Engineering Sustainability
Volume 165 Issue ES4

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ice | proceedings

Proceedings of the Institution of Civil Engineers
Engineering Sustainability 165 December 2012 Issue ES4
Pages 281–292 http://dx.doi.org/10.1680/ensu.11.00005
Paper 1100005
Received 16/02/2011 Accepted 22/09/2011
Published online 31/07/2012
Keywords: recycling & reuse of materials/service life/sustainability

ice
Institution of Civil Engineers
publishing

Carbon dioxide reduction in the building life cycle: a critical review

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The construction industry is known to be a major contributor to environmental pressures due to its high energy consumption and carbon dioxide generation. The growing amount of carbon dioxide emissions over buildings' life cycles has prompted academics and professionals to initiate various studies relating to this problem. Researchers have been exploring carbon dioxide reduction methods for each phase of the building life cycle – from planning and design, materials production, materials distribution and construction process, maintenance and renovation, deconstruction and disposal, to the material reuse and recycle phase. This paper aims to present the state of the art in carbon dioxide reduction studies relating to the construction industry. Studies of carbon dioxide reduction throughout the building life cycle are reviewed and discussed, including those relating to green building design, innovative low carbon dioxide materials, green construction methods, energy efficiency schemes, life cycle energy analysis, construction waste management, reuse and recycling of materials and the cradle-to-cradle concept. The review provides building practitioners and researchers with a better understanding of carbon dioxide reduction potential and approaches worldwide. Opportunities for carbon dioxide reduction can thereby be maximised over the building life cycle by creating environmentally benign designs and using low carbon dioxide materials.

1. Introduction

Human-induced climate change has become a dramatically urgent and serious problem, and is occurring as a result of increased atmospheric concentrations of greenhouse gas (GHG) emissions associated with human energy consumption. Increasing global temperatures are causing a broad range of environmental changes, including melting land ice and rising sea levels due to thermal expansion of the ocean (Lu *et al*., 2007). Recognised as the most pressing environmental, social and economic problem facing Earth, various mandatory or voluntary measures have been introduced to control GHG emissions and thus mitigate the impacts brought about by climate change (Lyon and Maxwell, 2004).

The widespread impact of climate change currently holds a dominant position in public awareness and many nations both in developed and developing regions have started taking action to address the challenges ahead. At a global level, two UN agencies, the World Meteorological Organisation and the United Nations Environment Programme, established the International Panel on Climate Change in 1988 to assess the scientific, technical and socioeconomic information relevant to understanding the risk of human-induced climate change. This was taken further in 1992, with the introduction of the Framework Convention on Climate Change at the Rio Summit, followed by the Kyoto Protocol in December 1997 – an international treaty aimed at preventing potentially dangerous anthropogenic interference with the climate system. The Copenhagen Accord in 2009 reaffirmed the scientific case for keeping temperature rises below 2°C and urged nations to realise emissions reduction targets by 2015.

As defined by the Kyoto Protocol, GHGs consist of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride (ISO, 2006; WRI/WBCSD, 2004). Among these GHGs, carbon dioxide is the most important anthropogenic gas, accounting for nearly 80% of the enhancement of the global warming effect (Borges, 2011; IPCC, 2007). Carbon dioxide emissions caused by electricity production from non-renewable sources, the burning of fossil fuels, transport operations, agricultural processes and industrial activities have contributed significantly to increased carbon dioxide levels (USEPA, 2010).

As a major sector in most countries, the construction industry produces GHG emissions directly and indirectly from various activities. Ürge-Vorsatz *et al.* (2007) claimed that buildings are responsible for a third of global carbon dioxide emissions. Statistics provided by the USCB (2010) have shown that buildings in the USA consume approximately 40% of the nation's energy, while in the UK, building energy consumption consists of over 60% of all primary energy used. Other studies have confirmed the high energy intensity of the construction industry and thus its significant contribution to GHG emissions, ecological destruction and resource depletion (e.g. CICA, 2002; Melchert, 2007; Zimmerman *et al.*, 2005). Consequently, the global effort to combat climate change would be severely undermined without an improvement in the energy efficiency of building facilities (IEA, 2006).

