CONSTRUCTION INDUSTRY COUNCIL
建造業議會

ZCB Zero Carbon Building JOURNAL

Volume 3 January 2015

Towards Zero Carbon

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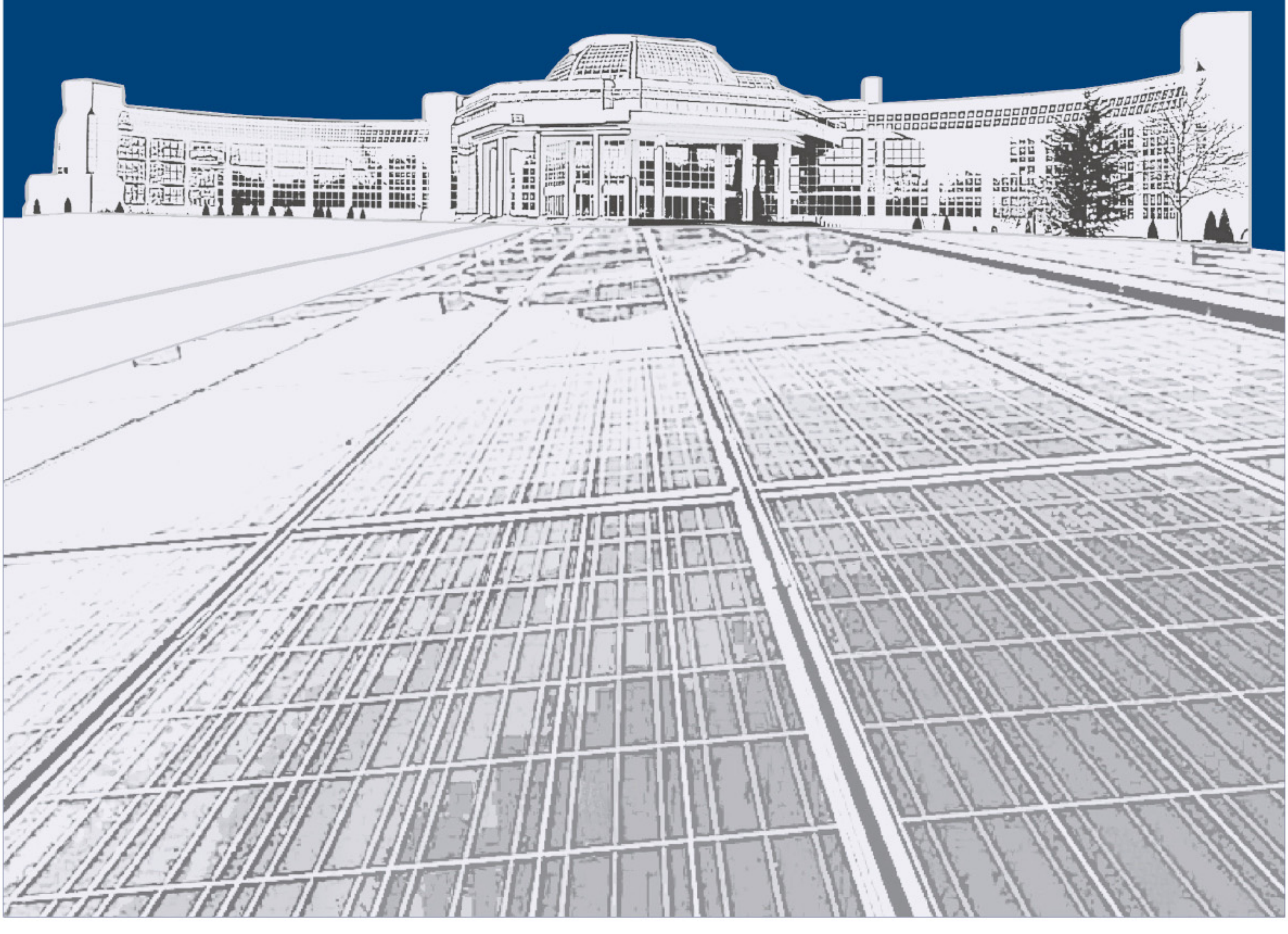

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ISSN 2311-7400

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Zero Carbon Building Journal is
Design and Published by
Edge Media Limited
www.edgemedia.com.hk

Printed in Hong Kong

FSC MIX Paper from responsible sources
www.fsc.org FSC® C003609

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Preface

Mr YU Wai-wai, JP
Chairman, Zero Carbon Building Limited

For hundreds of years, Hong Kong has always been in a very unique position for every aspect of life.

Today, carbon neutral and net-zero energy design are key design concepts in our society. When successfully applied to a high-density high-rise urban environment, these designs will effectively minimise resource use and reduce the environmental impacts of our building ecologies throughout their life cycles while improving comfort for the occupants.

The vision for ZCB is to become a leading exhibition, information and education center for low/zero carbon building practices. Being the first zero carbon building in Hong Kong, we tackled the problem of climate change through reduction of greenhouse gas emissions, onsite renewable energy generation and minimising initial and recurring embodied energy.

ZCB showcases low/zero carbon building design and technologies to the construction industry with a view to promote their wider application in Hong Kong. We hope, our ***Zero Carbon Building Journal***, will pave the way for the construction industry to share ideas, research, practical applications, and further identify ways for Hong Kong to transition into a low carbon built environment.

As a leading world city, our society's awareness of this new ethos of living is paramount. This transition requires voluntary schemes as well as a regulatory framework that encourage practices beyond existing standards, while supported by valid cost evaluations and propositions, which are crucial considerations for all of us. Only with the collaborative and integrated efforts of HK Government, statutory bodies such as the Construction Industry Council, various stakeholders and the broader community, the vision for Hong Kong as a leading competitive, low carbon and sustainable city can be realised.

We hope that ZCB, as a pioneering and signature project in Hong Kong, has contributed to the unfolding of this journey.

Mr YU Wai Wai
Chairman
Zero Carbon Building Limited

Editorial

There are various definitions of zero carbon buildings or zero energy buildings. They all have one thing in common—significant reduction in building energy consumption and use of renewable energy sources. Even with today's technologies, achieving zero carbon emissions for high-rise buildings remains a significant challenge. This is fully substantiated by Wei Pan and Kaijian Li in their review of clusters of some 404 zero carbon buildings across the world and by Sam C.M. Hui who provides a critical evaluation of zero carbon buildings in high density urban cities.

None the less, what is important is that the best available technologies for reducing building energy consumption and for utilising renewable energy sources are applied to all new buildings wherever possible, regardless of whether it is a low-rise, high-rise, residential, commercial or institutional building. This is the spirit of this Journal! This issue brings to readers a collection of international zero carbon building practices and experiences, much of which has relevance for Hong Kong.

The United Kingdom (UK) has been at the forefront in reducing the carbon footprint of buildings through the government's ambitious policy that all new homes need to be zero carbon from 2016. Much effort and preparation have been made by the UK building industry to achieve the target. As a result, the UK principle of 'fabric first', followed by on site renewable energy generation and an allowance to mitigate any remaining carbon near or off site, is being considered by other countries around the world. Rob Pannell gives a comprehensive summary of the UK experience in delivering zero carbon housing, which also touches on the common problem of performance gaps and costs. A key message behind the UK experience is that government leadership is critical in transforming to a low carbon built environment.

Zero carbon building practices around the world today primarily focus on new buildings while most of the electricity is actually consumed by the existing building stock. Aurélie Cleraux, Ronald Le Roux and Devani Perrera show us a way forward by demonstrating how a zero carbon renovation is achieved for a large existing office complex in France. Aside from achieving zero carbon emission, the renovated office complex also achieves zero waste water and enhances local biodiversity.

Lei Shi presents a detailed account of net zero energy building practice in Qingdao, China, whereby the ventilation system has to cater for both summer cooling and winter heating. Jimmy Tong, Jason Tse and Raymond Yau present a number of low/zero carbon building case studies and emphasize the importance of going beyond individual buildings to development at a community level. This is also echoed by Rob Pannell in his UK experience and by Chi-kwong Chan and Edwin Chan in their paper on principles of policy for low carbon built environment.

The 'fabric first' principle is also strongly supported by T.T. Chow who discusses a range of state-of-the-art façade technologies to achieve zero carbon. Photovoltaic (PV) panels are the most common and generally considered the most affordable means of renewable energy generation. Cost concerns have been a major factor inhibiting their wider application. As such, many countries provide subsidies for the use of PV panels and have a feed-in tariff policy to promote wider adoption. Contrary to common belief, Hongxing Yang, Lin Lu, Jinqing Peng and Aotian Song's research advocates that there is significant potential for renewable energy generation from PVs in Hong Kong. With the continual reduction in costs, they predict that PV generated electricity is expected to be able to fully compete with traditional modes of electricity generation in the near future. A main challenge facing Hong Kong is whether it has the will for large scale adoption of these technologies, such as turning the rooftops of low-rise residential buildings/village houses in the New Territories, or unsightly rooftops of high-rises into solar farms for example.

