from the British Isles. However, this was not feasible for most materials, and the best available *embodied energy* data from foreign sources had to be adopted (using, for example, European and worldwide averages). A much stronger preference was given to *embodied carbon* data from UK sources, due to national differences in fuel mixes and electricity generation.

(*d*) *Age of data*. Preference was given to modern sources of data (this was especially the case with embodied carbon); historical changes in fuel mix and carbon coefficients associated with electricity generation give rise to greater uncertainty in the embodied carbon values.

(*e*) *Embodied carbon*. Ideally, data would be obtained from a study that considered life-cycle carbon emissions, for example via a detailed LCA. However, there is often an absence of such data. In many cases substitute values therefore 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. Additional carbon (non-energy related) carbon was added as indicated in section 4.1 above (see also Fig. 2).

In addition to these selection criteria, the data primarily focused on construction materials. The embodied energy and carbon coefficients selected for the database were representative of typical materials employed in the UK market. In the case of metals, the values for virgin and recycled materials were first estimated, and then a recycling rate (and recycled content) was assumed for the metals typically used in the marketplace. This enabled an approximate value for embodied energy in industrial components to be determined. In order to ensure that the data were representative of typical products (taking timber as an example), UK consumption of various types of timber was applied to estimate a single 'representative' value that could be used in the absence of more detailed knowledge of the specific type of timber (plywood, chipboard, softwood, etc.). Finally, the aim was to select data that represented readily usable construction products, i.e. semi-fabricated components (sections, sheets, rods, etc. that are usable without further processing), rather than (immediately) unusable products such as steel ingot.

4.3. Capabilities of the inventory

A detailed material profile was created for the 30 main material categories (aggregates, aluminium, cement, etc.) adopted for the database. These material profiles contained the data required for use in real-world case studies

(*a*) information on the number of data points and statistical information on these sources (mean, standard deviation, etc.)
(*b*) explanatory information and comments
(*c*) scatter graphs (i.e. embodied energy versus timeline (year of data); see Fig. 4)
(*d*) fuel split
(*e*) historical (normalised) embodied carbon (Fig. 5)
(*f*) physical properties (density, thermal conductivity, etc.).

Over 250 data sources were used during the selection of embodied energy and carbon values for the inventory; a (simple) comparative embodied energy analysis for timber, steel and concrete, using data extracted from the literature,[27–32] is shown in Table 1. The full data range, from all of the 250 collected sources, displays a large scatter for all three materials. The selection of 'best' values is therefore uncertain. However, comparisons of the results obtained using the database[5] with those from commercial inventories provided an element of verification. This is presented by way of case studies in section 5. Embodied energy and carbon coefficients taken from the beta version v1.5[5] are shown in Table 2 for six important building materials: bricks, cement, concrete, glass, steel and timber.

Large quantities and types of cement, mortar and concrete are consumed in the construction of many buildings. Consequently, a simple sub-model was devised and incorporated into the database. This allows estimation of the embodied energy and carbon for cements, mortars and concretes according to their constituent materials. For example, in the case of cement, its

