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Embodied Carbon: The Concealed Impact of Residential Construction

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23.1 Introduction

Modern society is underpinned by a complex web of economic and social activities; commerce, transport, and leisure interweave providing support to not only sustain, but also enhance our way of life. In doing so we have created unprecedented environmental impacts and a burden that must be carried by our planet and our planet alone. Much of this burden is associated with cities, which appear to 'sustain' immense populations and satisfy the consumption activities of its many inhabitants. Unfortunately such activities normally require a quantity of natural resources well beyond the bio-capacity of its locality. For example, the 'Georgian' city of Bath, in the UK, has been estimated to have an environmental footprint 20 times larger than that of the neighboring land in the area (Doughty and Hammond, 2004). In modern times such trends in over-consumption are not uncommon. Urban immigration is expected to continue, and it is estimated that by the year 2025 three-quarters of the world's population will be living in a city (Rogers, 1997). This places greater burden on existing city infrastructure and potentially hinders progress toward true sustainability. It is therefore clear that widespread change is required, and without which we will quickly deplete the carrying capacity of our planet. It has already been estimated that we are currently exceeding the carry capacity of our planet by 20% (Loh, 2002). Clearly concerted action must be taken not only to limit but also to reverse potential long-term damage, and thus ensuring that we live on this planet in a sustainable manner.

Sustainable development can be defined as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Such aspirations require broad sweeping actions in order to ensure economic and social development, while securing environmental protection, across each sector of the economy. Each sector has its own part to

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play, and the building sector is a large energy-consuming and carbon-releasing sector, that is responsible for almost half of the UK's total energy consumption and carbon emissions (Brown et al., 2006). However, the additional embodied impact of construction must be considered. The construction industry requires the extraction of vast quantities of materials, resulting in the consumption of energy resources and the release of deleterious pollutant emissions to the biosphere. Each material has to be extracted from the Earth, then processed, and finally transported to its place of use. The energy consumed during these activities is therefore critically important for human development, but they also put at risk the quality and longer-term viability of the biosphere as a result of unwanted or 'second'-order effects. Many of these side effects of energy production and consumption give rise to resource uncertainties and potential environmental hazards on a local, regional, or national scale (Hammond, 2000). Energy and pollutant emissions, such as carbon dioxide (CO_2), may be regarded as being 'embodied' or associated with materials. Here embodied energy is 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 total of the energy consumed over the major part of the material supply chain or life cycle. 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 that 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. Embodied impacts are often forgotten and apparently concealed from view. With estimates of 7.6 to 10.8 million new dwellings to be constructed in the UK by the year 2050 (Palmer et al., 2006), the embodied or 'concealed' impact of such residential construction must be considered.

23.2 Method

23.2.1 Energy analysis

Energy analysis may be used to estimate the embodied energy of a product. Several differing methods of energy analysis have been developed (Boustead and Hancock, 1979; Champan, 1976; Hammond and Jones, 2008a; Slesser, 1978), the most significant being statistical analysis, input–output (I-O) analysis, process analysis, and hybrid analysis. The latter method bridges elements of I-O and process analyses in an attempt to remove some of the downfalls of each individual method (see for example Treloar et., al., 2000). The analysis of a product over its life cycle is a complex and involved activity. It requires the consideration of a large number of processes, and as such gaps often appear in the data. Studies often have different boundary conditions or cut-off points. In 1974 the International Federation of Institutes for Advanced Study (IFIAS) described the concept of 'level of regression' for analysis (IFIAS, 1974), which is a structured method of pruning a data tree. Figure. 23.1 displays this concept, indicating the relative contribution (in many cases) of each level to the total life cycle energy (the area of the triangle).

A first level of analysis includes only the direct energy consumption. It is normally expected that the results of a first-level regression will represent the majority of the life cycle energy. This does not, however, imply that a first-level analysis is sufficient on its own, as this is rarely the case. A second level of regression additionally considers energy that was required to manufacture feedstock materials (material production energy). It has been estimated that in many cases a second order of analysis can account for 90% of the total life cycle energy (Slesser, 1978). This is, however, merely a guideline, and deviation from this ‘rule’ does occur. While this may hold true for many building materials there will be many systems and activities that fall outside of this ‘rule of thumb.’ Analysis beyond this level is time consuming and hence studies of this order and above are rare. A third level of regression includes energy consumed while manufacturing capital equipment (energy required to manufacture machines). And finally the machines from the third level of analysis were themselves manufactured from other machines. As such a fourth level of regression exists.

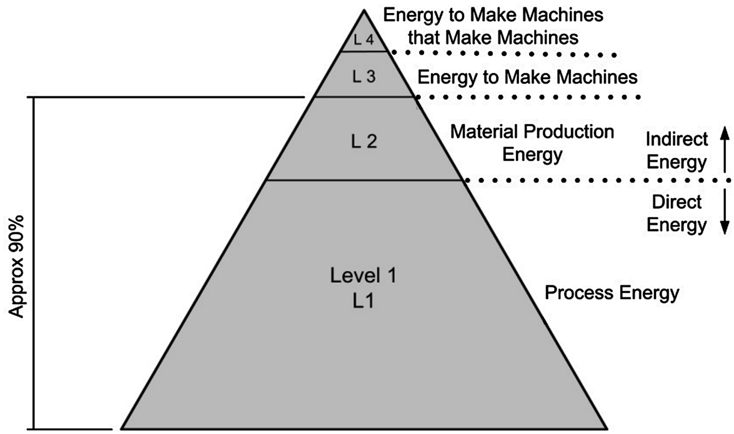

Fig. 23.1 Pyramid of representation.