To date, many nations have introduced mandatory and/or voluntary policies and regulations for carbon dioxide reduction throughout the building life cycle. Mandatory codes include those for controlling energy use in buildings (Lee and Chen, 2008), carbon dioxide or energy tax (Baranzini *et al.*, 2000; Gottinger, 1995) and tradable permits. Voluntary schemes, on the other hand, usually involve unilateral agreements, negotiated agreements, eco labels (Lee and Yik, 2004) and rebate schemes (Boyle, 1996; USDOE, 1995). For construction-related carbon dioxide reduction policies, five elements are required for an effective global response: (a) the pricing of carbon dioxide, implemented through tax, trading or regulation; (b) the support of innovation and the deployment of low carbon dioxide technologies; (c) the removal of barriers to energy efficiency; (d) information and education of individuals about what they can do to respond to climate change; and (e) an agreed GHG reduction target at both international and national levels (Stern, 2006, 2009).

Buildings typically emit large amounts of carbon dioxide throughout their life cycles, and many aspects and stages throughout the building development and utilisation stages – from planning, design, construction and commissioning to their operation, maintenance and disposal – affect their energy and environmental performance. As a result, it is necessary to scrutinise the carbon dioxide emitted during the building life cycle. The aims of this paper are to provide building practitioners and researchers with a better understanding of the potential for carbon dioxide reduction, and approaches currently adopted worldwide to minimise environmental impact over the building life cycle by adopting environmentally benign designs and low carbon dioxide materials.

2. Carbon dioxide emissions in the building life cycle

To produce useful information concerning carbon dioxide emissions in the building construction industry, many researchers have studied energy consumption at different stages of the building life cycle and have concluded that each phase has different effects (e.g. Bevington and Rosenfeld, 1990; Gustavsson *et al.*, 2010; Horne, 2009; USEPA, 1994). Carbon dioxide emissions are commonly expressed in terms of the life cycle stages involved – that is, planning, design, construction, installation, test, commissioning, operation and disposal (Gangolells *et al.*, 2009). USEPA (2002) categorise these stages into the three consecutive phases, namely 'cradle to entry gate', 'entry gate to exit gate' and 'exit gate to grave'. Sodagar and Fieldson (2008), on the other hand, have represented these in three distinct stages: (a) initial impact – covering the content of materials in the construction process; (b) operational impact – from the operational to maintenance phases; and (c) end of life impact – the deconstruction process to waste materials. Alternatively, the life cycle of buildings can be represented in five phases, including (a) the planning and design phase; (b) materials (embracing all manufacturing and transportation) and the construction process phase; (c) the operational phase; (d) the maintenance and renovation phase, and (e) the deconstruction and disposal phase (Figure 1).

The planning and design phase is of paramount importance for carbon dioxide reduction as decisions made during this stage are influential on operational efficiency (Erlandsson and Borg, 2003). A good design would not only increase the potential for emission reductions over the building life cycle, but should also eliminate the need for costly and disruptive carbon dioxide reduction measures during the post-occupancy stage (Fieldson *et al.*, 2009; Li and Colombier, 2009). For instance, emissions can be reduced by introducing ventilation corridors between buildings and at the podium garden level so as to facilitate better air ventilation and thereby cut down on electricity consumption. Through prudent design, any extra embedded emissions caused by the thermal mass can be outweighed by a reduction in operational carbon dioxide. According to Fieldson *et al.* (2009), designers should examine the interaction between climate conditions, building form and shape, building thermal characteristics, and how occupants influence a building's environmental performance before a design solution is formulated. Wan and Yik (2004), on the other hand, stressed the importance of appropriate building services system designs. To facilitate clients and design team members finding out how environmentally