Dr Guiyi Li
Chief Editor

A Cluster Analysis of 'Zero Carbon Buildings'

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The 'zero carbon building' approach has been promoted in many countries and regions to address anthropogenic climate change. As a result, many 'zero carbon buildings' have emerged worldwide, with more in the pipeline. Cross-context learning of the practices is thus important, but is severely constrained, with a perceived knowledge gap particularly on achieving zero carbon for high-rise buildings. The aim of this paper is to reveal the clusters of 'zero carbon buildings' reported worldwide, in order to elaborate on the perceived knowledge gap, and to support efficient cross-context learning. The examination was carried out through a two-step cluster analysis of 404 reported 'zero carbon buildings' identified through an onerous search process. The 'zero carbon building' clusters were revealed using a number of variables including building ownership, climatic zone, building type, location, and number of storeys. Five clusters of 'zero carbon buildings' were revealed, indicating the dominance of low-rise new-build residential buildings in temperate zones. The significant paucity of high-rise cases is clearly identified. The findings should help with understanding the complex profiles of 'zero carbon buildings', and support cross-context learning of the practices.

Keywords: zero carbon building, cluster analysis, high-rise, learning

Dr Wei Pan is an academic based at The University of Hong Kong specialised in sustainable construction and management. His research interest focuses on zero carbon building, prefabrication and technological innovation. He is a Chartered Builder, Chartered Environmentalist and Fellow of the Higher Education Academy. He has 20 years of working experience in academia and practice internationally in building engineering, construction innovation and management.

Kaijian Li is a researcher specialised in zero carbon building solutions. His research interests focus on off-site prefabrication and lean construction. Currently, he is a research assistant at The University of Hong Kong, working on the topics of high-rise low/zero carbon buildings and lean construction standards and tools in Hong Kong.

Introduction

The 'zero carbon building' approach has been promoted in many countries and regions to address anthropogenic climate change (see e.g. Koch *et al*., 2012; Panagiotidou and Fuller, 2013; Pan and Ning, 2015). As a result, many 'zero carbon buildings' have emerged worldwide, with more in the pipeline (Musall, 2013; Pan, 2014). Cross-context learning of the practices is thus important, though is severely constrained, with a perceived knowledge gap particularly in achieving zero carbon for high-rise buildings (Pan and Ning, 2014). Previous research on zero carbon building has debated on the term and methodology, e.g. net, nearly or lifecycle zero carbon or zero energy (see Kibert and Fard, 2012; Marszal *et al*., 2011), and on policy (Pan and Ning, 2015). More recent research explores the systematic understanding of zero carbon building practices, e.g. dynamic simulation for designing zero carbon buildings (Jankovic, 2012) and system boundaries of zero carbon buildings (Pan, 2014). However, there is a lack of studies of the patterns and profiles of zero carbon buildings that have emerged and been reported. The perceived gap in knowledge on achieving zero carbon for high-rise buildings remains largely anecdotal.

The aim of this paper is thus to reveal the clusters of 'zero carbon buildings' reported worldwide, in order to elaborate on the perceived knowledge gap, and to facilitate cross-context learning. The paper first reviews the concept of zero carbon building and examines the variables for studying the profiles and patterns of zero carbon buildings. It then examines 404 'zero carbon buildings' identified through a two-step cluster analysis, and then elaborates on the revealed 'zero carbon building' clusters. The paper finally discusses the implications of the identified knowledge gap for achieving zero carbon for high-rise, drawing on the case of Hong Kong as a typical urban environment.

The Concept of Zero Carbon Building

Research on buildings' energy and carbon emissions dates back to at least the 1940s (Da Graca *et al*., 2012), but the concept of 'zero carbon building' probably first emerged in 2006, in the United Kingdom (UK) Government's policy publication seeking a step-change in sustainable homebuilding practice (DCLG, 2006). The UK Government's zero carbon building policy signaled the start of government policy promotion for the zero carbon building approach in many other countries and regions. In addition to 'zero carbon homes' and 'zero carbon non-domestic buildings' in the UK (DCLG, 2008), a number of similar but different terms, often used interchangeably, have emerged. They are mostly associated with their relevant policy frameworks, e.g. 'nearly zero-energy building' in the European Union (EU) (European Commission, 2010), 'zero emission building' in Australia (ASBEC, 2012; Riedy *et al*., 2012), and 'net-zero energy buildings' in the United States (US) (Energy Independence and Security Act, 2007; Federal Office, 2009).

Some researchers have expanded the scope of the 'zero carbon building' concept to also include many other relevant building energy and carbon concepts/terms in their studies. For example, the Concerted Action report (Erhorn and Erhorn-Klutt, 2011) presents 23 different terms under the banner 'high performance buildings', which are used in 14 EU member states. They suggested that the many terms could be broadly categorised as referring to low energy consumption (e.g. low energy house, energy saving house, ultra-low energy house, 3-litre-house[1], zero heating energy house, zero energy house, plus energy house, very low energy house, energy self-sufficient house and energy autarkic house); low emissions (e.g. zero emission house, zero carbon house, emission-free house and carbon free house); or sustainable or green aspects (e.g. eco-buildings, green buildings, code for sustainable homes, bioclimatic house and climate: active house). For another example, Riedy *et al*. (2012: iv) reviewed the definitions and identified many similar terms in common use, such as 'near zero energy; zero energy; zero net energy; passive house; energy plus; fossil fuel free; 100% renewable; zero carbon; net zero carbon; carbon neutral; climate neutral; climate positive and positive development.' Most of these terms are used in actual building projects targeting 'zero carbon'. The many terms coupled with their associated policies, calculation methodologies and practices make the concept of zero carbon building so complicated that learning the practices in different contexts becomes difficult if not impossible. To examine the variables, or attributes, of zero carbon buildings emerging in different contexts is thus critical to build up an effective understanding of practices and cross-context learning.

The Variables of 'Zero Carbon Buildings'

Previous studies have examined the metrics of zero energy buildings, the characteristics of net zero energy buildings, and the system boundaries of zero carbon buildings. Torcellini *et al*. (2006: 5) proposed several definitions of zero energy buildings, depending on metrics including site, energy source, energy cost, and energy emissions, and differentiating supply side options of on site net zero energy buildings from off site counterparts that have a portion of their renewable generation supplied by off site sources. Marszal *et al*. (2011) advanced the systems thinking of Torcellini *et al*. (2006) by developing a framework of the seven most important issues in defining zero energy buildings, namely: the metric of the balance; the balancing period; the type of energy use included in the balance; the type of energy balance; the accepted renewable energy supply options; the connection to the energy infrastructure and the requirements for energy efficiency; the indoor climate; and in the case of grid-connected zero energy buildings, the building grid interaction. Sartori *et al*. (2012) described the characteristics of net zero energy buildings using the five criteria and sub-criteria of the building system boundary (the physical boundary, balance boundary and boundary conditions), weighting system (the metrics, symmetry and time dependent accounting), net zero energy building balance (the balancing period, type of balance, energy efficiency and energy supply), temporal energy match characteristics (the load matching and grid interaction) and measurement and verification. Their framework explored the boundaries of zero energy buildings and embedded the systems approach.

The varied terminologies and definitions may be confusing and pose problems for communication. Riedy *et al*. (2012) identified a number of key points of difference between the definitions of zero carbon buildings. These are life cycle boundary, assessment methods and metrics, timeframe, grid connection, sector differences, building type, spatial boundary, allowable emission reduction options and conditional requirements. This framework expands the components and boundaries of zero energy buildings which were identified in previous research, and was useful for shaping a suitable definition. However, the theoretical grounds on which the 'key points of difference' were identified are unclear. This restricts the quality of comparisons with existing definition frameworks and therefore limits its transferability. The 'key points' also mix the boundaries

[1] A pilot project in Germany, designed to consume only 3 litres of heating petrol fuel per m^2 per annum.

with the assessment methods and requirements of zero carbon buildings which require clarification. Pan (2014) advocated that zero carbon buildings are complex socio-technical systems and developed a conceptual model of system boundaries of zero carbon buildings. This model specifies eight types of boundaries: the policy timeframe, building lifecycle, geographical, climatic, stakeholder, sector, density and institutional boundaries. Pan (2014) argued that without an explicit specification of the boundaries, a comparison of cases in different contexts is like 'comparing apples to pears'.

However, no previous research has explicitly examined the variables of 'zero carbon buildings'. This may be attributed to the many similar but different concepts/terms, relevant to building energy and carbon, and their different policy contexts. This may also be due to the different methodologies for calculating the energy consumption and carbon emissions of buildings and the subsequent difficulties in benchmarking and cross case comparisons. These factors hinder elaboration of the knowledge gaps of zero carbon building and effective cross-context learning.

Methodology

The research was carried out through a two-step cluster analysis of zero carbon buildings which were identified through an onerous search process. The variables used for the analysis were first identified through a literature review of the metrics, characteristics and system boundaries of zero carbon or zero energy buildings, and then narrowed down to several critical ones through cluster analysis.