In the case of steel production a first level of regression would include the energy consumed in direct production processes. This includes energy consumed directly in the blast furnace and fabrication processes. The second level of analysis would include energy that was consumed during the quarrying and mining of feedstock materials, such as the iron ore consumed during the steelmaking process. A third level of regression would include energy that was required to manufacture the blast furnace (capital equipment). And a fourth level would consider the energy that was required to manufacture the machines that manufactured the blast furnace. The contribution from a fourth level of analysis is usually minor and very time consuming to determine. However, if a fourth level of analysis was never undertaken its ‘insignificance’ could never be concluded with absolute certainty. As such in the first investigation of a system it is desirable to complete an energy analysis to the highest attainable level of regression that is possible.

23.2.2 Life cycle thinking

Energy analysis preceded environmental life cycle assessment (LCA) and it shares much of the same fundamental methodology (Hammond and Jones, 2008a). It is widely recognized 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. This has led to the development of ecotoxicology, a study of the harmful effects of releasing chemicals into the environment, and a range of analytical techniques that now come under the ‘umbrella’ of environmental LCA. 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.’ The aim of the LCA is often to identify opportunities for environmental improvement by detecting the areas with the most significant impacts. In the case of non-energy-consuming products, for example, buildings materials, the energy result of an environmental life cycle assessment can often be taken to be its ‘embodied energy.’ The latter is often confined within the boundaries of cradle to site to separate it from the operational energy. However, end-of-life impacts are inevitable and as such are often integrated into the boundaries of embodied energy studies. An LCA should ideally conform to international standards (ISO 14040, 2006a; ISO 14044, 2006b).

Determination of a product’s life cycle is invariably difficult; it requires the elementary understanding of material, energy, and emission flows across a broad spectrum. It is complicated by the fact that many such contributions are apparently hidden or ‘concealed’ from view. For example, if a consumer were to estimate the full impact of its activities they would need to consider a significant number of ‘concealed’ activities. It may be considered that many consumers live in a ‘virtual world’ in which they interact directly. This bears the bulk of their considerations. But what lies outside this world is an unavoidable and essential web of ancillary activities. The consumer is rarely exposed to such activities and as such they have little awareness of the resulting impacts. The marriage of the two worlds leads to the real, ‘actual world,’ as represented by Fig. 23.2. In the case of driving a car, as illustrated in Fig. 23.2, a consumer believes that he/she achieve 50 miles to the gallon (mpg) fuel economy (5.65 liters per 100 km). However, this does not bear the full environmental impact. There is an entire web of ancillary activities that must be considered, which includes each process leading up to the delivery of fuel into their vehicle in a usable format and at a convenient location. Progression up the production tree would reveal such activities as fuel pumping, delivery, refining, shipping, storage, oil well operations, drilling, and exploration activities. Once the impact of such activities is accounted for the actual (or ‘true’) fuel economy may be only 45 mpg (6.28 liters per 100 km). In reality the consumer may have only a modest direct influence on such ancillary activities. But were they to start considering them from a consequential point of view, then they might exhibit wider environmental concern than just taking into account

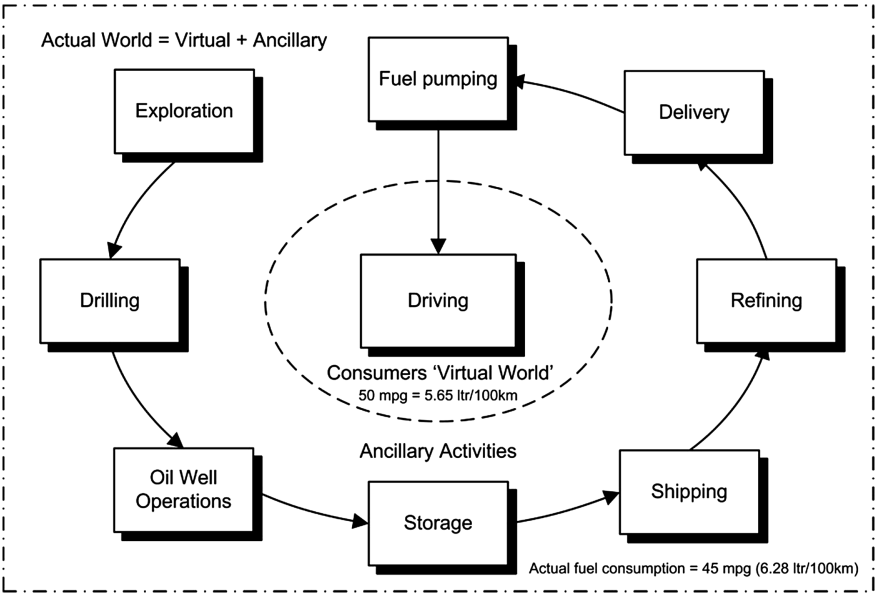

Fig. 23.2 Consumers' 'virtual world' versus the 'actual world' Adapted from: Hammond and Jones 2007.

the burden of their virtual world (i.e., their own interactions). Thus, they may become impelled to think about not only conserving energy, but conserving all that they undertake and consume.

