Critical Evaluation of Zero Carbon Buildings in High Density Urban Cities

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Many countries are now developing policies and measures to promote zero or low carbon buildings. However, as a clear definition of zero carbon building (ZCB) and effective evaluation methods for buildings' carbon footprints are not available, people are often confused about the performance of ZCBs. This research investigates the meaning of ZCBs and develops methods for evaluating their carbon footprints. The definition of ZCB and its related concepts are described. The meaning of footprints and the rationale for using carbon footprints as indicators to measure sustainability are presented. It is found that footprint-based assessment requires a clear understanding of emissions categories, assessment boundaries and carbon accounting principles. The assessment outcome depends on the problem definition and interpretation methodology. The main influences on carbon footprints include building functions, site conditions, energy and carbon intensity of the building systems and components. In order to develop systematic methods for assessing ZCBs, a holistic approach to carbon accounting and footprint calculation is needed. When applying the concepts to assess the buildings in high density cities like Hong Kong, some key factors for urban density and community sustainability should be considered, such as transportation strategy, urban form and typology.

Keywords: carbon emissions and reduction, carbon footprints, high density urban cities, Hong Kong, zero carbon building

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Introduction

To achieve sustainability and combat climate change, developing low carbon cities and societies is a global trend (ADEME, 2010; DCLG, 2007; NIES, 2009; Zuo *et al*., 2012). Low or zero carbon design is essential to carbon reduction targets (Brown, 2010). Among all sectors, buildings are one of the largest sources of carbon dioxide and greenhouse gas (GHG) emissions, as these gases are by-products of electricity consumption, which is used extensively in buildings. The building sector also presents the most cost effective opportunities for GHG reductions (IPCC, 2007). In recent years, many countries are developing policies, measures and demonstration projects to promote zero or low carbon buildings with the aim of reducing carbon emissions and ecological footprints (ASBEC, 2011; Pan and Ning, 2015). Energy efficiency and carbon emission reduction in buildings have become important trends in the world (Boake, 2008; Hui, 2012; Loper *et al*., 2008).

However, as a clear definition of zero carbon building (ZCB) and effective evaluation methods for assessing buildings' carbon footprints are not available, people are often confused about the performance of ZCBs and the strategy to reduce their carbon footprints (Hui, 2010). This research investigates the meaning of ZCBs and develops assessment methods for evaluating their carbon footprints. The definition of ZCB and its related concepts are described. The meaning of footprints and the rationale for using carbon footprints as indicators to measure sustainability are presented. The current situation in Hong Kong and key factors for urban density and sustainability are discussed.

Zero Carbon Buildings

The terms 'zero energy', 'zero carbon' or 'zero emission' are applied to buildings that use renewable energy sources on-site to generate energy for their operation, so that over a year the net amount of energy generated on-site equals the net amount of energy required by the building. Studying the definitions of the terms associated with ZCB is important because the meaning of ZCB and the related concepts are often expressed unclearly and are sometimes misunderstood (Hui, 2010).

Zero Energy and Zero Carbon Buildings

'Zero energy building' (ZEB) is often used in conjunction with ZCB. ZEB can be defined as a building that produces as much energy on-site as it consumes on an annual basis. Torcellini *et al*. (2006) provided four definitions of ZEB: net zero site energy, net zero source energy, net zero energy costs, and net zero energy emissions. A classification system based on renewable energy supply options is also used to distinguish different types of ZEB. Table 1 shows a summary of the terms and definitions.

In recent years, many researchers and governments have investigated the definitions of ZEB and ZCB with the goal of developing an international consensus and consistent definition (ASBEC, 2011; DCLG, 2008; ECEEE, 2009; Fulcrum, 2009; Marszal, *et al*., 2011; Sartori, *et al*., 2012; UK-GBC, 2008). It is believed that promotion of ZEB and ZCB can help control carbon emissions and improve building performance. In general, ZEB design differs from ZCB design in that it is more concerned with the reduction of operating energy requirements for a building, focusing on the eventual use of zero fossil energy. By using renewable and low-carbon energy sources, it is possible to offset or balance the carbon emissions produced from the building.