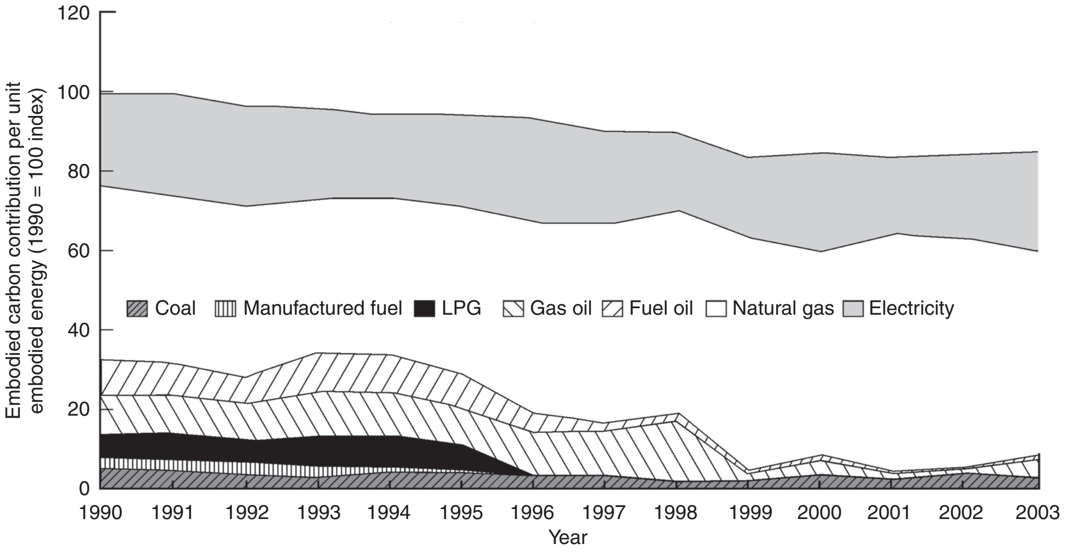

Fig. 5. Variation in embodied carbon per unit embodied energy for clay and bricks over time

embodied energy per kilogram (E) may be modelled using

$$E = (1 + M)(Cx_{\mathrm{C}} + Sx_{\mathrm{S}} + Ax_{\mathrm{A}} + Wx_{\mathrm{W}} + Rx_{\mathrm{R}} + Px_{\mathrm{P}} + O) + T \tag{1}$$

where M is the wastage factor (%), C, S, A, W, R and P are masses (in kg) of cement, sand, aggregate, water, cement replacements and plasticisers respectively, O is the operational energy and T the transport energy of the final product. The parameters x_{C}, x_{S}, x_{A}, x_{W}, x_{R} and x_{P} are the embodied energy coefficients (MJ/kg) for the six materials listed above. The results of this model displayed good agreement with results from the literature. The model provided flexibility and greater detail/accuracy when applying the inventory to real-world case studies.

5. CASE STUDIES

5.1. Background

Once the values of embodied energy and carbon for early versions of the database had been selected, it was possible to apply the data in practical situations. The embodied energy and carbon of typical dwellings were analysed by first determining the quantities of material consumed during construction (including waste). Eleven case studies were adopted from secondary sources (Table 3). In addition, three further case studies were devised from an analysis of bills of quantities for real-world buildings. All 14 case studies are presented in Table 3[15,33–37] for comparison. The focus was obviously to collect UK construction data, and twelve of these case studies were UK-based. However, two other studies were chosen from the USA. These were adopted in order to facilitate analysis of an energy-efficient house (comprehensive data for such a house were only available for a US property). A standard US house case study was also selected, from the same source, in order to allow comparison of an energy-efficient house and a standard house. The data sources given in Table 3 refer to the sources for material quantities consumed during construction. Subsequently, the database[5] was applied to estimate the embodied energy and carbon associated with these dwellings.

Selected source	Embodied energy: MJ/kg		
	Steel	Timber	Concrete
Alcorn *et al.*[27,28]	35·9	0·3–24·2	0·81–2
Eaton and Amato[29]	31	13–36	0·84–1·36
Franklin Associates[30]	44·6	14·9	–
West *et al.*[31]	32	5·7–10	–
Berge[32]	25	3–16	1
All database sources	6–81·8	0·3–61·3	0·07–23·9

Table 1. A comparative embodied energy analysis of timber, steel and concrete[27–32]

5.2. Results

The embodied energy associated with the 14 building case studies is presented in Fig. 6. Comparable results for embodied carbon are depicted in Fig. 7. Both sets of data were obtained using the database. The latter figure suggests that there is a factor of two variation in the embodied carbon of recent new-build dwellings.[4] In three specific cases, the original source provided independent estimates of the embodied energy; this provided a basis for verification of the present inventory.

(*a*) Case study CS-01-H.[33] This case study represents a typical English new-build house. The database provided embodied energy estimates that were 20% higher than the original source.

(*b*) Case study CS-03-H.[35] This case study represents a typical British house design of the type produced by a large builder. The basic construction is a double brick cavity wall with mineral wool insulation and aluminium window frames. The present inventory produced results that were 16% lower than the original source.