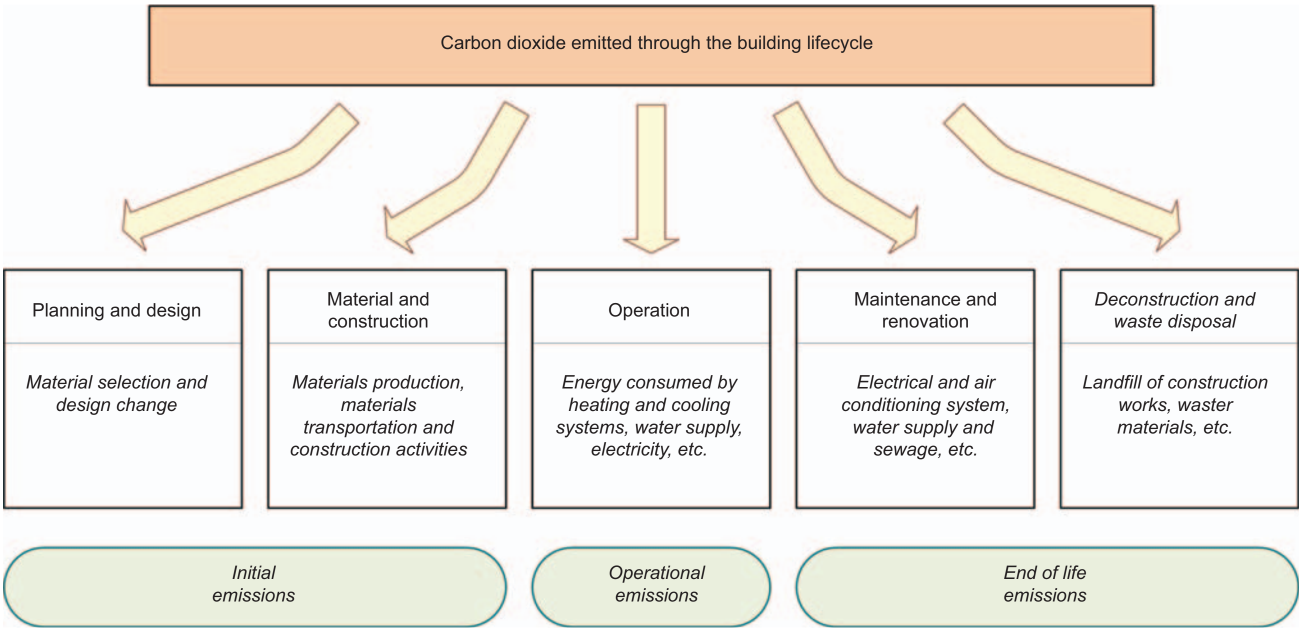

Figure 1. Carbon dioxide emissions in the building life cycle

responsible the design is, various building environmental assessment tools such as the leadership in energy and environmental design (LEED) in the USA and the Building Research Establishment (BRE) environmental assessment method in the UK have been developed (Ding, 2006).

Furthermore, the correct selection of materials and technology during the planning and design phase can provide an opportunity for carbon dioxide reductions in the industry (Gerilla *et al*., 2007). A study of three terraced houses in Spain by González and Navarro (2006) has confirmed that the choice of materials and construction method has a significant impact on carbon dioxide emissions, influencing both the embodied and operational energy of the buildings (Treloar, 1996). The design team should, therefore, pay extra attention to the choice of materials (González and Navarro, 2006), and determine which is the most suitable technology and construction method for the project (Hendrickson and Au, 1989).

Carbon dioxide emissions during the materials and construction process phase occur as a result of the extraction and processing of raw materials, the production of construction materials, materials transportation between processes and on-site installation, materials delivered to site and disposing construction waste to landfill (Adalberth *et al*., 2001; Gerilla *et al*., 2007). Many studies have shown that this is an important phase within the building life cycle as the energy and materials consumed in construction are largely non-renewable due to the costs and benefits (Chau *et al*., 2007; Monahan and Powell, 2011). Manufacturing alone can contribute to as much as 70% of the GHG emissions in the construction stage (Smith *et al*., 2002), or 15% of a building's life-time energy consumption (Harris, 1999; WBSCD, 2007). Based on a commercial building construction case, Yan *et al*. (2010) concluded that 6–8% of carbon dioxide emissions in the construction process are due to the transportation of materials. In order to minimise carbon dioxide impact, transportation distance and mode should not be overlooked (Chishna *et al*., 2010; Duffy, 2009).

Several studies focusing on energy use and associated emissions during the operational phase have found that this phase accounts for 70–80% of the environmental impact throughout the building life cycle (Chwieduk, 2003; Junnila, 2004; Scheuer *et al*., 2003). Research into office buildings in the Netherlands has suggested that energy consumption during building operation consists of more than three-quarters of their environmental load (Van Den Dobbelsteen *et al*., 2009). Similarly, operational emissions of office buildings in Japan contribute to approximately 80% of total carbon dioxide emissions in the entire building life cycle (Suzuki and Oka, 1998). The high proportion of energy consumed during this phase is attributable to the extensive use of electrical appliances, including heating, cooling and lighting systems over a long building life span.

Approaching the end of building life, a decision will be taken either to demolish the building or extensively refurbish it in order to extend its economic value (Fieldson *et al*., 2009). In the latter case, inefficient building component elements such as the external envelope that may lead to a high heat gain/loss (Sodagar *et al.*, 2009) and building services equipment are replaced to increase operational performance. When demolishing such building components, carbon dioxide will be emitted while operating the dismantling plant and when demolished materials are removed (Junnila, 2004).