Identification of 'Zero Carbon Buildings'

The concept of zero carbon building is complex, coupled with a number of similar but different concepts and terms. While no previous research has explicitly examined the variables of 'zero carbon buildings', the studied metrics, characteristics and system boundaries of zero carbon or zero energy buildings vary from each other. These factors rendered the identification of 'zero carbon buildings' for the present analysis difficult. Also, not many building cases report their designed energy performance and carbon emissions, fewer still with measured data. Those that report relevant data often do not provide details of the scope of energy use and carbon emissions and their calculation methodology. These factors made any verification of the claimed 'zero carbon' or 'zero energy' or effective cross comparison of cases virtually impossible. Therefore, the identification of 'zero carbon buildings' for this study was based on three considerations: (1) the keywords of net, nearly and/or lifecycle zero carbon or zero energy building were used to describe and report the cases; (2) information was available on the identified building cases from publicly accessible sources and channels; and (3) the search for the cases of zero carbon buildings was not constrained to specific countries, but aimed to represent a worldwide overview of practices.

Three important sources were identified in the search. First was the database in the form of Google maps view developed by the research group within the International Energy Agency's 'Towards Net Zero Energy Solar Buildings' Project (Musall, 2013). This database analyses and evaluates the conceptual approaches and performances of 'net zero-energy and energy-plus buildings' worldwide, as of June 2013, with a primary focus on Germany and the rest of Europe. This database also presents basic project data and provides web-links to most of the projects included. Second was 'Low Impact Housing', in the form of a website with a search function that was the outcome of a survey of low impact houses in the world, with a focus on North America (LIH, 2006). The building profiles in this source were provided through a two-round survey with relevant professionals and professional organisations. Third was a source provided by the Zero Carbon Hub, which is an independent non-profit public/private partnership, established to take on the day-to-day operational responsibility for coordinating the delivery of low and zero carbon new homes in the UK (ZCH, 2013). These sources were complemented by a wide search over the internet taking into account the three above mentioned considerations. Through the search, 600 'zero carbon buildings' were initially identified for this study.

Variables Considered for Cluster Analysis

In addressing the aim of this paper to examine the patterns of the identified zero carbon buildings worldwide, an analysis was carried out using descriptive and explanatory variables of the building cases. The descriptive variables help to describe the tangible features of the cases, and include year of completion, climatic zone, building type, location, number of storeys and building size. The explanatory variables help to explain the less tangible features of the cases to enable a better understanding of the patterns of the cases, and include building ownership, status, grid connection, and geographic boundary. The use of the combined variables helps to elaborate the perceived knowledge gap and to reveal 'zero carbon building' clusters for more effective cross-context learning of the practices.

However, the energy use and carbon emissions of the buildings are not included in the analysis reported in this paper for three reasons. First, some of the zero carbon buildings identified do not provide estimated and/or measured energy use or carbon emissions; many do not specify the scope of energy use or carbon emissions, hence have no detailed data on the energy and carbon for lighting, ventilation, heating/cooling, hot water, etc. Second, the underlying methodologies for calculating the buildings' energy use and carbon emissions varied from one country/region to another, e.g. the UK (ZCH, 2013), US (Energy Independence and Security Act, 2007; Federal Office, 2009) and EU (European Commission, 2010).

Third, the policy targets for the 'zero carbon' standards changed in recent years even in the same countries/regions, e.g. the evolution of energy performance requirements towards net zero energy buildings levels in Denmark (Erhorn and Erhorn-Kluttig, 2012), and the changes to zero carbon building policies and targets in the UK (Pan and Ning, 2015). These factors made the benchmarking and cross comparison of energy use and carbon emissions of the building cases identified worldwide a 'mission impossible'.

The variables considered for cluster analysis are further explained below:

- 'Year of completion' denoted the year of construction or renovation of the building;

- 'Climatic zone' was used as a proxy for the geographic location of the building, which followed the Köppen climate classification scheme that divides climates into five main groups, each having several types and subtypes, and combines average annual and monthly temperatures and precipitation, and the seasonality of precipitation (Peel *et al.*, 2007);

- 'Building type' denoted the functional type of the building, e.g. experimental buildings that were built to demonstrate or test low or zero carbon technologies and were usually owned by clean energy suppliers, institutions, or government sectors; services buildings included recreation and transportation facilities such as sports centre and land port of entry;

- 'Location as per density' denoted the location of the building in relation to urban density, e.g. urban areas that were characterised by higher population density and vast human features, suburban areas stood for an outlying part of a city or town or a smaller community adjacent to or within commuting distance of the urban area, and rural areas that were neither urban nor suburban;

- 'Number of storeys' referred to the building's maximum number of storeys;

- 'Building size' denoted the gross floor area (GFA) of the building, inside the building envelope, including the external walls but excluding the roof;

- 'Building ownership' referred to the sector of the primary ownership of the building, e.g. public buildings that were government funded, including government offices, educational buildings, transportation infrastructures, public affordable houses, and recreation facilities etc.; private buildings that were owned by private developers or individuals, including private houses, commercial buildings and private offices etc.; and mixed-ownership buildings that were jointly developed by government and private developers or individuals;

- 'Building status' meant the major status of the building, e.g. new-build, renovation and mixed;

- 'Grid connection' described if and how the building was connected with a power grid. Those buildings that produced energy on-site and fed electricity into the mains or national grid were categorised as 'on-grid (two-way)'; those that only took electricity from a grid but did not feed into the mains or national grid were categorised as 'on-grid (one-way)'; those that were not connected with the mains or national grid were termed 'off-grid'; and

- 'Geographical boundary' referred to the scope of the facility in relation to energy and carbon, e.g. the building itself, the project, the community or the city.

Method of Cluster Analysis

The SPSS TwoStep Cluster method was applied to identify the 'zero carbon building' clusters. The method was designed to discriminate natural groups from a set of variables stabilising the nearness criterion, with a hierarchical agglomerative clustering whose centres are far apart (Fraley and Raftery, 1998). Likelihood was selected as the distance measure, which defines the normal density for continuous variables and the multinomial probability mass function for categorical variables (Fraley and Raftery, 1998). Compared to classical cluster analysis methods, SPSS TwoStep Cluster can deal with both continuous and categorical attributes. Moreover, the method can automatically determine the optimal number of clusters. The SPSS TwoStep Cluster involved the following two steps:

- Pre-clustering step: the data records were scanned one by one and the algorithm decided whether the current record could be added to one of the previously formed clusters, or it started a new cluster, based on the distance criterion;

- Clustering step: the clustering stage had sub-clusters resulting from the pre-cluster step as input and grouped them into the optimal number of clusters. To determine which number of clusters was optimal, each of these cluster solutions was compared using Schwarz's Bayesian Information Criterion (BIC) as the clustering criterion. An optimal number of clusters will have a smaller BIC value, a reasonably large Ratio of BIC Changes, and a large Ratio of Distance Measures.

Silhouette coefficient (Rousseeuw, 1987), a measure of density of all the data in the cluster, was utilised to measure the goodness-of-fit of the outcome. This index combines both cohesion (based on the average distances between all the objects in a cluster) and separation (based on the average distance of any object to all the other objects not contained in the same cluster), and can range between -1 and +1; values below 0 are indicative of inappropriate fit, between 0 and 0.2 are considered to be poor, between 0.2 and 0.5 are fair, and indices above 0.5 are good.

Results and Analysis

Variables and Relevant Values

Six descriptive and four explanatory variables were initially considered for the cluster analysis (Table 1). The use of a combination of these variables aimed to enable a better understanding of the patterns of the building cases and elaborate the perceived knowledge gap. The results of the analysis of the identified zero carbon buildings indicate diverse values or a wide range of values of the building cases against the variables (Table 1).

Variable	Type	Identified values or the range of values
Year of completion	Descriptive; Ordinal	From 1988 to 2014
Climatic zone	Descriptive; Nominal	Tropical, arid, temperate, cold, polar and breakdown climatic zones
Building type	Descriptive; Nominal	Residential, commercial, services, industrial, experimental, educational, mixed use
Location as per density	Descriptive; Nominal	Urban, sub-urban, rural
Number of storeys	Descriptive; Scale	From 1 to 71
Building size	Descriptive; Scale	From 40 to 32,4975m²
Building ownership	Explanatory; Nominal	Public, private, mixed
Building status	Explanatory; Nominal	New-build, renovation, mixed
Grid connection	Explanatory; Nominal	On-grid (two-way), on-grid (one-way), off-grid
Geographic boundary	Explanatory; Nominal	Low-rise building, med to high-rise building, development, project, community, city, island

Table 1 The range and values of the variables for cluster analysis

The Optimal Number of Clusters and Relevant Variables

In order to reveal the 'zero carbon building' clusters more effectively, all the variables were further examined. This examination involved three considerations: (1) to avoid variables that were dominated by only one value of the variables; (2) to avoid variables that included significant missing data; and (3) to use the resultant silhouette coefficient of 0.2 or above as a control.