(*c*) Case study CS-13-EFA.[37] The Beddington zero energy development (BedZed) is the UK's largest mixed-use 'eco-community'. It was developed for the London Borough of

Material	Embodied energy: MJ/kg	Embodied carbon: kgC/kg
Bricks		
General	3	0·060
Limestone	0·85	–
Cement		
General	4·6 ± 2	0·226
Portland cement, wet kiln	5·9	0·248
Portland cement, semi-wet kiln	4·6	0·226
Portland cement, dry kiln	3·3	0·196
Portland cement, semi-dry kiln	3·5	0·202
Fibre cement	10·9	0·575
Mortar (1:3 cement:sand mix)	1·4	0·058
Mortar (1:4)	1·21	0·048
Mortar (1:0·5:4·5 cement:lime:sand mix)	1·37	0·053
Mortar (1:1:6 cement:lime:sand mix)	1·18	0·044
Mortar (1:2:9 cement:lime:sand mix)	1·09	0·039
Soil-cement	0·85	0·038
Concrete		
General (1:2:4 as used in construction of buildings under three storeys)	0·95	0·035
Precast concrete, cement:sand:aggregate	2	0·059
1:1:2 (high strength)	1·39	0·057
1:1·5:3 (used in floor slabs, columns and load-bearing structures)	1·11	0·043
1:2·5:5	0·84	0·030
1:3:6 (non-structural mass concrete)	0·77	0·026
1:4:8	0·69	0·022
Autoclaved aerated blocks (AACs)	3·5	0·076–0·102
Fibre-reinforced	7·75	0·123
Road and pavement	1·24	0·035
Road example	2085 MJ/m^2	51 kgC/m^2
Wood-wool reinforced	2·08	–
Glass		
General	15	0·232
Fibreglass (Glasswool)	28	0·417
Toughened	23·5	0·346
Steel		
General, 'typical' (42·3% recycled content)	24·4	0·482
General, primary	35·3	0·749
General, secondary	9·5	0·117
Bar & rod, 'typical' (42·3% recycled content)	24·6	0·466
Bar & rod, primary	36·4	0·730
Bar & rod, secondary	8·8	0·114
Engineering steel, secondary	13·1	0·185
Galvanised sheet, primary	39	0·768
Pipe, primary	34·4	0·736
Plate, primary	48·4	0·869
Section, 'typical' (42·3% recycled content)	25·4	0·485
Section, primary	36·8	0·757
Section, secondary	10	0·120
Sheet, primary	31·5	0·684
Wire	36	0·771
Stainless	56·7	1·676
Timber		
General	8·5	0·125
Glue laminated timber	12	–
Hardboard	16	0·234
MDF	11	0·161
Particle board	9·5	0·139
Plywood	15	0·221
Sawn hardwood	7·8	0·128
Sawn softwood	7·4	0·123
Veneer particleboard (furniture)	23	0·338

Table 2. Selected database[5] embodied energy and carbon coefficients

Sutton in 2002 and sold to the Peabody Trust. It was designed by Bill Dunster Architects with Bioregional Development Group[37] as the environmental consultants. Only renewable energy sources (making maximum use of passive solar gain) and small-scale combined heat and power (CHP) plants are used to meet the low operational energy needs of the development. It is therefore notionally 'carbon neutral', and has received multiple awards for

Case study	Data source	Dwelling type	Country
CS-01-H	Ireland[33]	House	UK
CS-02-H	Wiedmann *et al.*[34]	House	UK
CS-03-H	Harris[35]	House	UK
CS-04-H	Gartner and Smith[15]	House	UK
CS-05-H	Gartner and Smith[15]	House	UK
CS-06-H	Primary data	House	UK
CS-07-H	Primary data	House	UK
CS-08-H	Keoleian[36]	House	USA
CS-09-A	Primary data	Apartment	UK
CS-10-A	Gartner and Smith[15]	Apartment	UK
CS-11-A	Gartner and Smith[15]	Apartment	UK
CS-12-EFH	Keoleian[36]	Energy-efficient house	USA
CS-13-EFA	Lazarus[37]	Energy-efficient apartment	UK
CS-14-EFA	Wiedmann *et al.*[34]	Energy-efficient apartment	UK

Table 3. Details of the fourteen case study dwellings[15,33–37]

architectural design, energy performance and sustainability. Embodied energy estimates had previously been made by the BRE; the results from the ICE database[5] were only 1% higher than the BRE estimates.