While the construction industry worldwide consumes approximately 40% of raw materials, about the same proportion of construction and demolition waste will end up in landfill at the end of building life (EPD, 2002; Koroneos and Dompros, 2007). Environmental impacts during the demolition phase include demolition activities and the transportation of any waste building materials to the landfill site or reusable materials to a recycling site (Junnila, 2004). The large amount of scrap building materials produced at the disposal stage of the building life cycle highlights the need for the reuse or recycling of materials to reduce carbon dioxide emissions in the building industry. Gerilla *et al.* (2007) claimed that carbon dioxide emitted as a result of maintenance and disposal processes contributes to approximately 9% of the total carbon dioxide emissions for a housing development. There has been a significant change towards recycling the construction and demolition waste in recent times. In the UK, the proportion of recycled construction and demolition waste was approximately 49% in 2001 and increased to 52% in 2005 (Defra, 2009). More broadly, waste levels suggest the need for a unified policy for material recycling, suitable financial support from the government, and clear guidelines on the use of recycled materials for various purposes.

The above studies relating to energy consumption and carbon dioxide emissions throughout the building life cycle indicate that the highest proportion of emissions occur in the operational phase, followed by the materials and construction phase. Although there are only limited studies of emissions in early stages (the planning and design phase), building design plays a significant role in reducing both embodied and operational carbon dioxide emissions, because materials and building service systems are determined at this time.

3. Carbon dioxide reduction strategies and measures in the building life cycle

The following section provides a review of carbon dioxide reduction studies in terms of the five phases of the building life cycle illustrated in Figure 1 – that is, (a) planning and design; (b) materials and construction; (c) operation; (d) maintenance and renovation; and (e) deconstruction and waste disposal.

3.1 Planning and design

Building design has a significant effect on the environmental impact of a project, and many studies have proposed a 'green building' approach in order to reduce associated emissions. By understanding the implications of designs arising from the design phase, contractors for instance can predict the emissions produced in later phases. Furthermore, by recognising the impact of each phase and the relationship between these phases in the whole life cycle, designers can identify GHG emission potential and produce solutions to mitigate high impacts through the design of low carbon facilities. In order to emphasise the importance of building design in reducing carbon dioxide emissions, the UK studies of Fieldson *et al.* (2009) found effective design and accurately anticipated that the design life of a building can significantly reduce carbon dioxide emissions in the operational phase. Various techniques allow for carbon dioxide reduction in buildings, such as natural ventilation, suitable orientation, solar geothermal and other renewable energy integration, bioclimatic architecture design, and enhanced mechanical ventilation with optimised heat recovery systems. Such designs and operating improvements can lead to substantial reductions in building energy consumption, while providing adequate and in some cases superior thermal comfort for residents (Harvey, 2006; Salat, 2006).

Studies have also pointed to the use of low energy buildings and green building designs in an effort to reduce emissions. For example, the case study of 60 residential and non-residential units in nine countries by Sartori and Hestnes (2007) demonstrates the design benefit of low energy buildings in encouraging both a net benefit in total life cycle energy demand and an increase in embodied energy. Similarly, the analysis of Norwegian houses by Winther and Hestnes (1999) and Feist (1996) showed low energy buildings to be a result of specific design criteria, demanding less operating energy and less total energy than those built according to conventional criteria. Levine *et al.* (2007) suggested a simple strategy to reduce heating and cooling loads by isolating the building from the environment by using high levels of insulation, optimising the glazing area and minimising the infiltration of outside air. A more effective strategy is to treat the building envelope as a filter, accepting or rejecting any solar radiation and air infiltration selectively, as the heat capacity of the building structure can be used to shift thermal loads on a given time scale.

Other design strategies for promoting energy-efficient buildings include reducing the loads, selecting systems that make the most effective use of ambient energy sources and heat sinks, and using efficient equipment and effective control strategies. Studies have been conducted by Yolles (2010) and the South West Regional Development Agency to examine life cycle impacts of various design considerations and those adhering to various building design standards. In addition, there are some examples of cutting edge sustainable design, such as the 'Gardens by the Bay' project in Singapore, which combines a wide range of passive and active technologies to deliver an extraordinary design that has close to zero net carbon dioxide under a tough climate condition. Levine *et al.* (2007) stressed the importance of an integrated design approach to ensure architectural elements and engineering systems work effectively together.