Taking into account the first consideration, it was decided the 'building status' variable would not be included in the cluster analysis. This was because the building cases against this variable were dominated by 'new-build' 'zero carbon buildings' (506; 87.7%).

Taking into account the second consideration, it was also decided the variables 'grid connection' and 'building size' would not be included in the cluster analysis. This was because of missing data for a significant number of building cases against these two variables: 217 (36.2%) and 205 (34.2%), respectively.

After that, a preliminary cluster analysis was conducted using the remaining seven variables. However, the resultant silhouette coefficient was equal to 0.1, considered poor and indicated that goodness-of-fit was not achieved. Therefore, taking into account the third consideration as well as the purpose of revealing meaningful clusters, the seven variables were further narrowed down to five: building ownership, climatic zone, building type, location as per density, and number of storeys. As a result, 404 (67.3%) of the zero carbon buildings were included in the further analysis.

With the five final variables, each of the cluster solutions was compared using Schwarz's BIC as the clustering criterion in order to determine the optimal number of clusters. The optimal number of clusters should have a smaller BIC value, a reasonably large Ratio of BIC Changes and a large Ratio of Distance Measures. The results of this analysis suggest that the optimal number of clusters was five, with a smaller BIC value (2353.658), a larger Ratio of BIC Changes (0.311) and a larger Ratio of Distance Measures (1.549) (Table 2). These results suggest that goodness-of-fit was achieved, with fair average silhouette coefficient equal to 0.30.

Number of Clusters	Schwarz's Bayesian Information Criterion (BIC)	BIC Change[a]	Ratio of BIC Changes[b]	Ratio of Distance Measures[c]
1	3435.351	-	-	-
2	2965.696	-469.655	1.000	1.403
3	2658.389	-307.306	0.654	1.584
4	2499.766	-158.623	0.338	1.052
5	**2353.658**	**-146.108**	**0.311**	**1.549**
6	2293.357	-60.301	0.128	1.001
7	2233.150	-60.207	0.128	1.231
8	2202.264	-30.885	0.066	1.160
9	2188.877	-13.388	0.029	1.105
10	2185.910	-2.966	0.006	1.199
11	2199.344	13.434	-0.029	1.125
12	2221.933	22.589	-0.048	1.001
13	2244.584	22.651	-0.048	1.061
14	2271.461	26.878	-0.057	1.017
15	2299.496	28.034	-0.060	1.355

Table 2 The indices for identifying the optimal number of clusters

a. The changes are from the previous number of clusters in the table

b. The ratios of changes are relative to the change for the two cluster solution

c. The ratios of distance measures are based on the current number of clusters against the previous number of clusters

The Clusters Revealed

Through the two-step cluster analysis, five 'zero carbon building' clusters (404; 67.3%) were revealed. These clusters involved the use of five variables: building ownership, climatic zone, building type, location as per density, and number of storeys. These five clusters (Figure 1) comprised sample sizes of 86 (21.3%), 75(18.6%), 100 (24.8%), 54 (13.4%), and 89 (22.0%). The ratio of sizes, comparing the largest to smallest cluster, was 1.85. Figure 1 illustrates the accumulative distribution of the building cases grouped in the five clusters against the five critical variables.

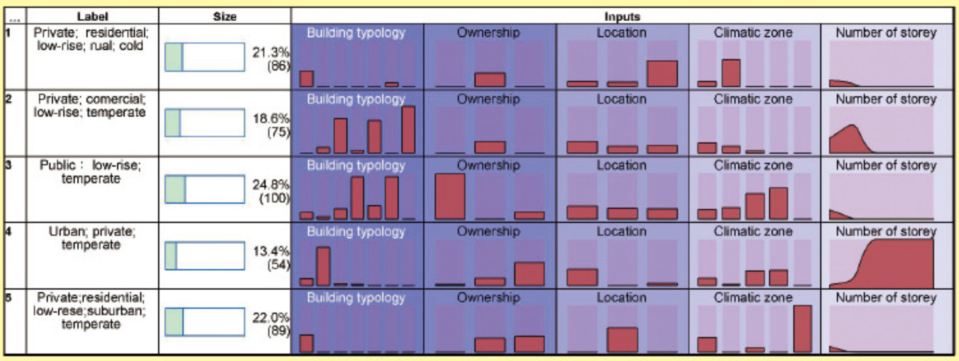

Figure 1 Profiles of the revealed clusters of 'zero carbon buildings'

The revealed five clusters (Table 3) were:

- **Cluster 1** - dominated by private (100%) residential (98.8%) low-rise (2.31) rural (60.5%) zero carbon buildings in the cold zone (65.1%);
- **Cluster 2** - dominated by private (100%) commercial (77.3%) low-rise (3.41) zero carbon buildings in the temperate zone (80%);
- **Cluster 3** - dominated by public (99%) low-rise (2.42) zero carbon buildings in the temperate (58%) zone;
- **Cluster 4** - dominated by private (88.9%) urban (92.6%) zero carbon buildings in the temperate (77.8%) zone; and
- **Cluster 5** - dominated by private (97.8%) residential (100%) low-rise (2.36) suburban (100%) zero carbon buildings in the temperate (95.6%) zone.

Variable	Total sample (n=404)		Cluster1 (n=86)		Cluster 2 (n=75)		Cluster 3 (n=100)		Cluster 4 (n=54)		Cluster 5 (n=89)	
Building type - residential	246	(100.0%)	85	(34.6%)	0	(0.0%)	36	(14.6%)	36	(14.6%)	89	(36.2%
Building type - commercial	79	(100.0%)	0	(0.0%)	58	(73.4%)	18	(22.8%)	3	(3.8%)	0	(0.0%)
Building type - services	12	(100.0%)	1	(8.3%)	0	(0.0%)	11	(91.7%)	0	(0.0%)	0	(0.0%)
Building type - industrial	6	(100.0%)	0	(0.0%)	6	(100.0%)	0	(0.0%)	0	(0.0%)	0	(0.0%)
Building type - experimental	10	(100.0%)	0	(0.0%)	7	(70.0%)	3	(30.0%)	0	(0.0%)	0	(0.0%)
Building type - educational	34	(100.0%)	0	(0.0%)	2	(5.9%)	31	(91.2%)	1	(2.9%)	0	(0.0%)
Building type - mixed use	17	(100.0%)	0	(0.0%)	2	(11.8%)	1	(5.9%)	14	(82.4%)	0	(0.0%)
Ownership - public	102	(100.0%)	0	(0.0%)	0	(0.0%)	99	(97.1%)	3	(2.9%)	0	(0.0%)
Ownership- private	296	(100.0%)	86	(29.1%)	75	(25.3%)	0	(0.0%)	48	(16.2%)	87	(29.4%)
Ownership - mixed	6	(100.0%)	0	(0.0%)	0	(0.0%)	1	(16.7%)	3	(50.0%)	2	(33.3%)
Location - urban	140	(100.0%)	16	(11.4%)	35	(25.0%)	39	(27.9%)	50	(35.7%)	0	(0.0%)
Location - suburban	72	(100.0%)	18	(25.0%)	25	(34.7%)	40	(55.6%)	0	(0.0%)	89	(23.6%)
Location - rural	92	(100.0%)	52	(56.5%)	15	(16.3%)	21	(22.8%)	4	(4.3%)	0	(0.0%)
Climatic zone - tropical,	9	(100.0%)	0	(0.0%)	0	(0.0%)	6	(66.7%)	3	(33.3%)	0	(0.0%)
Climatic zone - arid	22	(100.0%)	0	(0.0%)	1	(4.5%)	12	(54.5%)	7	(31.8%)	2	(9.1%)
Climatic zone - temperate	276	(100.0%)	30	(10.9%)	60	(21.7%)	58	(21.0%)	42	(15.2%)	86	(31.2%)
Climatic zone - cold	96	(100.0%)	55	(57.3%)	14	(14.6%)	24	(25.0%)	2	(2.1%)	0	(0.0%)
Climatic zone- polar	1	(100.0%)	0	(0.0%)	0	(0.0%)	0	(0.0%)	0	(0.0%)	1	(100.0%)
Number of storeys	3	(5.04)	2	(1.32)	3	(3.03)	2	(1.12)	7	(12.56)	2	(0.83)

Table 3 Comparison between the revealed clusters

Note: Values against the variable 'Number of storeys' are the integers closest the relevant means, with the standard deviation in brackets. Values against the other variables are numbers of building cases, with shares in brackets.

Discussion

The profiles of 'zero carbon buildings' are perceived to be complex due to the many concepts and terms and their unique policy contexts and varied methodologies for calculating buildings' energy use and carbon emissions. This paper revealed five 'zero carbon building' clusters that have emerged and been reported worldwide.