23.2.3 The Inventory of Carbon and Energy (ICE)

In order to enable the determination of embodied energy and embodied carbon of buildings a robust, reliable, and transparent database is required. Initial research proved that finding such a database in the public domain would be difficult, this was especially true for embodied carbon (embodied carbon coefficients naturally carry a higher uncertainty than embodied energy as a result of variations in fuel mixes, electricity generation technologies, and process technologies). For these reasons the present authors at the University of Bath decided to develop their own database for a wide range of materials. This resulted in the creation of '*The Inventory of Carbon and Energy*' (ICE) (Hammond and Jones, 2008a and 2008b). This inventory contains the embodied energy and carbon of approximately 200 materials and has been released freely into the public domain. The ideal data would involve undertaking complete environmental LCA for each individual material, but with a likely material inventory amounting into the hundreds, and each LCA requiring up to 9 months to undertake, this was not considered feasible. For such reasons the data were sourced from the literature and may be considered to be a summary of the current knowledge base.

During the creation of ICE it was quickly discovered that estimating the embodied carbon from literature sources would present difficulties, even more so than any difficulties experienced for embodied energy. In the first instance it was determined that only 20% of the collected data was usable for estimating embodied carbon. The ideal resource was to obtain embodied carbon from a full-scale environmental LCA. But these were not normally available. For the majority of materials the embodied carbon was therefore estimated through calculation. When considering a material list in the region of 200 materials it is vital that an efficient and reliable method be applied in the conversion of embodied energy to embodied carbon. A generic emissions factor would be the quickest way to achieve this, and such methods are available in practice. However, there are a number of reasons for avoiding such methods. Application of a generic emissions factor (i.e., the average UK emissions per unit energy consumed) may offer acceptable results for a large number of materials. There are many cases when errors are induced. Possible causes of such errors include:

- A generic emissions factor neglects to consider that certain industries have fuel mixes that differ significantly from the average. As an example, worldwide aluminum production is known to utilize a high percentage of hydroelectricity. The net effect of this is to reduce the embodied carbon below that based on national emissions factors. Despite this the absolute embodied carbon of aluminum per kilogram remains high.
- Generic factors do not account for non-fuel-related emissions of individual materials (process emissions). Such emissions play an important role for several key building materials. In the manufacture of cement, for example, carbon dioxide is released into the atmosphere as a result of material processing. In this case it contributes in the region of 60% to the total embodied carbon; the remaining 40% is attributable to fuel-related carbon dioxide (Hammond and Jones, 2008a and 2008b). Cement is the largest process-related carbon dioxide emitter. Other materials that experience non-fuel-related emissions are glass and ceramics, the latter including clay and bricks.

Further errors may be induced as a result of the following:

- Embodied energy is a measure of primary energy and as such it is vital that the correct emissions factors are applied. Emissions factors for delivered electricity differ by an approximate factor of 3 with those converted into its primary energy equivalent.
- It is important to understand what the data include. Many of the traditional energy analysis studies are calculated via the gross calorific value (also known as the higher heating value). Environmental LCA results are often (although certainly not exclusively) calculated by net calorific value (also known as the lower heating value). In the case of embodied energy this could result in a 5–11% difference, although this should in theory have no effect on the embodied carbon results unless errors subject to the above misinterpretations have been induced. For example if carbon emissions factors for gross

calorific values were applied to embodied energy calculated by its net calorific value.

There is additionally the complication of organic materials, materials such as timber which absorbs carbon dioxide during the growth phase of trees. Whether to include or exclude this factor is not a simple matter. The authors of this chapter prefer to exclude the sequestered carbon dioxide from their data until such a time that timber demonstrates to be operating in a globally sustainable manner (see Amato, 1996; Eaton and Amato, 1998; Hammond and Jones, 2008a). At present this is not the case, and consequently global tree populations are in decline.

After consideration of the above matters, a methodology for converting embodied energy to embodied carbon was developed. The method has proven to be effective and reliable. It represents a large improvement over industry-wide (generic) emissions factors and is displayed in Fig. 23.3 below.

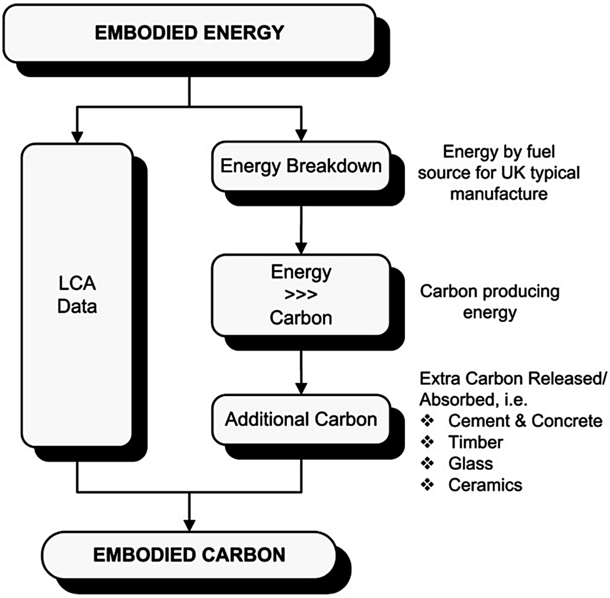

Fig. 23.3 Embodied energy to embodied carbon.