A number of green design initiatives have been undertaken around the world with aims to reduce life cycle carbon dioxide emissions of buildings. For example, BRE developed 10 low carbon dioxide homes in their innovation park to test various construction innovations and designs that comply with the Code for Sustainable Homes (BRE, 2011). These include solar thermal panels to supply hot water, automatic window shutters to prevent overheating, and rainwater harvesting to provide water to flush toilets. Li and Colombier (2009) believed a significant reduction in mechanical equipment can be achieved by optimising initial building designs and simply incorporating passive ventilation and passive solar cooling and heating.

In order to help decision-makers with the selection of appropriate materials, Lacouture *et al.* (2009) proposed a mixed integer optimisation model that incorporates design and budget constraints while maximising the number of credits reached under the LEED rating system. Their case study showed the importance of 'green' materials' availability, and without this availability, LEED-based requirements are nearly impossible to meet. Another study by Huberman and Pearlmutter (2008) has shown that the selection of low environmental impact materials can save cumulative energy over a 50-year life cycle by substituting high embodied energy materials (such as reinforced concrete) with alternative materials (e.g. hollow concrete blocks, stabilised soil blocks or fly ashes as a replacement for cement with high embodied energy). The importance of applying building materials with low environmental loads during their life cycle is also stated by Nie and Zuo (2003) in a Chinese case study. Nevertheless, the life cycle cost of materials should be cautiously considered during the material selection process (Norris, 2001). In Hong Kong, the HKHA (2005) and EMSD (2006) have developed an integrated decision support tool to aid selection and procurement of building products and components in an environmentally responsible and cost efficient manner from a whole life cycle perspective.

3.2 Materials and construction

The embodied carbon dioxide of a building material can be taken as the total carbon dioxide emission released, including extraction, manufacturing and transportation of the material (Hammond and Jones, 2008). Many studies show that different materials contain differing embodied carbon dioxide amounts and therefore have a range of environmental impacts. Hammond and Jones (2010), for example, have published an embodied energy and embodied carbon dioxide database that covers a broad range of construction materials employed in the UK. Some countries have been encouraging their designers to include in the specifications the use of indigenous, recyclable, long-lasting and low embodied energy materials, as reflected in some of the means of building environmental assessment tools (Lam *et al.*, 2011; Treloar *et al.*, 2001).

Of particular relevance for the building life cycle are concrete, metal and wood due to their extensive consumption and significant carbon dioxide emissions (Howard, 1996). The case study by Asif *et al.* (2007) of eight construction materials for a dwelling in Scotland found that concrete alone consumed 65% of the total embodied energy of home construction and its share of environmental impacts was even more crucial. The case study by López-Mesa *et al.* (2009) in Spain showed the environmental impact of a building structure with precast concrete floors to be 12% lower than one with insitu cast floors for a defined functional unit. From a recycling point of view however, Harris and Elliot (1997) found, in comparing a steel frame and concrete frame of a simple building, recycling concrete had a minimal effect on total embodied energy compared with recycling steel. However, all other things being equal, the greatest carbon dioxide savings from the industry are likely to be achieved by the inclusion of supplementary cementitious materials (Tyrer *et al.*, 2010), such as fly ash (Pedersen *et al.*, 2008) or ground granulated blast-furnace slag (O'Rourke *et al.*, 2009). A unique cementitious binder based on magnesium oxide has also been developed, and the manufacturer has claimed that their product produces only half the carbon dioxide when compared with that of ordinary Portland cement.

In terms of metal, the study by Chen *et al.* (2001) of the energy embodied in the building envelope of two typical high rise public housing blocks in Hong Kong showed that the energy embodied in aluminium and steel ranked first and second largest in energy demand and was likely to account for more than three-quarters of the total embodied energy use. Similarly, the analysis of 10 types of building materials and 10 types of building service components in commercial buildings by Chau *et al.* (2007) ranked concrete, reinforcing bars, copper power cables and copper busbars as the four most significant materials or components in total life cycle environmental impact. The results are analogous to the findings by Alcorn (2003).