The results of the 'zero carbon building' clusters indicate the dominance of new-build, low-rise residential buildings in temperate zones. This dominance can be explained by several factors. First, the bulk of research on zero carbon building in the literature is focused on low-rise residential buildings (see e.g. Bojic *et al*., 2011; Leckner and Zmeureanu, 2011). There are general perceptions that it is not feasible to achieve 'zero carbon' or 'zero energy' for high-rise buildings due to their high energy demand and limited renewable energy technology (see e.g. Fong and Lee, 2012). Second, new-build homes in the residential sector are a high priority for government policies on 'zero carbon' or 'zero energy'. For example, the UK policy targets achieving zero carbon new-build homes from 2016 (DCLG, 2007), followed by zero carbon non-domestic buildings from 2019 (HM Treasury, 2008); US policy in California specifies all new residential construction in California to achieve zero net energy by 2020, followed by all new commercial construction in California to achieve zero net energy by 2030 (California Public Utilities Commission, 2008).

The analysis of the zero carbon building clusters was carried out using six descriptive variables and four explanatory variables, which together helped to describe and explain the their features. Nevertheless, the energy use and carbon emissions of the buildings were not included in the analysis because of insufficient information on them, and inconsistent definitions and methodologies for calculating them. Future research can obtain and verify the data on the buildings' energy use and carbon emissions to enable effective cross comparisons. For such research, the unit of balance, period of balance, energy scope and any connection with the grid should be explicitly identified. Analyses drawing on such future research should elicit a better understanding of the performance of 'zero carbon buildings'.

The strategies for achieving 'zero carbon' adopted in the buildings were not included in the analysis. However, a preliminary check suggests that many of the zero carbon buildings in all five clusters have adopted a range of low or zero carbon technologies, for both building energy efficiency, and energy generation and supply. Despite the diversity of technologies adopted, the preliminary check indicates that the buildings' energy efficiency strategies addressed building envelope, ventilation, heating, cooling and lighting, and the energy generation and supply strategies included predominantly PV plus other technologies such as solar thermal, wind, biofuel, geothermal, combined heat and/or power district heating etc. The buildings clearly demonstrated systems integration of design strategies including passive design and energy efficiency and renewable energy technologies.

From the analysis, the paucity of high-rise cases is clearly identified. The results substantiate the perceived knowledge gap in zero carbon for high-rise buildings. Hong Kong is a typical case of an urban environment for high-rise buildings. In Hong Kong, buildings consume 90% of the electricity and contribute 60% of the carbon emissions of the city (EPD and EMSD, 2010), which are much higher than worldwide averages in the range of 30-45% (Butler, 2008; Pan and Garmston, 2012). Hence, buildings in Hong Kong impose an even more significant challenge to, but also offer a better opportunity for carbon emission reductions.

The Construction Industry Council (CIC, 2012) in Hong Kong completed the first 'Zero Carbon Building' ('ZCB') in Hong Kong in June 2012. The estimated operational energy use of the building (116MWh/year) and the landscape area and others (15MWh/year) is to be offset by the estimated output from a biodiesel tri-generation system (143MWh/year) coupled with PV panels (87MWh/year), yielding an estimated surplus energy export of 99MWh/year via grid-feed-in. However, this 'ZCB' is only three storeys high including the basement, with a building footprint of approximately 1400m^2 and a landscape area for public use on a 14,700m^2 site (CIC, 2012). The features of the 'ZCB' are drastically different to the vast majority of buildings in Hong Kong, which are high-rise and high-density. Despite growing practices of low carbon buildings in Hong Kong, the design and delivery of high-rise zero carbon buildings in dense urban environments are still largely unknown (Pan and Ning, 2014). Because of the very different building features, to transfer the knowledge and learning from the 'ZCB' to mainstream practice of high-rise buildings in Hong Kong, poses tremendous challenges in technical, commercial and socio-cultural terms.

Conclusions

This paper has identified clusters of 'zero carbon buildings'. The examination was carried out through a two-step cluster analysis of 404 'zero carbon buildings' that have emerged and been reported worldwide. Five 'zero carbon building' clusters were revealed: (1) private residential low-rise rural 'zero carbon buildings' in the cold zone; (2) private commercial low-rise 'zero carbon buildings' in the temperate zone; (3) public low-rise 'zero carbon buildings' in the temperate zone; (4) private urban 'zero carbon buildings' in the temperate zone; and (5) private residential low-rise suburban 'zero carbon buildings' in the temperate zone. The findings indicate the dominance of low-rise, new-build residential buildings in temperate zones among the hundreds of pioneering cases targeting zero carbon. The significant paucity of high-rise cases is clearly identified.

The findings should help with understanding the complex profiles of zero carbon buildings and support cross-context learning of the practices. However, such learning should take into account the different characteristics of the buildings against the relevant variables. The variables examined in this paper provide a useful framework for developing cross-context learning of practices. The examined variables were descriptive and explanatory: the former consisting of year of completion, climatic zone, building type, location, number of storeys; and the latter consisting of building size, and building ownership, status, grid connection, and geographic boundary. Future research could include analysis of other variables of building energy and carbon performance, and address the insufficient information on building energy use or carbon emissions, inconsistent definitions, and calculation methodologies. Such future research should lead to a regression analysis of building energy and carbon performance. A systems integration of design strategies including passive design, energy efficiency, and renewable energy technologies was observed for zero carbon buildings. Future research could also explore the relationship between energy performance and technologies used. Emerging technologies should also be explored for application in high-rise buildings in advancing towards zero carbon.

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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

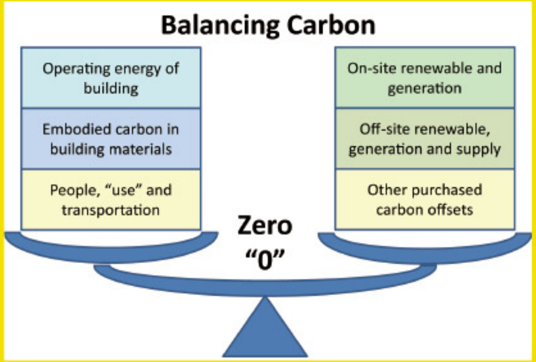

Figure 1 Balancing carbon concept for ZCB

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)

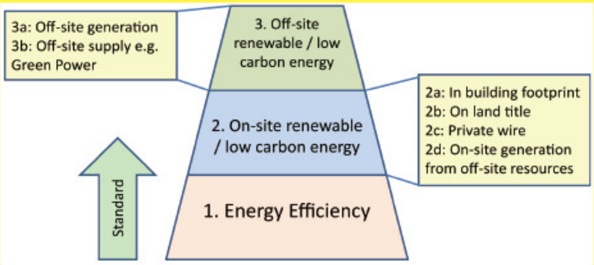

Figure 2 Allowable emission reduction options for ZCB (adapted from ASBEC, 2011)

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).