Balancing Carbon Concept

Figure 1 shows the balancing carbon concept for ZCB. To develop a systematic methodology for studying ZEB/ZCB, Sartori *et al*. (2012) identified two major types of balance, namely the import/export balance and the load/generation balance, which are suitable for defining ZCB and ZEB, respectively.

Terms	Definitions/Meanings
Zero energy building (ZEB) or net zero energy building (NZEB)	A building that produces as much energy on-site as it consumes on an annual basis
Net zero site energy building (site ZEB)	Amount of energy provided by on-site renewable energy sources is equal to the amount of energy used by the building
Net off-site zero energy building (off-site ZEB)	Similar to net zero site energy building, but considers purchasing energy off-site from 100% renewable energy sources
Net zero source/primary energy building (source ZEB)	Produces as much energy as it uses in a year, when accounting for the source. For electricity, only around 35% of the energy used in a fossil fuel power plant is converted to useful electricity and delivered. Site-to-source conversion multipliers are used to calculate a building's total source energy
Net zero energy cost building (cost ZEB)	The cost of purchasing energy is balanced by income from sales of electricity to the grid of electricity generated on-site
Net zero energy emissions building, zero carbon building (ZCB), zero emission building	The carbon emissions generated from the on-site or off-site fossil fuel use are balanced by the amount of on-site renewable energy production

Table 1 Terms and definitions of ZEB and ZCB

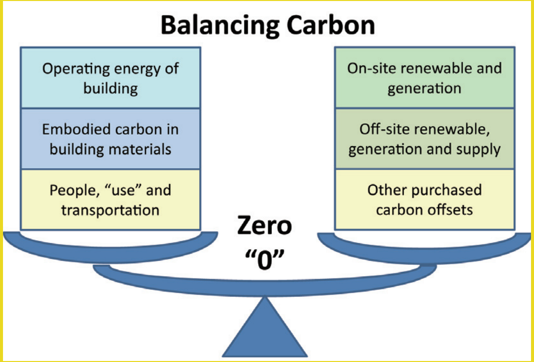

Figure 1 Balancing carbon concept for ZCB

After reviewing the definitions and calculation methodologies of ZEB, Marszal *et al*. (2011) identified the following sources of differences between definitions:

(a) The metric of the balance (e.g. primary energy, final energy, carbon emission)

(b) The balancing period (monthly, seasonal, operation year, life cycle)

(c) The type of energy use included in the balance (e.g. HVAC, lighting, appliances)

(d) The type of energy balance (import/export and load/generation)

(e) The accepted renewable energy supply options

(f) The connection to the energy infrastructure (grid connected or standalone)

(g) Other requirements relating to energy efficiency, the indoor climate and building-grid interaction.

Definitions of ZCB

In Australia, ASBEC (2011) has tried to develop a suitable definition for ZCB to assist stakeholders to progress towards zero emissions. Their definition is:

"A zero carbon building is one that has no net annual Scope 1 and 2 emissions from operation of building incorporated services.

- *Building-incorporated services include all energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope, water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation*
- *Zero carbon buildings must meet specified standards for energy efficiency and on-site generation;*
- *Compliance is based on modelling or monitoring of greenhouse gas emissions in kg CO2-e/m²/yr."*

Some variations of ZCB were identified by ASBEC (2011) as shown in Table 2. The scope and nature of ZCB must be clearly defined to avoid misunderstanding. Sometimes, for the sake of simplicity, the definition of ZEB/ZCB might include only the balance between daily operating energy of the building and the renewable energy generation. Another method of zero carbon calculation is to consider building structure, building materials and equipment, production, transportation, construction process etc., in order to indicate the 'embodied energy' or 'embodied carbon emissions'. Integrating embodied impacts into ZCB assessment will present research and development challenges for stakeholders (Lützkendorf *et al*., 2015).

A more stringent and broader definition would consider the whole life cycle, from planning and design, building materials production, materials transportation, construction process, daily building operations, renovation and maintenance repairs, waste disposal. However, the calculations for this zero carbon life-cycle building are very difficult and complicated (Hernandez and Kenny, 2010). Thus, it is not practical to apply such a definition.