In general, the advantages of using wood are quite pronounced. Many studies in Japan, Spain and Sweden (e.g. Gerilla *et al.*, 2007) have shown it to have a lower energy use than either concrete or steel. Aiming to determine the energy use and carbon dioxide emissions due to technological choices and managerial decisions in the production process, Gustavsson and Sathre

(2006) compared wood and concrete frames based on a four-storey apartment building containing 16 apartments – and found the former to have lower energy use. Also, Koch (1992), using US data from the 1970s, and Buchanan and Honey (1994), using New Zealand data from the 1980s, calculated the energy use and carbon dioxide emissions from wood materials to be lower than those of concrete or steel. Similarly, Buchanan and Levine (1999) observed that the energy needed to manufacture building materials decreased between 1983 and 1998, with buildings with higher wood content having lower carbon dioxide emission values. More recently, the Consortium for Research on Renewable Industrial Materials found two wooden houses to have lower embodied energy and global warming potential than equivalent designs in steel or concrete (Lippke *et al*., 2004).

Some further comparisons between different types of wooden structures have also identified important effects. For instance, the input/output analysis by Suzuki *et al*. (1995) of eight houses in Japan found energy consumption for the structural work of wooden single-family houses to be only 11% of the energy consumption for multifamily houses and impacting less on the environment. It is also important to use wood waste for energy to improve carbon dioxide balance (Scharai-Rad and Welling, 2002) or to be recycled to produce other products such as chipboard. This reflects the importance of end of life management in the overall environmental impact of a building as renewability does not automatically confer the attribute of sustainability to a material (Amato, 1996). However, considering the world resource of wood and its consumption as a complete system, then clearly much greater quantities of wood are being consumed than are being replenished at present, most being consumed as fuel in third world countries (Hammond and Jones, 2010). It is, therefore, incorrect to think of wood as having a negative global warming potential, for much is eventually incinerated or contributed to land-fill, which generates 0·0036 kg carbon dioxide and 1·47 kg carbon dioxide per kg of wood, respectively, according to the Swiss Oekoinventare database, neutralising its temporary effects on carbon dioxide balance (Peuportier, 2001). Therefore, like any other construction materials, wood should be reused or reprocessed as much as possible to preserve the environment.

During the construction process, the operation of building equipment, vehicle travelling and disposal of wastes are the main causes of environmental impact (Li, 2006), and reducing emissions from these processes is extremely important in minimising environmental effects. Proposed measures are using energy saving construction technology and 'green' construction methods. With growing concern about the environmental impact of construction activities, Tam *et al*. (2004) suggested a green construction assessment of the environmental performance of contractors because most existing assessment methods are not designed for construction activities, which is analogous to the civil engineering environmental quality assessment and award scheme in the UK with a desire to improve the sustainability of civil engineering and public projects. This could help evaluate contractors' performance, provide a yardstick for performance benchmarking and also help contractors keep track of their own environmental achievements. Adopting off-site prefabrication has also been suggested as an effective alternative. For example, the questionnaire survey and case study of recently completed Hong Kong building projects by Jaillon *et al*. (2009) indicated that prefabrication reduces construction waste by approximately 52% compared with more conventional methods. Apart from its heavy reliance on careful pre-planning and notorious lack of flexibility, prefabrication can provide other benefits on site, such as improved quality control, a tidier and safer working environment, improved environmental performance and a potential reduction in construction time and labour requirements.

3.3 Operation, maintenance and renovation

Numerous suggestions have been forthcoming for improved energy efficiency in the operational stage. Increasing energy efficiency is seen as the most effective way of improving the security of energy supply, reducing carbon dioxide emissions and increasing competitiveness (IEA, 2006). Levine *et al*. (2007) identified the GHG mitigation options in buildings and equipment, including the thermal envelope, heating and cooling systems, lighting systems, household appliances, solar, geothermal and other renewable energy integration, and so on. However, a key factor in determining whether these potentials will be realised is the costs associated with the implementation of the measures to achieve the emission reductions. Taking the scale of savings into consideration, designers should strive to improve the insulation and district heating for properties in colder climates while measures can be introduced to increase the efficiency of space conditioning in facilities located in warmer climate zones. Other measures that rank high in terms of cost saving potential are solar water heating, efficient lighting and efficient appliances, as well as building energy management systems (Levine *et al*., 2007).

More specifically, Balaras (2001) indicated that passive technology can reduce energy use for heating, while Claridge *et al*. (2001) proposed the conversion of ventilation systems to reduce nearly 40% of energy use in heating, cooling and ventilation. Furthermore, Harvey (2006) pointed out that solar and cooling programmes can save 25–80% in space heating. Another study by Pérez-Lombard *et al*. (2008) found that a lack of consistent data impedes an understanding of underlying changes affecting energy consumption, and proposed both private and government initiatives in promoting energy efficiency, new technologies for energy production, limiting energy consumption and raising social awareness on the efficient use of energy. Börjesson and Gustavsson (2000) observed that reducing carbon dioxide emissions during building life cycles depends on the choice of materials used in construction, and the extent to which the selected materials fulfil energy requirements for heating and cooling.