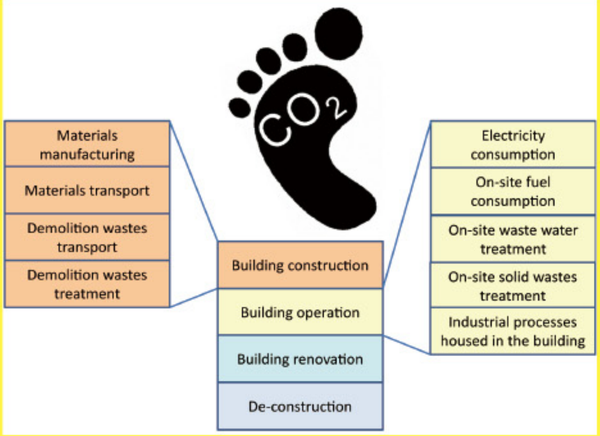

Figure 3 Carbon footprint of a building and its components

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

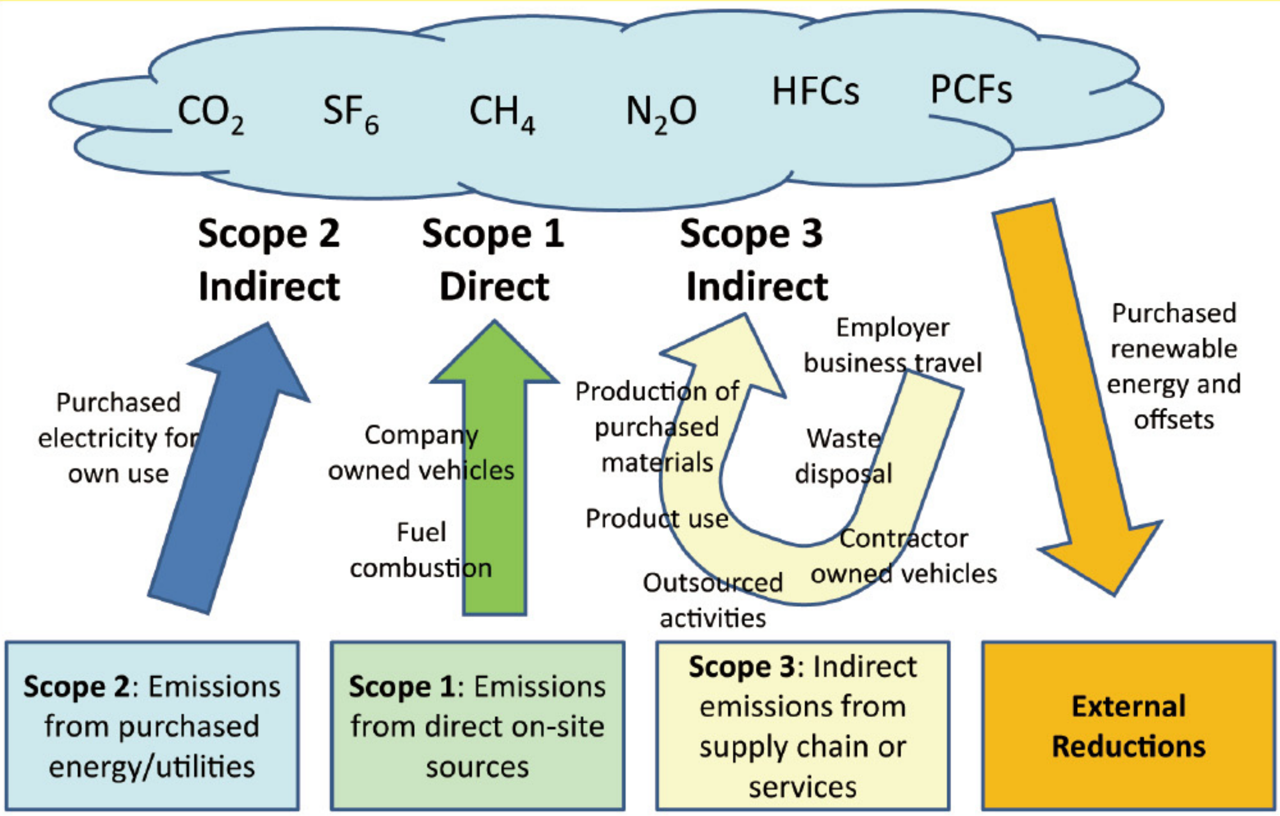

Figure 4 Greenhouse gas emissions and removals for buildings

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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Principles of Policy for Low Carbon Built Environment

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Buildings deliver benefits and adverse impacts to society and our environment in a wide variety of ways. Improvements to energy efficiency of buildings by means of technological, regulatory, voluntary measures and fiscal and economic incentives are desirable. In addition to technology in building, low carbon built environment should be conceived at city level as urban areas provide great potential for developments for energy efficiency, or low carbon buildings and the built environment. With this view, spatial planning can play a major role in supporting current policy for the promotion of energy efficient buildings and built environment.

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Introduction

Various voluntary and legislative means have been employed around the world to promote energy efficient, low-energy, or low-carbon buildings over the last few decades. Without government intervention or supporting policy, development of these buildings will be slow to achieve expected targets or goals. This paper presents findings of a literature review of ongoing research on development control policy in the face of climate change. It provides snapshots of regulations and green building practice to promote energy efficiency in buildings, and posits that spatial planning can play a major role in supporting policy for the development of energy efficient buildings and built environment. Within the context of this article, the term spatial planning is referred to as strategic planning that is concerned with more than land use and physical development of land although spatial planning can be defined in a number of different ways (Koresawa and Konvitz, 2001). Similarly, the terms low energy building and low carbon building are used interchangeably although they have sophisticated definitions.

Energy Consumptions in Buildings

From the perspective of the life cycle of building, building consumes energy and generates greenhouse gases (GHG) throughout the processes of product manufacture, transportation of materials and products, construction, operation, renovation, and deconstruction of the building (UNEP, 2007).

The pattern of energy consumption in buildings and thus GHG emissions can be influenced by many factors. For example, at national level, the geographical location, size of population, and levels of economic and industrial development. At the sectoral level, factors include the climatic zone in which the building is located, building type and usage, and the availability of energy efficient products or technologies in the local market. Nonetheless, the most common pattern in countries worldwide is that most energy consumption takes place during the operation phase of buildings. In countries of the Organisation for Economic Co-operation and Development (OECD), the building sector as at 2000 accounts for 25–40% of final energy consumption (OECD, 2003). In Asia, as at 2006, the building sector accounts for 40–50% of the final energy consumption of the jurisdictions (IEEJ, 2006). Most of the energy consumption is attributed to, for instance, room heating, indoor air conditioning, artificial lighting, water heating, mechanical ventilation systems, and running of household and office appliances. Furthermore, the amount of energy consumption by the sector is expected to increase rapidly in the near future due to population growth and urbanisation, particularly in developing countries in Asia (Wen *et al*., 2007).

Coupled with the issue of significant energy consumption in buildings are challenges relating to the environmental impacts posed by buildings, for example: (a) consuming a large amount of natural resources in terms of land, natural materials, and water resources; (b) generating a large amount of solid waste and sewerage; and (c) emitting large quantities of pollutants that affect outdoor and indoor environment (OECD, 2003; UNEP, 2007). Green building practice has been deployed as the key solution to tackle the environmental performance of buildings (Adshead, 2011; Cole, 1998), while regulations on energy efficiency of buildings and appliances are recognised as core policy instruments for reducing energy consumption in buildings (Laustsen, 2008; UNEP, 2007).

Green Building Practice

Since the early 1990s, green building practice emerged and prevailed as a key solution to enhance the energy efficiency of buildings and tackle the environmental challenges posed by buildings. Unlike conventional buildings, green buildings have to be designed, constructed, and operated to minimise impacts on the built and natural environment. As to what would qualify as green buildings, Theron and Dowden (2011) interpret green building as "the practice of creating structures using processes that are environmentally responsible and resource efficient throughout the life cycle of a building from siting to design, construction, operation, maintenance, renovation and deconstruction". By this interpretation, characteristics of green buildings that interact with the environment have to be measurable and justified.

Green building rating systems initiated either by government, or non-governmental organisations or both, serve the purposes of measurement and justification for green buildings through environmental assessment and certification or labelling processes. The most common sets of criteria of green building rating systems include: sustainability of the development of the building site; efficient use of land, energy, water, and material; environmental loading; and indoor air quality and environment. Some rating systems may also consider aspects of transport, culture, and innovation in the design of buildings (Emmanuel and Baker, 2012). Green building rating systems can also help building owners and practitioners target the environmental performance of buildings so as to reduce energy consumption and the operation costs (Cole, 1998). Moreover, one of the main characteristics of green buildings is using energy more efficiently than conventional buildings, otherwise it is not seen as actually 'green' (Howe, 2010).

Today, government support for green building practices is increasing. In the UK, although the Building Research Establishment's Environmental Assessment Method (BREEAM) is not mandatory at the national level, local authorities require building development to achieve specific BREEAM ratings as part of planning requirements, and all new government buildings have to achieve an Excellent BREEAM rating (Adshead, 2011; BREEAM, 2014). In Asia, Taiwan's green building rating system (known as EEWH[1]) is mandatory for both private and government buildings since 2001 (Chen and Chiu, 2011). In Hong Kong, the green building rating system BEAM Plus is a voluntary system, but all new government buildings with a construction floor area exceeding 10,000m^2 are required to obtain at least 'Gold' rating of BEAM Plus (HKG Press Release, 2009). However, Murphy (2011) cited that in most European countries, green building practice is still not mainstream in the building industry, particularly in those countries where existing building stock is a primary concern. Without well designed government policy, the improvement of energy efficiency in buildings, and steering of green building development will be slow.

Regulatory Control of Energy Efficiency in Buildings

Building development worldwide is traditionally subject to regulatory control, and thus building regulations are expected to be a vital policy instrument to provide a yardstick and framework for enhancing energy efficiency or reducing energy consumption in buildings. Regulations for these purposes probably began in Europe in 1960s. In 1961, Denmark first introduced thermal insulation requirements in their building regulations to limit loss of room heating energy through the envelope of new houses (Engberg, 2012). Sweden, the US and the UK adopted similar regulations for houses in the 1970s. In Asia, Singapore and Japan introduced regulations for energy efficiency of commercial buildings (Wen *et al*., 2007).

[1] EEWH denotes Ecology, Energy, Waste and Health

Other than focusing on the building envelope, European countries also mandated minimum energy efficiency standards for major household appliances. For instance, France and Russia introduced mandatory energy efficiency standards for household refrigerators in 1966 and 1976 respectively. However, the mandates had little effect on energy consumption due to weak legislation and poor implementation (Waide *et al*., 1997). In the US, the Energy Conservation Program for Consumer Products under the Energy Policy and Conservation Act of 1975, empowered state governments to regulate the energy efficiency of major appliances such as refrigerators, freezers, clothes washers and dryers, air-conditioners and heat pumps. The state of California was the pioneer and gained success in introducing the mandatory labelling system in 1978 (Miller 1997; Turiel, 1997).