Emission Reduction Options

One critical issue to consider for ZCB is the allowable options for emission reduction. Figure 2 shows the options proposed by ASBEC (2011), which include both on-site and off-site methods for renewable/low carbon energy sources. This is a three-tier approach that includes a target for energy efficiency of the building design and construction as a priority. In addition, there is a target for on-site low or zero carbon energy generation. The third tier includes off-site solutions, which should only be considered after maximising the previous two tiers.

Zero carbon occupied building	Include occupant emissions
Zero carbon embodied building	Include embodied emissions
Zero carbon life-cycle building	Include all emission sources in the building life cycle
Autonomous zero carbon building	No grid connection
Carbon positive building	Achieves less than zero emissions

Table 2 Variations of ZCB (adapted from ASBEC, 2011)

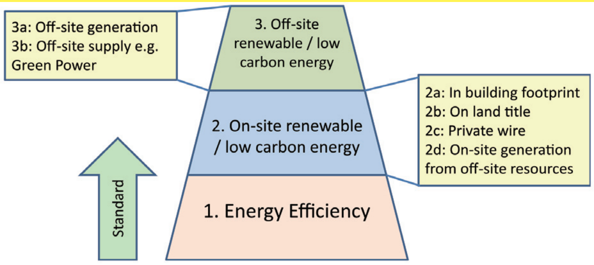

Figure 2 Allowable emission reduction options for ZCB (adapted from ASBEC, 2011)

From a holistic life-cycle point of view, a building is considered sustainable in the model if by the end of its expected lifetime the total carbon emissions are completely offset (Bendewald and Zhai, 2013). In general, 'zero carbon' demands a numerical assessment and validation of the building design. ZCB compliance requires designers to numerically validate the effectiveness of their approaches; there are various means by which this can be done, as well as relative scales of the problem that might be examined (Boake, 2008). Therefore, it is important to clearly describe the calculation methods and assumptions when assessing ZCB.

Assessment of Carbon Footprints

Carbon is frequently used as shorthand for either carbon dioxide (CO_2) or carbon dioxide equivalents (CO_2-e), which includes both CO_2 and other gases with significant global warming potential (GWP). A 'footprint' is a quantitative measurement indicating the appropriation of natural resources by humans; it describes how human activities can impose different types of burdens and impacts on global sustainability (Čuček *et al.*, 2012).

Carbon footprint is a measure of the exclusive direct (on-site, internal), and indirect (off-site, external, embodied, upstream, and downstream) CO_2 emissions of an activity, or over the life cycle of a product, measured in mass units. A process-oriented life-cycle carbon footprint analysis is an analytical tool that focuses attention on hot spots and inefficiencies over the entire life cycle, and provides a framework for trade-offs and optimisation (Hernandez and Kenny, 2010).

Carbon Footprint of Buildings

The carbon footprint of a building is the total amount of CO_2 and other GHGs emitted over the life cycle of that building, expressed as kilograms of CO_2 equivalents (kg CO_2-e). This includes all GHGs generated in the manufacture of raw materials, construction of the building, transport of materials to the construction site, operation of the building, periodic refurbishment and replacement of materials, and end-of-life disposal of the building materials. Figure 3 shows a building's carbon footprint and its components. Most of the carbon footprint emissions for buildings come from 'indirect' sources, i.e. fuel burned to produce electricity. Thus, the most effective way to reduce a carbon footprint is to either decrease the amount of energy needed for production or to decrease the dependence on carbon emitting fuels (Brown, 2010).