Once the embodied energy has been determined the process of converting to embodied carbon begins. In the absence of LCA results containing embodied carbon the present method was applied (see Fig. 23.3). First it was necessary to estimate the embodied energy breakdown by fuel type. To achieve this, the fuel mix used in the most relevant industrial sector was applied. Appropriate emissions factors were then applied to obtain the fuel-related carbon dioxide emissions. Once the additional carbon dioxide release has been determined the total embodied carbon had been estimated from the sum of these and fuel-based emissions.

23.2.4 System boundaries

The system boundaries for this study were adopted as appropriate for 'cradle-to-site' studies. Feedstock energy was included only if it represented a permanent loss of valuable resources, such as fossil fuel use. Thus, fossil fuels utilized as feedstock for the petro-chemicals used in the production of plastics were included (although identified separately). However, the calorific value of timber has been excluded. This approach is consistent with a number of published studies and methodologies, including the BRE methodology for environmental profiles (Howard et al., 1999). The effects of carbon sequestration (for example, in the case of timber) were considered, but not integrated into the data. Non-fuel-related carbon emissions have been accounted for (process-related emissions) and a recycled content, or cut-off approach, was preferred for the handling of recycling (i.e., metals).

23.3 Results

23.3.1 ICE domestic building model

The ICE database (Hammond and Jones, 2008a and 2008b) has been applied to real-world applications. A number of case study buildings were collected from both domestic (Hammond and Jones, 2007) and non-domestic building sectors, not only from the literature-based resources but also utilizing primary case studies. It was not always possible to determine a sufficient specification of the buildings under analysis. However, building specification has profound effects upon results of embodied energy and carbon. Therefore, to enable embodied estimates for bespoke buildings to be determined, an ICE Domestic Building Model was developed. The model operates with the following variable parameters:

- Building type: detached, semi-detached, terraced, bungalow, or low-rise apartment
- Fabric reconstruction: a range of predetermined walls, floors, and roofs allow a building to be reconstructed to specified thermal standards
- Total floor area and height of each floor
- Window type and area
- Finishes: floor finishes (carpets, vinyl, laminate, timber floorboards), wall finishes (paint, wallpaper, tiles), and window furnishes (a range of curtains and blinds)
- Garage (single, double) and driveway (concrete, gravel , brick, tarmac)
- Housing development impact (connecting roads, pathways, walls, etc.)
- Conservatory (small, medium, large)
- Grid electricity carbon coefficient and electricity generation efficiency

The model utilized flow charts, one of which is displayed as a schematic in Fig. 23.4. This flow chart may be used along with appropriate coefficients to estimate the output of the ICE Domestic Building Model. Figure 23.4 depicts the simplified representation of a semi-detached building. In contrast, the full ICE