With the rising concern for climate change since the 1980s, there has been a number of publications, such as the four reports published by the United Nations' Intergovernmental Panel on Climate Change in the 1990s. These reports asserted that the burning of fossil fuel through human activities generates a significant amount of carbon dioxide which is released into the atmosphere, resulting in global climate change. As a result, governments worldwide aim to stabilise carbon emissions under international treaties like the Kyoto Protocol. Actions taken include: extending the coverage of energy efficiency regulations to include more appliances and fixed installations like escalators and lifts; and adopting a wide range of policies other than regulations, such as voluntary, financial and economic incentives or programs, in order to encourage more stakeholders to participate in the improvement of energy efficiency in buildings (Vorsatz *et al*., 2007).

One of the influential policies of the European Union (EU) is the implementation of Energy Performance of Buildings Directives (EPBD) 2002/91/EC in 2006 and 2010/31/EU in 2010. The Directive 2002/91/EC requires EU member states to implement: (a) a calculation methodology for assessment of energy efficiency of buildings as per Article 3 of EPBD; (b) minimum energy efficiency standards for new and existing buildings as per Articles 4, 5 and 6 of EPBD; (c) energy performance certification system for buildings when the buildings are constructed, sold or rented out, with the validity of the certificate not longer than 10 years as per Article 7 of EPBD (European Commission, 2003). Under Article 9 of EPBD 2010/31/EU, Member States are required to: (i) ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings (NZEB), and by 31 December 2018, new buildings occupied and owned by public authorities are NZEB; and (ii) draw up national plans for increasing the number of NZEBs (European Commission, 2010).

Under the influence of the EPBD, the focus of regulatory policies on energy efficiency in buildings has progressively shifted towards energy labelling or certification systems which have formed part of green building rating systems, and on highly energy efficient, low-energy or low carbon buildings that are powered by renewable energy sources (Kibert and Fard, 2012; Liu, 2011).

Policy for Low Carbon Buildings, the Built Environment and Spatial Planning

Regulatory controls of energy efficiency in buildings and household appliances are seen to have arisen from concerns over the security of energy resources, and the high costs of fossil fuels (Bell *et al*., 1996). These concerns remain. However, within the regime of building control, options for enhancing the energy performance of buildings are limited. Examples include upgrading the thermal and insulation properties of the components of building envelope, tightening up of thermal standards, setting minimum standards for fixed electrical installations, promotion of passive design for heating and cooling, and installation of integrated photovoltaic facilities in buildings (Levine *et al*., 2007). There are many barriers that hinder large scale improvement of energy efficiency in buildings. Some of these include: the high investment cost of energy efficient facilities; traditional techniques of construction practiced by builders; insufficient incentives offered to building owners; and fragmented process in the design and construction of buildings (Levine *et al*., 2007).

The United Nations advocate that an essential requirement to promote and achieve greater energy efficiency in buildings as well as the city is an integration of spatial planning with relevant policy (UNECE, 2011). For example, whilst the promotion of more energy efficient housing is clearly desirable in itself, it is also essential to ensure that inhabitants have access to an effective system of public transport. Therefore, enhancing energy efficiency in buildings should not be restricted to building control. In a survey conducted by Sovacool and Brown (2010), it was found that urban areas contribute to GHG emissions from five main sectors, namely building, industry, transport, waste and agriculture. The building sector consumes the most electricity power and dominates carbon emissions in most cities. While technology can help, improvement of energy efficiency in buildings could be enhanced by taking into account elements of spatial planning such as: (a) spatial aspects of a building development such as the situation, site, aspect and spatial orientation of the buildings; (b) the relationship between the building and its environment; and (c) the development pattern of the city in which buildings are located.

For spatial aspects of buildings, most green building rating systems have included criteria for designers to consider. Mandatory green building practice should therefore be a pursuit of government policy. A successful policy example can be seen in the US where buildings in New York, Philadelphia, Houston, and San Francisco are mandated to achieve a certain rating of the Leadership in Energy and Environmental Design (LEED) system (Shannon *et al*., 2008).

Spatial planning that addresses the relationship between buildings and the built environment is crucial. Jackson (2002) conducted studies and suggested that providing sufficient greenery and open spaces in the built environment would not only enhance the energy efficiency of buildings within or near such spaces, but also contribute to society's well being. Successful cases in Hong Kong include most public housing estates (e.g. Kai Tak Estate, and Yau Tong Estate). In line with this approach, the Policy Address 2009–2010 by the Chief Executive of HKSAR targeted: (a) all new public housing incorporate at least 20% greenery area; (b) low-rise public buildings will be constructed with green roofs; and (c) vertical greening will be provided for public buildings where feasible (HKHA, 2010).

Planning decisions on land use and urban form contribute to long term benefits for energy efficiency in buildings and the built environment, for instance, establishing the level of residential density of certain areas, good public transit, and energy efficient infrastructure (Golubchikov and Deda, 2012).

A successful example of providing energy efficient infrastructure is Hong Kong's Pilot Scheme for Wider Use of Water-Cooled Air Conditioning System launched in 2000. The system is a centralised cooling system which provides chilled water to the air-conditioning system of non-residential buildings. The central chiller plant supplies chilled water and this is transported to buildings via an underground chilled water pipe network. A review of the Pilot Scheme in 2008 revealed that there has been a growing trend in energy savings and associated applications. The scheme has been well received by developers, building owners and property management. The Pilot Scheme was therefore converted into a standing scheme on 1 June 2008 and renamed as Fresh Water Cooling Towers Scheme for Air Conditioning System. As at April 2009, 396 applications were received, representing 86 designated areas covering about 74 million m^2 of non-domestic GFA, or 75% of total non-domestic GFA in Hong Kong (Audit Commission, 2009).

Urban areas provide great potential for low carbon built environment. To support low energy/low carbon buildings and built environment, spatial planning should embrace the following principles (Emmanuel and Baker, 2012):

Clear Government Leadership and Commitment

Leadership and government commitment can be demonstrated by the declaration of national policy with objectives in terms of energy or emission targets to be achieved. The objectives should be capable of withstanding challenges raised from the stakeholders concerned. In the UK, the national Planning Policy Statements 1 and 22 declared that local authorities are required to: (a) develop policies for mitigation of climate change impacts; and (b) provide guidance for the implementation of low carbon technologies. By these policy statements, the planning system has been used to encourage the adoption of renewable energy facilities. Under the planning policy, building development of more than 1,000m^2 or 10 dwellings are required to submit renewable energy targets during planning submission, and to demonstrate the achievement of renewable energy targets upon completion of building construction. As at 2007, 113 out of 350 building developments provided a saving of 135 ktonnes CO_2/year, achieving the expected saving targets stipulated in the prevailing building regulations (Day *et al*., 2009).

Integration with National Policy and Legislations

This integration can be achieved by linking, for example, planning permission with environmental standards, certification and enforcement, as required by building regulations, and national energy policies.

In Singapore, the strategy for sustainable built environment is integrated with its national energy policy, planning policy and building regulations. For example, the government do not offer energy subsidies to the public to minimise overconsumption. Rather the government encourages greater market competition; decentralised commercial centres to reduce the need to travel and reduce peak hour traffic congestion; and a high rating of Green Mark (the green building rating system in Singapore) is imposed as a condition for land sales for new buildings within strategic districts (MEWR and MND, 2009).

Maintain Collaboration with Stakeholders

This can be achieved by maximising stakeholder engagement and public consultation, working closely with community groups and local representatives, to create place-specific solutions.

In 1977, California became the first state to develop mandatory building standards in order to reduce the high level of energy consumption in buildings. According to the law, building permits for newly designed buildings would not be granted unless the law had been fully complied with. The building industry expressed concerted opposition to the legislation and the level of compliance with the statutory standards was reportedly low. In the face of industry opposition, the state failed to enforce the legislation, and thus gradually substituted legislation with 'soft-path' training and education for designers, builders, and building officials on how to enhance energy efficiency in buildings (Wilms, 1982). Therefore, successful promulgation of a mandatory scheme depends on going through an effective public consultation process, to ensure the industry supports and helps to modify the scheme to an acceptable level (Qian *et al*., 2011).

Balance Between Voluntary and Mandatory Approaches

There are successful cases of implementing mandatory energy efficiency in buildings. Taiwan initiated a voluntary approach to reducing carbon emissions from buildings and progressed to a mandatory approach (Chen and Chiu, 2011). In the UK and the Netherlands, a voluntary approach is used alongside regulations (Adshead, 2011). Although Rui (2011) advocates that developing countries like China may need to rely on strong legislative provisions, with threats of sanctions to achieve the required results, other studies (Lai and Lorne, 2013; Lai, 2014; Qian and Chan, 2011) found that major barriers to promoting green buildings in developing countries depend on institutional arrangements and the transaction costs incurred in the promotional system. Mandatory requirements can potentially be more damaging than voluntary incentive approaches.