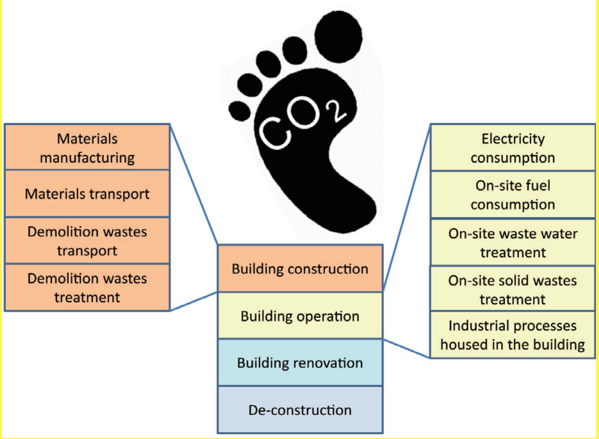

Figure 3 Carbon footprint of a building and its components

Measuring Carbon Footprints

A building's carbon footprint can be measured by undertaking a GHG emissions assessment or other calculative activities denoted as 'carbon accounting' (Kennedy and Sgouridis, 2011). The following international standards are often applied for carbon footprint analyses using the principle of life-cycle assessment and GHG protocol.

- ISO 14040: Life Cycle Assessment - Principles and Framework
- BSI: PAS 2050 - Specification for the Assessment of Life-Cycle GHG Emissions of Goods/Services
- WRI/WBCSD: Greenhouse Gas Protocol
- IPCC: 2006 Guidelines for National Greenhouse Gas Inventories

In Hong Kong, a set of carbon audit guidelines for buildings has been developed to report on GHG emissions and removal (EPD and EMSD, 2010). Figure 4 shows the scopes of GHG emissions and removals. The assessment process focuses on the following aspects:

- Physical boundaries (usually the site boundaries of the building)
- Operational boundaries (to identify and classify the activities to determine the scope)
- Scope 1 – direct emissions and removals
- Scope 2 – energy indirect emissions
- Scope 3 – other indirect emissions
- Reporting period (usually one year)
- Collecting data and information to quantify GHG performance