Levine *et al*. (2007) stressed that the actual building energy performance depends critically on how well the building is operated and maintained. Continuous performance monitoring, automated diagnostics and improved operator training are complementary approaches to improving the operation of buildings. Post-occupancy evaluation is a useful complement to on-going monitoring of equipment and is also useful for ensuring that the building operates efficiently (Bordass *et al*., 2001). However, acknowledging the existence of a huge stock of inefficient buildings, with most still expected to function beyond 2025, the ability to reduce significantly the GHGs emitted from existing buildings by means of various sustainable refurbishment initiatives is imperative to the community (Gorer *et al*., 2008; RICS, 2007; Ürge-Vorsatz and Novikova, 2008). Francisco *et al*. (1998) estimated that an average of 15–20% of annual household heating and air conditioning energy use in the USA can be saved by retrofitting air sealing alone. Other studies showed that 50–75% of energy consumption in commercial buildings can be saved by integrating various green measures (Levine *et al*., 2007; Rosenfield and Shohet, 1999).

3.4 Deconstruction and waste disposal

Limited research has focused on the demolition or deconstruction of buildings as the energy consumed during the process and transportation stage only accounts for 0·2% of the life cycle primary energy consumption (Scheuer *et al*., 2003). However, recycling building materials is considered to be essential in reducing the environmental burden associated with materials embodied in the building (Thormark, 2002) – an observation supported by the case study by Blengini (2009) in Turin, Italy, which revealed that recycling could reduce life cycle energy by approximately 30% and GHG emissions by 18%. For some materials, such as steel or aluminium, recycling can confer savings of more than half the embodied energy as well as GHG emissions (Yan *et al*., 2010).

Tam (2009) has commented that recycling concrete waste should be one of the best methods to improve its environmental impact but, in studies of the Australian and Japanese construction industries, major difficulties were found to be involved. In the UK, the majority of recycled and secondary aggregates have been used as alternatives to primary aggregates in local fill and related aggregates markets. Research shows that virtually all the recycled aggregates in the waste stream are already being reused, and have replaced over 25% of primary aggregates in 2009 (MPA, 2010).

Driven by the depletion of natural construction materials and concerns over climate change, there is a political and industry drive to improve waste management. RICS (2010) recommended greater recycling content in construction materials resulting in more energy-efficient and less wasteful materials, alternative technologies and consequently more innovative construction techniques, all contributing to reducing the net energy consumption for each new dwelling. WRAP (2010) has also highlighted the importance of using recycled/secondary aggregates for construction and the handling of wood wastes in the construction sector.

4. Discussion

These carbon dioxide emission studies confirm the construction industry's high levels of energy consumption and production of a significant amount of carbon dioxide throughout buildings' life cycles. Each phase of the life cycle contributes a different level of carbon dioxide emissions. The operational phase is the highest contributor, followed by the materials and construction process phase, the maintenance and renovation phase, the deconstruction and disposal waste material phase, and the planning and design phase. It is argued, however, that the most significant influence on emissions occurs in the early stages of the project life cycle as the greatest potential carbon dioxide savings can be realised in the design phase before construction. As this involves building design and materials, any changes will affect the other phases, generating waste materials that eventually produce carbon dioxide emissions.

When choosing materials, it is clear that the embodied energy of building materials must be carefully considered along with the operating energy in order to reduce the total life cycle energy use. By replacing those materials that require a significant amount of energy to produce (e.g. concrete or steel) with those consuming minimal energy during the production process (e.g. wood), this will help cut down on the energy embodied in buildings. Designers should also consider not only the direct environmental impact of materials chosen; but also the locations of their associated manufacturers for relatively low embodied carbon dioxide materials such as sand and aggregates. Whether this can reduce the energy use on a life cycle basis, however, depends on the energy requirements for heating and cooling the facility over its lifetime and whether the materials are recyclable at the end of their life (Börjesson and Gustavsson, 2000; Lenzen and Treloar, 2002). This stresses the potential and importance for the construction industry to adopt a cradle-to-cradle concept of reducing dependence on raw materials, and thus the negative impacts caused by producing new materials, and instead intensify the recycle and reuse process.