Comparative estimates of embodied carbon values are quite rare within the construction literature. But here it was possible to contrast the results for the BedZed case study (CS-13-EFA)[37] with those obtained using the database.[5] The latter embodied carbon results were 10% lower than those estimated by BRE (see Lazarus *et al.*[37]). It would appear that the database provides estimates of embodied energy and carbon that are in reasonable agreement with the (albeit rather) limited available comparators.

Case study CS-06-H, derived from primary data, enables a breakdown of embodied energy and carbon by building material (Fig. 8). The figure shows that concrete and bricks make the greatest contribution to embodied energy, and an even larger contribution to embodied carbon. Concrete has a high embodied carbon per unit embodied energy, due to the conversion of limestone to cement during the production process. This results in extra non-fuel-related carbon emissions embodied in the derived material.

The mean embodied energy of the 14 real-world case studies (Fig. 6) was determined to be 5340 MJ/m^2 (habitable floor area) and the corresponding value of mean embodied carbon (see Fig. 7) was 110 kgC/m^2 (403 kgCO$_2$/m^2) ($CO^2 = [(12 + 32)/12] \times C \sim 3{\cdot}67$ equivalent carbon, on the basis of molecular weights). There is little in embodied energy and carbon between apartments and houses. However, two qualifying observations should be noted.

(*a*) The embodied energy/carbon figures were estimated per square metre of habitable floor area. This was defined to include all floor space enclosed by the front door. For houses, this included hallways. However, in the case of apartments, communal hallways and stairs (external to the apartment and not considered a living area) were excluded. Consequently, an apartment would require a smaller floor area to provide the same real living space as a house.

(*b*) The physical, or spatial, footprint of an apartment block is much smaller than that of a housing development. Although

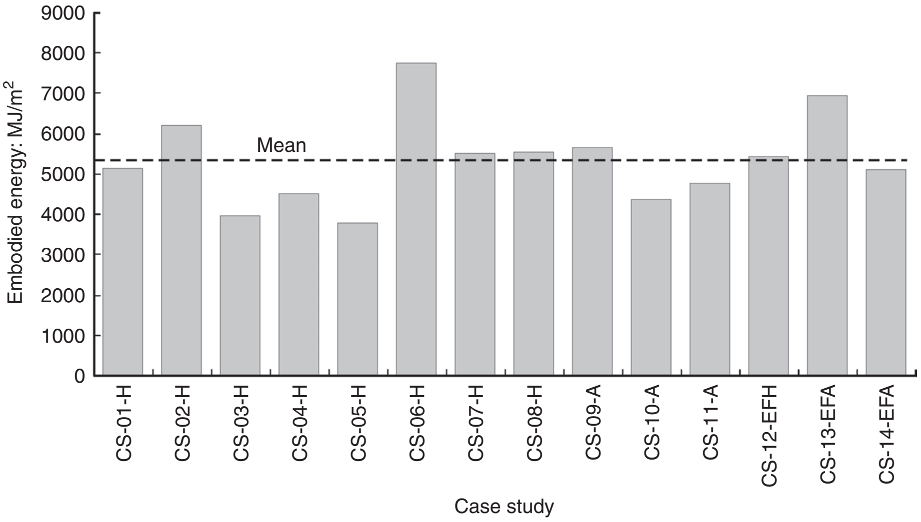

Fig. 6. Embodied energy of 14 case studies (Table 3)