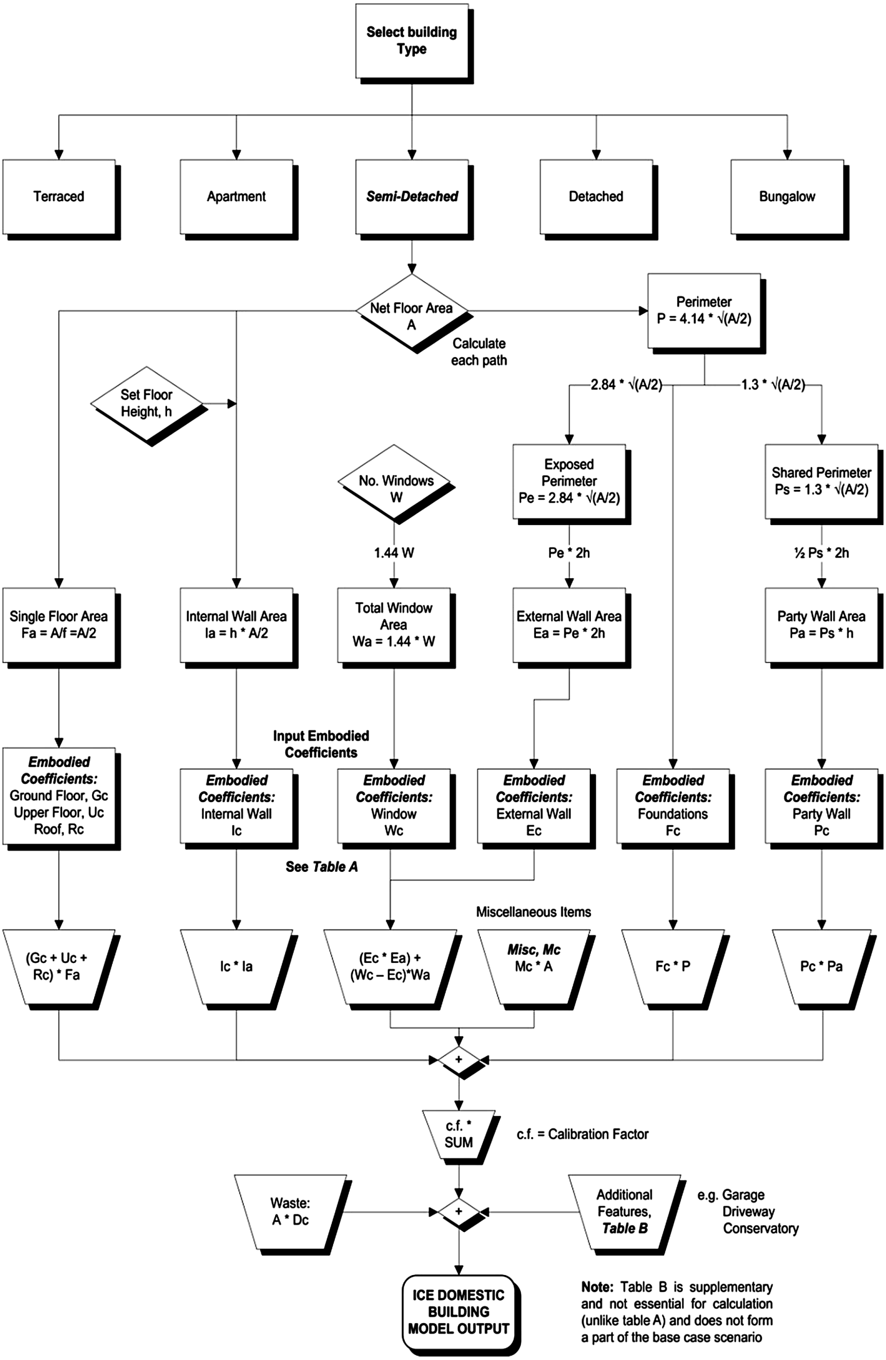

Fig. 23.4 Schematic of the ICE Domestic Building Model.

Domestic Building Model retains higher detail, ease of use, and dynamic assumptions, although the simplified ICE Flow Charts produce results with good proximity of the full ICE Domestic Building Model. The full model is tied into the generation efficiency and the carbon coefficient of electricity as a variable parameter. To calculate the embodied energy and embodied carbon it is required to run through the flow chart twice, once for embodied energy and once for embodied carbon. Two tables accompany the flow charts (not included in whole herein); 'Table A' contains embodied energy and embodied carbon coefficients for construction elements, such as walls, floors, and roofs and a miscellaneous addition (which accounts for kitchens, bathrooms, and toilets as a function of floor area). A sample of embodied coefficients (from 'Table A') is shown in Table 23.1. These coefficients have been selected for a building that meets the 2006 (Part L) UK building regulations. 'Table B' contains embodied energy and carbon coefficients of extra building features, for example, driveway, garage, conservatory, energy to construct a housing development (i.e., connecting roads and pathways, etc.). 'Table A' is integral and must be applied, whereas 'Table B' is optional but is required to model the impacts of additional features such as a garage, driveway, and conservatory. Application of Table 23.1 to the flowchart (in place of 'Table A') allows an example building to be analyzed. In the case of a 100 m^2 semi-detached building with a floor height of 2.5 m and 14 windows (1.2m × 1.2m), for example, the embodied energy was estimated at 533 GJ and embodied carbon at 39.6 tonnes CO_2.

Table 23.1 Sample coefficients of embodied energy and embodied carbon.

Construction element	Embodied energy (– MJ/m^2)	Embodied carbon (–$kgCO_2/m^2$)
Ground floor, Gc	781	86.0
Upper floor, Uc	453	23.3
Roof, Rc	554	37.1
Internal wall, Ic	290	26.3
uPVC window, Wc	2,300	112.2
External wall, Ec	782	64.4
Foundations, Fc	867	103.0
Party wall, Pc	483	45.2
Miscellaneous, Mc	350	25.0
Waste, Dc	1,200	76.0
Calibration factor, c.f.	1.3	1.3

23.3.2 Benchmark results

Hammond and Jones (2007) analyzed semi-detached houses and provided benchmark results by building floor area for this single building type only. Results from the ICE Domestic Building Model have been analyzed to create benchmarks of embodied energy and embodied carbon for a broader range of dwelling types. The work has now been extended to include detached and terraced houses, bungalows (detached), and apartments (three storey blocks and four storey blocks). The results may be used to estimate the embodied impacts of residential buildings by floor area and building type. It is hoped that these results may be used by building professionals to determine a baseline, and therefore offer benchmarks for future carbon mitigation strategies.

The base case buildings were assumed to have a basic building specification. Each property conforms to 2006 UK building regulations with uPVC double-glazed windows. There were no additional features such as garages, driveways, or conservatories. The benchmarks therefore only estimate the embodied energy and carbon of the building itself and include no external additions. They allow the total embodied energy and total embodied carbon to be estimated based on the floor area and property type. Figure 23.5 shows the benchmark results for embodied energy and Fig. 23.6 for embodied carbon in the form of contour charts or plots.