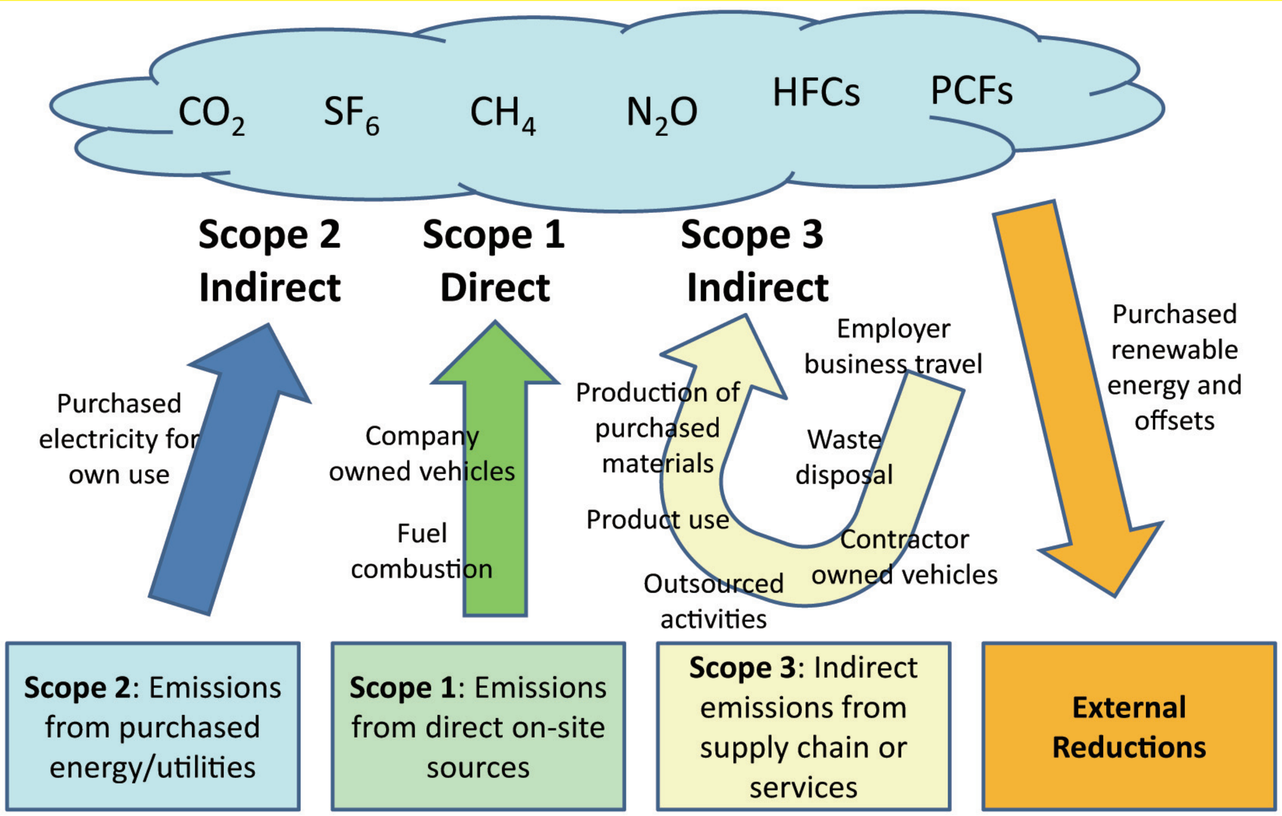

Figure 4 Greenhouse gas emissions and removals for buildings

The footprint-based assessment requires a clear understanding of emissions categories, assessment boundaries and carbon accounting principles (Čuček *et al*., 2012). Pan (2014) indicated the great diversity and complexity of ZCB boundaries in the world. It is important to clearly specify the boundaries and related assumptions. Moreover, the assessment outcome depends on the problem definition and interpretation methodology. The main influences on carbon footprints include building functions, site conditions, energy and carbon intensity of the building systems and components. In order to develop systematic methods for assessing carbon footprints, a holistic approach to carbon accounting and footprint calculation is needed.

Practical Issues

In practice, to assess the impact of buildings at the outset of a project, 'carbon estimators' are used to provide a more general figure on project inputs like building size, primary structural system, and site conditions (Boake, 2008). As the project proceeds, 'carbon calculators' that are more detailed and project-specific can be applied to assess GHG emissions. All calculations need to examine holistic aspects of the project, in order to achieve a balance between carbon costs and the ability of the project to sequester carbon. Once the size of a carbon footprint is known, a strategy can be devised to reduce it. Table 3 shows four approaches to carbon reduction (ASBEC, 2011).

Performing footprint analyses can be costly and time consuming. There are still many difficulties in implementing carbon debt accounting because building development and construction activities are fragmented and very complicated. Chen *et al*. (2011) have developed an evaluation framework for detailed life cycle carbon accounting for buildings based on multi-scale input-output analysis. Nine stages have been suggested: building construction, fitment, outdoor facility construction, transportation, operation, waste treatment, property management, demolition, and disposal for buildings.

Table 3 Different carbon reduction approaches

Strictly zero carbon	No carbon is emitted within Scopes 1 and 2; neither balancing nor offsets are allowed.
Net zero carbon	All carbon emissions within emissions Scope 1 are eliminated, and emissions within Scope 2 are balanced through export of low or zero carbon goods, internal or external sequestration, or import substitution of Scope 3 emissions.
Carbon neutral	Any and all emissions for which the building is responsible under Scopes 1 and 2 can be managed through the purchase of offsets from third parties that lie outside the building's boundaries.
Low carbon	Emissions under Scopes 1, 2 and 3 are reduced compared to a baseline. The reduction level is often not clearly specified.

Discussion

Carbon accounting is beginning to permeate multiple sectors. To systematically assess ZCB and develop effective strategies to reduce carbon footprints, it is essential to understand, quantify, and manage GHG emissions in a holistic and scientific way. It is also important to promote ZCB design strategies in society, to foster cultural change and sustainable lifestyles.