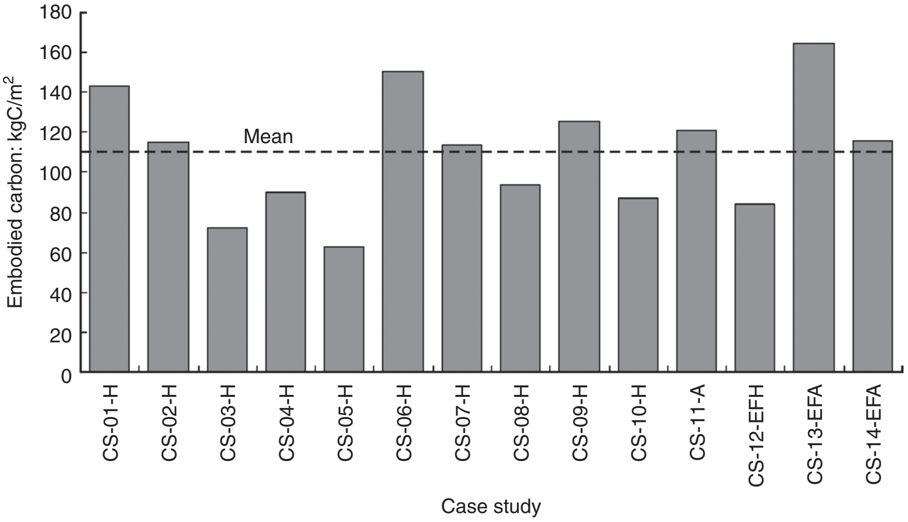

Fig. 7. Embodied carbon of 14 case studies (Table 3)

the construction of houses and apartment buildings accounts for similar embodied energy and carbon, those associated with external works (e.g. roads, connecting pathways), also need to be considered.

From analysis of several of the case studies, it was possible to estimate the energy and carbon requirement of external works. Case studies CS-06-H and CS-07-H (both housing schemes) were taken from the same development but one set of results included external works and the other did not (likewise for case studies CS-13-EFA and CS-14-EFA (BedZed low rise, energy-efficient apartments)). The external works were estimated to be within the embodied energy range 1844–2230 MJ/m^2 (habitable floor area) and embodied carbon range 36·8–48·2 kgC/m^2 (135–177 kgCO$_2$/m^2). However, with only two data points, it was difficult to estimate the accuracy of such results. In any case, few details on the developments themselves were available. However, for case study CS-06-H the external works included excavation and filling, concrete, walls, paving, kerbs, roads, fences, gates, painting, storm drainage and other ductwork. External works will be very site specific and as such it is perhaps best directly to compare buildings without external works. The impact of external works can then be managed (reduced) separately.

The above values would not apply to medium- and high-rise apartment blocks, due to the smaller building footprint per occupant. With regard to case study CS-09-A—a medium-rise apartment block (7 floors + 2 basement levels)—the external works constituted only 19·1 MJ/m^2 and 0·35 kgC/m^2, which could be regarded as negligible. Unfortunately, insufficient detail on this scheme was available and consequently it was not possible to determine whether this was a typical situation or if it was constructed in an area with a well-developed infrastructure. The latter might be considered more probable.

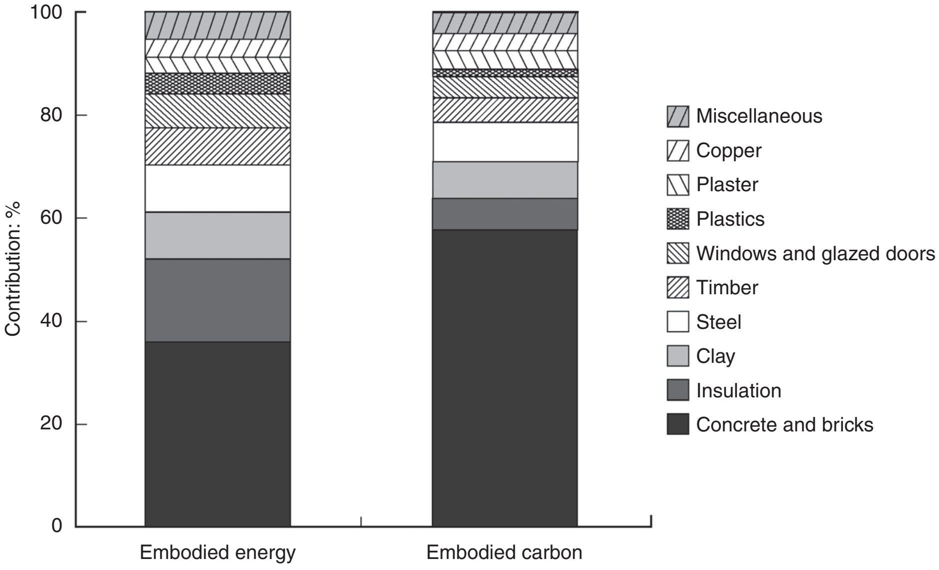

Fig. 8. Breakdown of embodied energy and carbon by material (case study CS-06-H; Table 3)