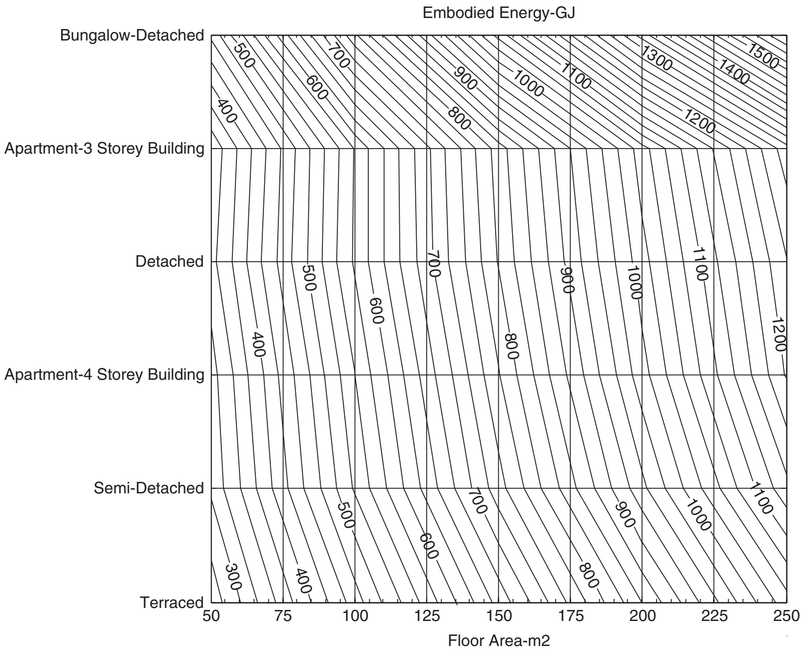

Fig. 23.5 Embodied energy guidelines for domestic buildings.

The uncertainty associated with these benchmarks was estimated to be ±30%. Using these charts a detached house of 150 m^2 was predicted to have an embodied energy of 800 GJ (see Fig. 23.5) and an embodied carbon of 59 tonnes CO_2 (see Fig. 23.6). Likewise a 100 m^2 semi-detached property was estimated at 530 GJ and 39.5 tonnes CO_2, which is comparable to the previous estimate (from the flow chart). These results may be used to estimate the embodied impacts of average

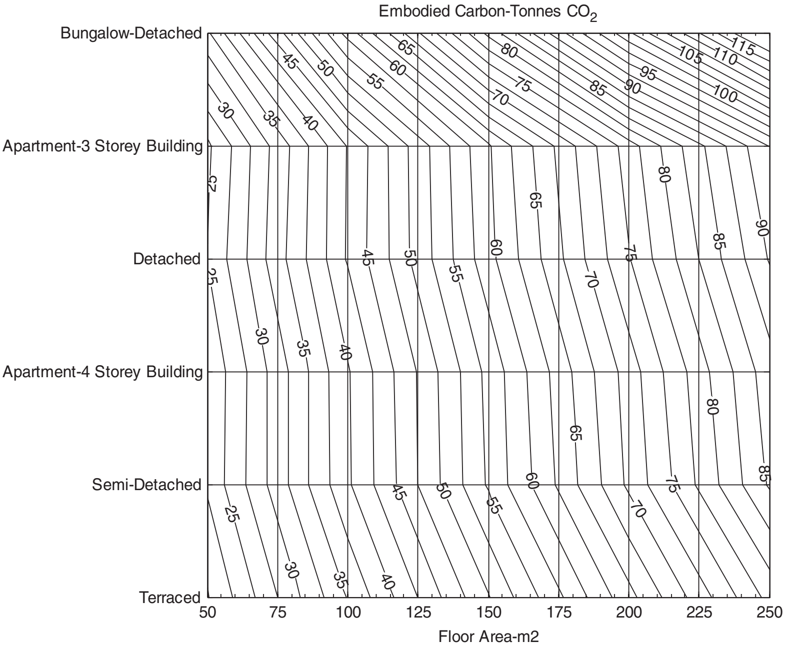

Fig. 23.6 Embodied carbon guidelines for domestic buildings.

UK dwellings. To do this the average floor area of each building type would be required. For English buildings (UK-wide data are not available) the average floor area of each newly built property type was obtained (ODPM, 2001). The benchmark results were then applied to the average floor areas to determine the typical embodied energy and carbon of each building type. These results are displayed in Table 23.2.

The weighted average embodied energy of a newly built property in the UK was estimated to be 480 GJ and its embodied carbon 36 tonnes CO_2 (Table 23.2). Average apartments and terraced properties were estimated to have similar impacts and were the lowest impact options; however, comparatively the terraced building was larger with an additional 18 m^2 floor area. An average semi-detached property was estimated to have a 30–35% higher impact than an average terraced or apartment building, but was only 7% larger in floor area than the former. Bungalows were determined to have a particularly high impact per unit floor area, especially in comparison to the alternative options. An average bungalow of 76 m^2 was estimated to have an embodied energy only 10% lower than an average detached house of 125 m^2, although the latter benefits from a 65% larger floor area.