Suitable Candidates for ZCB

Brown (2010) pointed out that not all buildings are suitable candidates for ZCB. Adhikari *et al*. (2012) raised some doubts about the affordability of ZCB/ZEB. Fong and Lee (2012) indicated that for subtropical cities like Hong Kong, only low energy design for buildings is possible, rather than zero energy. It is generally agreed that ZCB is an ideal goal at present, and it cannot be realised in some situations. For example, given the high operating loads in facilities such as hospitals, hotels and laboratories, sufficient energy reductions may be impractical. Also, buildings in urban areas may have inadequate solar exposure due to overshadowing from adjacent buildings and may not be able to achieve net zero energy. Furthermore, medium- to high-rise buildings are problematic candidates given the high ratio of solar panel surface to total floor area required for ZCB/ZEB.

It is believed that implementing ZCB/ZEB for low-rise residential buildings is more feasible (Fong and Lee, 2012). For commercial building developments, Zuo *et al*. (2012) found that the lack of a clear definition of carbon neutral building presents a significant barrier and the key success factors include market demand, material selection, facility manager's knowledge, government support and leadership. Often, an exemplar project, such as a ZCB, can play a pivotal role in promoting cultural change. In order to speed up the transformation and achieve significant carbon reduction in society, building refurbishment towards zero carbon is a critical aspect (Xing *et al*. 2011). Aside from the development of new building design and planning, existing building renovations should also play an important role in reducing GHG emissions. For instance, Australia has established a plan to demonstrate how all existing buildings can achieve zero emissions from their operation within ten years (BZE, 2013).

Green Building Sustainability Assessments

Ng *et al*. (2013) found that the current green building assessment schemes (such as BEAM Plus, BREEAM and LEED) focus primarily on operational carbon instead of emissions generated throughout the entire building life cycle. Also, the baselines and benchmarks for carbon evaluation vary significantly between the schemes. Bendewald and Zhai (2013) suggested that building sustainability assessment should evolve towards an absolute method using credible science such as carrying capacity. Čuček *et al*. (2012) advocate that carbon footprints can be used as indicators to measure sustainability. However, the definition of a suitable sustainability metric for supporting objective sustainability assessments is still an open and debatable issue.

As a type of environmental footprint, the carbon footprint has become an important environmental protection indicator in many disciplines. As described above, carbon footprint is an effective carbon accounting method for facilitating GHG trade-offs and optimisation in buildings. It is also a logical way to implement lifecycle thinking into building planning and design. For a wider perspective on sustainability assessment, composite indicators including environmental, social, and economic footprints can also be developed to satisfy the needs of multi-objective optimisation problems in society (Čuček *et al*. 2012).

ZCB Design Strategies

Hui (2012) discussed the meaning of ZCB and advocated that construction innovation and environmental design are crucial for ZCB design. In many cases, ZCB design may be more complicated than the design of general buildings because of the need to study the specific location, requirements and actual energy usage, to determine suitable arrangements for building energy efficiency and renewable/low-carbon energy. For many building categories, passive solar or low-energy design is often more cost-effective than active systems like photovoltaics (PV). Common building energy efficiency measures include natural lighting, natural ventilation, proper building siting and massing, energy-efficient lighting, energy-efficient cooling and heating, energy-saving office equipment and energy management. Table 4 shows a summary of the basic design strategies for ZCB.

- At the outset, the building project should take into account building energy efficiency and use of renewable energy
- Select the appropriate building site - with opportunities to utilise renewable energy and reduce transportation and food production needs
- Optimise passive design strategies by considering and protecting the natural environment to reduce energy demand
- Conserve water and reduce the demand for hot water
- Select appropriate materials in order to reduce environmental impacts
- Reduce energy use in all aspects of building operations
- Consider building energy efficiency before introducing renewable energy offsets

Table 4 Design strategies for ZCB

Often, the design of ZCB/ZEB requires dynamic building energy simulation and modelling in order to evaluate design options and control strategies (Jankovic, 2012). Numerical assessment and calculations are needed for the validation of the ZCB design. Usually the information obtained from building energy simulation is critical for estimating and monitoring energy use and related GHG emissions. It is also helpful to invoke life cycle assessment in the building development, design and management process (Hernandez and Kenny, 2010).

The Hong Kong Context

Over 60% of GHG emissions in Hong Kong are from buildings (Hui, 2012). When promoting ZCB and applying carbon footprint concepts to assess buildings in densely populated cities like Hong Kong, some key factors for urban density and community sustainability should be carefully considered.