6. DISCUSSION

The UK construction industry consumes over 420 Mt of materials, 8 Mt of oil and releases over 29 Mt of carbon dioxide annually, including a significant quantity of new materials disposed of as waste. There is thus ample scope for energy reduction and carbon dioxide abatement within this industry. Embodied energy and carbon estimates, of the type provided by the database,[5] are one aspect in the process of evaluating the life-cycle impact of construction. It is also important to evaluate the operational lifetime and maintenance requirements of building materials to enable the construction of true low embodied energy and carbon buildings.

A simple and effective measure to reduce the environmental impact of construction is responsible materials management at the construction stage.[25] At this high-wastage stage, 11·68 m^3 of waste are produced per 100 m^2 of constructed floor area.[38] This gives rise to an embodied energy of 1197 MJ/m^2 floor area and an embodied carbon of 20·7 kgC/m^2 floor area, equalling 96 GJ of energy and 1·66 t of carbon for a typical 80 m^2 house in the UK. By contrast, the case studies suggest that, for such a typical UK dwelling, the embodied energy and carbon are 427 GJ and 8·77 tC respectively. Hence, waste accounts for approximately 22% of embodied construction energy and 19% of embodied carbon.

Embodied energy and embodied carbon coefficients should generally be considered tentatively. They carry a natural level of variation, as seen in Table 1. There are a number of reasons for this uncertainty. Methodological differences in calculations, boundary conditions and general assumptions are a common cause of natural variation. Take, for example, the steelmaking industry. The manufacture of primary steel creates a by-product, blast-furnace slag. Blast-furnace slag is considered to be a valuable commodity and therefore it is often argued that it should take some of the environmental burdens from the steelmaking process. The procedure of apportioning this impact is termed allocation. The burdens can either be allocated on a mass basis, economic basis, volumetric basis, by system expansion (avoided burdens), or any other reasonable methodology. However, here lies one of the fundamental causes of natural variation in embodied energy and embodied carbon. If the burden was allocated on a mass basis the results would be different from those on an economic basis. Such differences often make studies difficult to compare on a common basis. In fact, in this case, the variation in coefficients of embodied energy and embodied carbon of steel do not vary widely because of the allocation issues of blast-furnace slag. This is because of the relatively high embodied energy (24 GJ/t) and carbon of steel products per tonne and the low quantity of slag. By comparison, blast-furnace slag is estimated to have an embodied energy of 1·33 GJ/t when allocated on an economic basis; however some studies consider blast-furnace slag to be a waste product and therefore assign it zero embodied energy. However, the low impact on these results for steel does not imply that it is unimportant to other sectors. Blast-furnace slag is often used in the cement and concrete sector as an additive. The embodied energy (0·99 GJ/t) and carbon of concrete is much lower than that of steel (for each tonne of material) and therefore the implications of methodological choices for blast-furnace slag have a more noticeable effect on final results.

Concrete, an important building material, experiences a wide variation in values of embodied energy and embodied carbon. The previously discussed variations in coefficients for blast-furnace slag are not the only cause of differences for concrete. Concrete is a mixture of the constituent materials cement, sand, aggregates and water. It may also contain further additives such as plasticisers, fly ash or blast-furnace slag. Of these materials the most significant contributor, in terms of energy and carbon impacts, is cement. Consequently, one of the primary causes of variations in embodied energy and carbon of concrete is the cement content. For example, the difference in embodied energy and carbon between a 'typical' concrete mixture and a weak or strong mixture may be plus or minus 50%. Other variations occur because of uncertainties associated with the calculation method, technological differences (different types of cement kiln require different quantities of energy) and different fuel mixes. Furthermore, it is possible that errors have created data anomalies. Such uncertainties and variations are unfortunately a part of embodied energy and carbon assessments. The database has endeavoured to consider such variations in the selection of embodied energy and embodied carbon coefficients.