These results demonstrate the importance of both floor area and building type in terms of total embodied energy and carbon. It is interesting to compare these building types by how well (environmentally) they perform to provide a set floor area. The results from Table 23.2 were therefore normalized to per unit floor area, as are displayed in Table 23.3. The results in Table 23.3 suggest that (detached) bungalows have the largest impact per unit living area and by a fair margin. In the case of a bungalow this was mainly attributed to the property having a single floor at ground level. Such buildings require a larger area of foundations and roofing than any other building type, consequentially resulting in a high embodied energy. Low-rise apartment blocks were, additionally, considered to have a high impact per unit floor area. But there are two other factors working in favor of apartment-style buildings. First of all the floor area is defined as the total floor area enclosed by the walls of the property. Low-rise apartment blocks in the UK require a level of communal space, such as stairways or hallways, which is dependent on the size of the building and not included in the floor area of the apartment. However, the embodied energy and carbon were estimated for the entire building and therefore each property takes its share of these burden. This implies that an apartment of area 80 m^2 is in effect more 'spacious' than a semi-detached or detached building of the same floor area. While this seems implausible, it is the absence of internal stairways and (possibly) reduced hallways that increases the comparative spaciousness of these properties. Furthermore it can be expected that a property arranged over a single level would utilize space more efficiently than one over multiple levels.

Table 23.2 Embodied energy and carbon of typical newly built English dwellings.

Building type	Percentage of new properties	Average floor area (–m^2)	Embodied energy (GJ)	Embodied carbon (tonnes CO_2)
Apartment *(three storey building)*	24	50	330	24
Apartment *(four storey building)*			315	23
Terraced	20	68	330	25
Semi-detached	15	73	410	31
Bungalow *(detached)*	11	76	620	47
Detached	31	125	690	51
Weighted average	100	83	480	36

The second factor is from the reduced physical footprint of the building. These buildings take up less space, not only of the building, but normally the surrounding landscape. Semi-detached, detached, and bungalows are likely to have their own gardens, driveways, and pathways, they may have a garage and further landscaping. In comparison apartment-style buildings could have communal gardens and perhaps individual garages, although a block of garages is considered to be a more efficient arrangement than the same quantity of separate garages. The combined effect may be to save embodied energy and carbon of these ‘external features’ whilst offering a more ‘spacious’ property for the same floor area. That said, low-rise apartment-style buildings which are well spaced apart (not within a single block), and with spacious surroundings (gardens), may negate any expected external works savings. The external works include the impacts from excavation and filling, concrete, walls, paving, kerbs, roads, fences, gates, painting, storm drainage, and other duct works (see Hammond and Jones, 2008a).

Table 23.3 Normalized embodied energy and carbon of typical newly built UK dwellings by floor area

Building type	Average floor area (–m^2)	Embodied energy (GJ/m^2)	Embodied carbon (kgCO$_2$/m^2)
Apartment *(three storey building)*	50	6.6	480
Apartment *(four storey building)*		6.3	460
Terraced	68	4.9	370
Semi-detached	73	5.6	425
Bungalow *(detached)*	76	8.2	620
Detached	125	5.5	410
Weighted average	83	5.8	435

External works were estimated to be within the embodied energy range 1844–2230 MJ/m^2 (habitable floor area) and embodied carbon range 135–177 kgCO$_2$/m^2. However, with only two data points, it was difficult to estimate the accuracy of such results. In comparison with Table 23.3 external works represent a significant extra impact. When applied to the average semi-detached house the embodied carbon would increase from 425 to 581 kgCO$_2$/m^2. Given its floor area of 73 m^2, the embodied carbon increases from 31 tonnes CO$_2$ to 42 tonnes kgCO$_2$, representing an increase of over 35%. For a complete and fair analysis, the impact of external works must obviously be considered on a case-by-case basis. However, these results indicate that further analysis of external works would be desirable.

23.4 Discussion

While it is important to consider the embodied impacts of new building designs this must not be the sole factor for selection. A full analysis of operational energy should be completed. Energy in operation presently has the largest impact over the lifetime of a property. With the current benchmarks it was estimated that the energy in operation would overtake the initial embodied energy within 7 years and the carbon would take almost 12 years (see Hammond and Jones, 2007 and 2008a). It was also discovered that the inclusion of a single garage, a driveway, a conservatory, and the contribution of a housing development would increase this to 12 years for energy and 19 years for carbon. This is a significant duration, especially considering the design life of such a house which may be 60 years, and over this time it will require further embodied energy and carbon inputs during refurbishment and routine maintenance. It is expected that this duration will increase over time as UK building regulations become more energy efficient and lower carbon. It is anticipated that by the year 2016 all newly built English dwellings will be zero carbon in operation. If this occurs embodied carbon will become the predominant life cycle impact.

These results demonstrate that the time required for the energy in operation to overtake the embodied energy is quicker than for embodied carbon, the climate change marker. This was mainly attributed to the release of non-fuel-related carbon into the atmosphere (as a result of manufacturing processes); cement is the key material with this additional release. The carbon in operation has originated from predominantly natural gas and electricity, which do not experience the same additional carbon releases. The net effect of this is to increase the relative size of the embodied carbon in comparison with operational carbon. This extends the duration for the operational carbon to overtake the embodied carbon. While it may be expected that organic materials, such as timber may negate this effect on a whole building, the chosen methodology did not allow for such carbon sequestration. The authors choose to neglect the effects of timber carbon sequestration until such a time that timber is utilized in a globally sustainable manner (consumption equals replenishment) and that the science of carbon pools and the carbon cycle is better understood.