The benefits of the cradle-to-cradle concept relate not only to reducing waste by the reuse and recycling of materials, but also to attracting developers to the potentially high economic returns from using a recycle and reuse process. For example, if designers decide to use reusable and recyclable materials such as steel or aluminium at an early stage, the cost of producing new materials will decrease together with the transportation costs involved in moving newly ordered construction materials to the site. In addition to economic returns and cost reductions, the cradle-to-cradle concept provides the potential for: (a) economic sustainability – by increasing profitability through more efficient resource usage, such as in materials recycling; (b) environmental sustainability – by reducing construction waste by reusing materials for other purposes; and (c) social sustainability – by providing high satisfaction to society through low carbon dioxide and low-cost materials.

Although the cradle-to-cradle concept seems highly suited to the construction industry, particularly in the long term, lack of current knowledge makes its implementation uncertain. Furthermore, existing building environmental assessment tools cannot fully support the method. They cannot, for instance, provide sufficiently comprehensive data to track material flows for the accurate calculation of energy use, nor analyse the whole building life cycle of the cradle-to-cradle concept, in which the reuse and recycling phase becomes very important. In addition, the existing building environmental assessment method is an unsuitable approach for generating environmentally benign products and processes because its linear nature does not allow for optimisation in the context of the cradle-to-cradle design (Braungart *et al.*, 2007).

5. Conclusions

This review has compiled and discussed recent studies about carbon dioxide emission reduction in construction in terms of the five phases of the construction life cycle: the design phase; the materials production phase; the materials production and construction phase; facilities usage, the maintenance and deconstruction phase; and the recycling and reuse phase. For the design phase, various studies have proposed green building design and provided valuable information on the selection of appropriate low carbon dioxide and embodied energy construction materials. In some cases, the high embodied energy of high-performance building envelope elements, such as krypton-filled double or triple-glazed windows, can be largely offset from savings in the embodied energy of heating and/or cooling equipment. Studies of the materials production phase show wood materials to have lower carbon dioxide emissions than concrete and steel, but that wood will eventually have a negative global warming impact – indicating the need for construction researchers and practitioners to pay more attention to developing innovative low carbon dioxide materials.

Various carbon dioxide reduction approaches are reviewed throughout the building life cycle. While facing immense financial and technical challenges, these strategies would be valuable to policy and regulatory development at the national and international level for meeting corresponding reduction targets. Several studies indicate the need to use local materials to reduce transportation carbon dioxide emissions in the materials distribution and construction phase. The use of prefabricated materials in construction is also identified as beneficial in reducing emissions, as well as reducing construction waste by more than 50% compared with conventional insitu construction; and with an additional role in reducing environmental impacts in the facility use, maintenance and demolition phase. The review also identified the importance of the cradle-to-cradle concept in which, in addition to reducing energy consumption and greenhouse gas emissions, long-term economic growth is possible. However, the prospects for implementation are limited at present due to a lack of experience and knowledge of consultants, contractors and owners, and their ability to work collectively. The lack of appropriate legislative frameworks is another contributing factor of the limited use of the cradle-to-cradle concept. In the report prepared by the Innovation and Growth Team (HM Government, 2010), which aims to identify measures to facilitate the UK construction industry to rise to the challenge of the low carbon dioxide agenda, it clearly highlights the importance of equipping engineers with the appropriate skills and techniques to achieve the low carbon dioxide city.

Finally, it should be pointed out that, although there have been a great number of studies relating to carbon dioxide reduction in building and residential construction, there is relatively little work to date on some other parts of the infrastructure. While several studies examine the environmental impact of roads and bridges, comprehensive environmental assessments of water treatment are rare, having been the subject of only a few papers (e.g. Friedrich, 2002; Herz and Lipkow, 2002). Further studies are also needed to analyse the embodied carbon dioxide and environmental impact of constructing port and harbour facilities for, although many actors have been concerned with the environmental impact of harbour activities, little attention has been paid to their construction. Likewise, the carbon dioxide reduction potential in refinery and power plant construction is also in need of investigation, because this also consumes a great deal of materials and generates considerable environmental impacts. A truly holistic approach is needed in analysing the life cycle carbon dioxide emissions of buildings and construction facilities.

Acknowledgement

The authors would like to thank the University of Hong Kong for financially supporting this research project through the CRCG Seed Funding for Basic Research (grant nos. 200911159011 and 201011159035).

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