Embodied carbon analysis has many complications. Non-fuel-related carbon, for example, is released or absorbed by a small number of materials. Two of the most common are timber[39] and cement.[17] Researchers sometimes assign timber products a carbon credit, but the database[5] treats them in the same as any other material (i.e. only the emissions from fossil fuel combustion are accounted for in terms of embodied carbon). There were a number of reasons for this. In essence, more carbon must become 'locked-up' in the timber than is released as a result of its use and manufacture. This requires a fundamental understanding of the carbon cycle, which is still a developing science. Timber is a renewable resource, but this does not confer on it the attribute of sustainability.[40] In the present situation, where global tree populations are in decline, carbon credits are not appropriate unless a steady-state balance is achieved between consumption and replenishment.

7. CONCLUDING REMARKS

The development of an open-access, reliable database for embodied energy and carbon (dioxide) emissions associated with the construction industry has been described. The inventory of carbon and energy[5] lists almost 200 different materials selected from the peer-reviewed literature on the basis of a defined methodology and a set of five criteria. The ICE database was initially devised to be used by various research consortia supported under the carbon vision buildings programme in the UK.[4] However, it was made publicly available via a website, and this has attracted significant interest from industry, academia, government departments and agencies, and others. Feedback from users has played an important part in the choice of best values for cradle-to-site embodied energy and carbon from the range found in the literature. Scatter in the published data stems from differences in boundary definitions (including geographic origin), age of the data sources and rigour of the original LCAs.[3,19,20] Although principally directed towards UK construction, the material set included in the database is of quite wide application across the industrial sector.

Use of the inventory has been illustrated in this paper with 14 case studies of real-world, new-build dwellings. These domestic dwellings were analysed drawing from a range of literature sources and analysis of bills of quantities. The average embodied energy was determined to be 5340 MJ/m^2 and the average embodied carbon 110 kgC/m^2 (habitable floor area). The results of embodied energy and carbon of the 14 dwellings displayed up to a twofold difference; at first sight it appeared that there was no discernable difference in embodied energy and carbon of apartments and houses However, a more detailed examination of the data revealed the influence of external works (energy inputs for roads, connecting pathways and so on) on the results. Waste from construction provided a significant contribution to the embodied energy (22%) and carbon (19%) of a dwelling; responsible material usage should thus be encouraged. This is in line with a recent environmental footprint study by Eaton *et al.*[25] who found that materials and waste together accounted for some 38% of the impact in both urban and rural areas.

The tendency, both in Europe and the UK, over recent years has been to move in the direction of 'zero carbon' housing. This is certainly the case with the current version of the UK Building Regulations, part L. However, this notion only addresses the operational energy use and carbon dioxide emissions emanating from homes. Thormak[18] examined energy use in Swedish low-energy buildings and found that, for a one-family home over a life span of 50 years, embodied energy accounted for some 45% of the whole-life energy requirements. In the UK, Rawlinson and Weight[19] noted that embodied carbon is becoming more important in comparison with operational emissions as building codes tighten. They suggest that the embodied energy in domestic buildings might be ten times the annual operating energy requirements and in commercial buildings the ratio could be as high as 30 : 1. Estimates based on the database suggest an energy 'payback' period of 7–12 years. The database provides a means for researchers and practitioners to estimate the embodied energy and carbon in a variety of buildings, civil engineering structures and related applications. Hinnells *et al.*[4] argue, on the basis of data extracted from the ICE, that low-energy dwellings need not be any more intensive in embodied carbon terms than traditional homes. However, they note that this finding is sensitive to thermal mass, choice of materials (e.g. for flooring) and the amount of recycling. The database will be updated and extended from time-to-time, with new versions placed on the website[5] for the benefit of its users. This will be partly aimed at reducing uncertainties in existing material entries, as well as adding new ones.

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