Normalized results per unit floor area may appear particularly attractive as benchmarks: they are simple to apply and easy to understand. However, it must be noted that the relationship of embodied carbon to floor area is not linear, and therefore buildings of different sizes (but same type) normalize to give very different results. For example, the ‘typical’ semi-detached building in Table 23.3 was estimated to require 425 $kgCO_2/m^2$ based on its 73 m^2 floor area. However, using the same benchmarks, a semi-detached property of 125 m^2 is estimated to have an embodied carbon of 47.5 tonnes CO_2 in total (Fig. 23.6). This normalizes to 380 $kgCO_2/m^2$, which is a significantly different (lower) value. Normalized results may therefore be unsuitable for domestic benchmarks. It would be preferential, and is recommended, that a model or formulae be applied (such as the results from Figs. 23.5 and 23.6, or the use of an equation [as in Hammond and Jones, 2007]). Normalized results of embodied energy and carbon may be particularly unsuitable for environmental policy making and legislation. The above analysis suggests that larger properties experience lower embodied carbon per unit floor area. If legislation required all semi-detached buildings to have an embodied carbon (per unit floor area) below a set threshold the easiest way to achieve this would be to increase its total floor area. This is naturally counterproductive and would increase the total embodied carbon of the property as a result of the larger floor area. In light of this, it is recommended that any environmental policy or legislation should set absolute benchmarks of embodied energy and carbon (such as Table 23.2,

Fig. 23.5, or Fig. 23.6) rather than normalized benchmarks (such as Table 23.3). Despite this recommendation valuable lessons can still be learnt from normalized embodied carbon results.

The study of a product or building over its life cycle 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. This unfortunately makes the improvement process complex, in that many businesses and economies are involved in the manufacture of a product. Therefore to achieve low or zero environmental burdens will require concerted efforts over a wide domain. Each business, nation, and individual must contribute in an altruistic manner, through acts of selfless wellbeing, rather than the current trend of egoism. Invariably such action may be too idealistic and is therefore unlikely to be achieved. But it may be encouraged with accepted international regulation and frameworks, providing examples of good practice and sustainable development.

23.5 Conclusions

The construction industry requires the extraction of vast quantities of materials, resulting in the consumption of energy resources and the release of deleterious pollutant emissions to the biosphere. Energy and pollutant emissions, such as carbon dioxide (CO_2), may be regarded as being 'embodied' or associated with materials. Here the embodied energy was viewed as the quantity of energy required to extract, process, and supply the material under consideration. Likewise the emission of energy-related pollutants, like CO_2 that 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. With an estimated 7.6–10.8 million new dwellings to be constructed in the UK by the year 2050 (Palmer et al., 2006), the embodied impact of such construction must be considered.

The ICE database (Hammond and Jones, 2008a and 2008b) has been applied to both domestic and non-domestic buildings. Forty case study buildings were collected for domestic buildings (Hammond and Jones, 2007). These were primarily extracted from a variety of literature resource, including several primary case studies. These resources did not always contain sufficient detail on the building specification and therefore the *ICE Domestic Building Model* was created. The model operates in a bottom-up manner; therefore allowing buildings to be reconstructed through the selection of walls, floors, roofs, etc. Application of this model and comparison with the case study results allowed initial embodied energy and carbon benchmarks to be created for semi-detached, detached, terraced, bungalow (detached), and apartment (three storey block and four storey block) dwellings. Benchmarks were created for 'typical' English buildings of each classification. The average detached property was determined to have the highest embodied impact; however, they also had by far the largest floor area (125 m^2). An average newly built (detached) bungalow was estimated to have a slightly lower impact but with a much reduced floor area (76 m^2) they were determined to be an inefficient method of construction. Semi-detached buildings (73 m^2) have significantly lower embodied impact and terraced buildings (68 m^2) lowest yet. Apartments were determined to have the lowest impact, but only provided an average floor area of 50 m^2.

Normalized results per unit floor area may appear particularly attractive to apply as benchmarks, they are simple to apply and easy to understand. However, it must be noted that the relationship of embodied carbon to floor area is not linear, and therefore buildings of different sizes (but same type) normalize to give very different results. Normalized results of embodied energy and carbon may be particularly unsuitable for environmental policy making and legislation. Analysis suggested that larger properties experience lower embodied carbon per unit floor area. Therefore if regulation required all semi-detached buildings (for example) to have an embodied carbon below a specified threshold (per unit floor area) the easiest way to achieve this would be to increase its total floor area. This would, however, increase the total embodied carbon of the property. In light of this it was recommended that any environmental policy or legislation should set absolute benchmarks of embodied energy and carbon (such as Fig. 23.5, Fig 23.6, or Table 23.2) rather than normalized benchmarks (such as Table 23.3). Such regulation would allow society to reduce the total (embodied plus operational) energy and carbon impact of residential construction, thereby minimizing 'concealed' impacts.

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