Urban Density

With a sub-tropical, hot and humid climate, Hong Kong is a densely populated city with many high-rise buildings. The land and space available for housing the population are very limited. Fortunately, Hong Kong has a highly efficient mass transit and public transportation system, which can greatly reduce transport energy consumption and the associated GHG emissions from private vehicles. Most current ZCBs are low-rise, with the attainment of zero carbon often considered impossible for high-rises due to enormous difficulties in socio-technical perspectives (Pan and Ning, 2014). High-rise buildings in urban areas are problematic candidates for ZCB. More creative ideas and innovative technologies are needed to overcome the difficulties and constraints of designing ZCB or low energy building in such a high density city (Hui, 2001). Preliminary exploration into ZCB/ZEB in low-rise residential buildings in Hong Kong may be helpful for developing future ZCB design strategies (Fong and Lee, 2012).

If Hong Kong is to achieve green building for society, comprehensive urban planning and efficient high-performance building designs are needed to control and reduce GHG emissions in high-rise, high-density building developments and the broader urban environment. By integrating a sustainable transportation strategy and urban form and typology, it is possible to significantly improve the urban living environment and building performance. To achieve these objectives, it is important to develop a clear green building policy and foster lifecycle thinking in building development, design and management for the whole of society. It is believed that carbon footprint analyses will be useful for developing effective assessments and guidance for key decision makers.

Community Sustainability

In Hong Kong, achieving ZCB on an individual basis is not easy (Civic Exchange, 2011). However, high population densities and the city's compact buildings provide opportunities for implementing larger scale community based energy systems and cost-effective energy and utility supply arrangements (Hui, 2001). At the community level, if the infrastructure for society and/or districts are planned and designed to optimise overall system efficiency and reduce the carbon footprint, a 'zero carbon community' could be established. For example, the use of district cooling systems, a waste-to-energy recovery approach, centralised solar thermal or other renewable energy systems, and community based greening and water recycling programmes can be applied to increase overall resource efficiency and environmental performance, and to reduce the community's overall GHG emissions.

By integrating architectural design, energy systems, community facilities, social development and environmental resources into a coordinated comprehensive approach, resource efficiency can be optimised. Holistic zero carbon or carbon neutral design seeks to reduce GHG emissions associated with all aspects of a project. The carbon footprint assessment for a project in Hong Kong will require consideration of the neighbourhood, and local or regional planning issues, as well as human activities directly or indirectly affected by the sustainable community measures.

Conclusions

Many countries in the world are developing zero- or low-carbon buildings in order to reduce GHG emissions and improve awareness of environmental design. It is believed that ZCB/ZEB will lead the transition into low-carbon societies. In the near future, ZCB and low-carbon buildings will become mainstream architecture. To overcome the barriers to ZCB, a clear definition and effective assessment methods are urgently needed. By examining the meaning of ZCB/ZEB and the rationale for using carbon footprints as indicators to measure sustainability, it is possible to improve the understanding of zero carbon life cycle design, and develop clear scientific calculation methods for evaluating ZCB and other building projects.

It should be noted that the market demand for ZCB/ZEB is still limited. The progression of green/sustainable building design to include issues of carbon is highly complicated. At present, the application of carbon footprints and other footprint-based assessments are often hindered by limited data availability and data uncertainties. More work is needed to develop reliable data and information for footprint or sustainability assessments of buildings. By developing integrated interdisciplinary ZCB design and technologies, and integrating environmental, social and economic considerations during decision making, it is hoped that an effective strategy can be developed to reduce GHG emissions and combat climate change.

To conclude, 'zero carbon' is a lifestyle, not a specific criterion. ZCB is created using a variety of means to reduce pollution, promote the rational use of waste, and encourage the use of clean energy sources to reduce GHG emissions. The ultimate aim is to achieve 'zero waste', 'zero energy' and 'zero carbon' in an ideal state. This spirit can be extended to zero-carbon transport, zero-carbon energy, zero carbon homes, as well as zero-carbon cities.

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