Conclusions

Government support worldwide has increased the energy efficiency in buildings significantly. This can be traced back to the 1970s, with the discourse on climate change, and the concerns over energy security and cost. Most policies for improving the energy efficiency of buildings are focused on the quality of buildings rather than on interactions between buildings and the built environment. Urban areas offer great potential for energy efficiency in buildings and the built environment. Spatial planning can play an important role in driving the building sector towards low carbon performance. To achieve successful implementation of policy for energy efficiency in buildings and the built environment, policy should embrace elements of spatial planning supported with clear government leadership and commitment, good integration with national policy and legislation, good stakeholder engagement, and appropriate balance between voluntary and mandatory approaches.

Acknowledgement

This paper was prepared with support from an RGC research grant provided by the Hong Kong Polytechnic University.

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The Delivery of Zero Carbon Housing in the UK

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The Zero Carbon Hub has helped industry and government define 'zero carbon' for new homes in the United Kingdom (UK). Based on the principle of `fabric first', followed by on site energy generation and an allowance to mitigate any remaining carbon near or off site, the definition was broadly well received and is now being considered by other countries around the world. This article explains the different components of the UK's zero carbon definition, and also discusses a number of connected challenges that need to be understood and addressed. These include: the impact on building costs for housebuilders; the risk of overheating in energy efficient homes; challenges for high-rise apartment buildings; the role of building users; and closing the gap in energy performance from design stage to completion. Hong Kong can learn many lessons from the UK experience.

Keywords: Zero Carbon Hub, energy, housing, United Kingdom

Rob Pannell is the Managing Director of the Zero Carbon Hub, a role to which he brings a wide range of knowledge regarding sustainability, innovations, technology prototypes, trials and solutions. This knowledge is a crucial asset for both the Hub and the government, with Rob working closely with ministers and senior civil servants to advise on zero carbon policy and the 2016 target. Prior to joining the Zero Carbon Hub, Rob was a senior figure in the construction industry with over 35 years of experience with Taylor Wimpey UK Ltd. where he held a series of senior level roles, most recently as UK Director of Production (construction and design). Within this position Rob investigated and established a cost base and technical compliance of practical renewable energy and building fabric solutions to meet various UK government policies.

Introduction

In 2006, the UK Government announced that all new homes needed to be zero carbon from 2016. To help achieve this, they invited industry to create a public/private partnership delivery vehicle to assist government and industry, and the Zero Carbon Hub ('the Hub') was born.

The primary aim of the Hub is to support the mainstream delivery of low and zero carbon homes in England. The Hub strives to ensure that tomorrow's new homes are deliverable on site across the UK and are attractive investments for purchasers, owners and lenders. Organisation objectives include creating confidence during periods of change; reducing risks and obstacles; and disseminating practical guidance. The Hub has worked with government and industry to deliver a workable definition of `zero carbon' for new UK homes, as well as raising build standards and reducing the risk associated with implementing the Zero Carbon Homes policy.

The Hub has carried out a number of detailed studies to understand the risks and challenges associated with the delivery of zero carbon homes in the UK. These include: an analysis of the cost impact for housebuilders (ZCH, 2014a); understanding and providing recommendations on the gap in energy performance from the design stage to completion (ZCH, 2013c, 2014b, 2014d); and the risk of overheating in new homes.

The Hub has also published a number of documents in developing and researching the Zero Carbon definition. These cover topics such as: the use of `allowable solutions' in helping housebuilders to mitigate carbon either near or off site (ZCH, 2011b, 2012b); developing Zero Carbon strategies for a range of house types (ZCH, 2013b); and analysing low energy best practice around the world (ZCH and NHBC Foundation, 2011c).

Although Hong Kong has a very different climate and urban typology to the UK, many of the principles and challenges of building to zero carbon remain the same, so the Hub is working closely with the Construction Industry Council of Hong Kong and the Zero Carbon Building Journal to share experiences and accelerate one another's learning.

UK Method and Zero Carbon Hierarchy

The Climate Change Act and Zero Carbon Buildings Policy

Energy conservation has been a part of UK building regulations since 1976, with successive governments showing a real commitment to sustainable growth and the green agenda. There have been various legally binding targets and standards, in particular the Climate Change Act 2008, which mandates an 80% reduction in carbon dioxide (CO_2) emissions by 2020, using 1990 levels as a baseline. This was the world's first legally binding climate change target.

To achieve this 80% target, the government set a Zero Carbon Buildings policy, requiring all new homes to be 'zero carbon' from 2016, with new non-domestic buildings to meet the same target from 2019. As well as helping to tackle UK carbon emissions, the targets also aim to deal with other nationally important issues such as energy security and fuel poverty in low income households. Hong Kong may have different national concerns, such as reliance on fossil fuels and imported electricity; air pollution; and a subtropical climate.

UK Climate Change Act (2008): 80% reduction in national CO_2 emissions by 2020
Zero Carbon Buildings Policy: new homes from 2016 to mitigate all carbon emissions produced on-site

The Hub's work began in 2008, marking the start of a unique period of collaboration between government and industry to develop an evidence-based definition for the large scale delivery of zero carbon housing. The Hub has kept a central role in this process, providing advice, guidance and facilitating the journey to 2016 and beyond. Most importantly, one of the Hub's main roles is to share all findings and recommendations, and organising events at which UK Ministers are invited to present[1] (Figure 1).

Figure 1 Nearer to Zero event, London 2014

European Union Nearly Zero Energy Standard

Beyond the UK, European Union (EU) member states have agreed that all new buildings will be 'Nearly Zero Energy' from 2020 under the Energy Performance of Buildings Directive (EPBD). For buildings owned and occupied by public authorities, this target is 2018. Only a broad definition is given for this, so that national authorities have flexibility to choose how to adapt their own laws to meet the goal (ZCH, 2014c).

[1] A video about these events is available at: http://www.youtube.com/watch?v=b75LQBhH6vs

EU EPBD Article 2, Nearly Zero Energy Building Definition:

"…'nearly zero-energy building' means a building that has a very high energy performance….The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby…"

The UK2016 Zero Carbon Homes Target

The zero carbon definition that has been developed in the UK is limited to consideration of 'regulated' energy use.

Regulated Energy Use:

- Includes: space heating and cooling, hot water and fixed lighting.
- Does not include: cooking and 'plug-in' appliances such as computers and televisions.

This accords with UK Building Regulations and reflects only the elements of the home that are controlled by the housebuilder.

Note also that this policy relates only to new homes. Although exempt from the targets, existing homes do have to comply with other policies: all homes must undertake a simple energy assessment before being sold or rented, and the resulting Energy Performance Certificate (EPC) has to be displayed in marketing material. From 2018, landlords will be required to ensure their properties achieve minimum performance on the EPC[2].

Originally, it was envisaged that new homes would mitigate all carbon emissions on-site, however following consultation with industry and the UK Green Building Council, the Zero Carbon Hierarchy was proposed as shown in Figure 2 below.

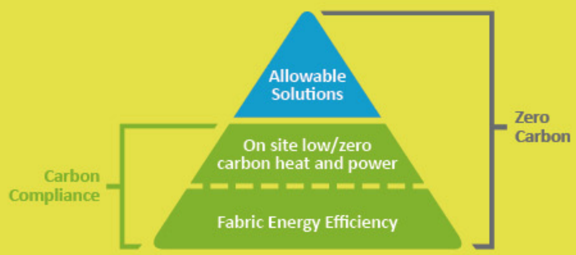

Figure 2 The Zero Carbon Hierarchy, with three core requirements for a home to qualify as zero carbon

The Fabric Energy Efficiency Standard

The hierarchy takes a 'fabric first' approach (Figure 3): prioritising the performance of the walls, roof and building materials, referred to as the building fabric (ZCH, 2013a). This aims to reduce the need to heat and cool the building, minimising energy demand, rather than using relatively expensive renewable energy technologies. The building fabric is typically the longest lasting element of a home, which occupants are unlikely to change, so it is crucial to get this right first.

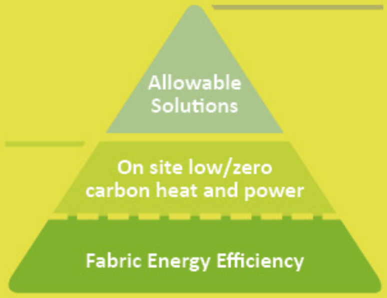

Figure 3 Fabric Energy Efficiency

The starting point of the Zero Carbon hierarchy is therefore a minimum standard for the energy efficiency of the fabric, referred to as the Fabric Energy Efficiency Standard (FEES). This is the proposed maximum space heating and cooling energy demand for new zero carbon homes, calculated as the amount of energy that would normally be needed to maintain comfortable internal temperatures.

Factors that impact on the fabric performance of a building

Thermal performance of the building elements: Each 'element' of the building envelope—a wall, roof, floor, window or door has a role to play in minimising heat loss from a home. The insulating effect of each of these elements is measured by its 'U-value' (W/m^2k)—the lower the U-value, the better its thermal performance.

Thermal bridging: Also known as 'cold bridges', these are weak points in the building envelope where heat loss is worse than through the main building elements. In a well insulated building, poor consideration of thermal bridges can account for up to 50% of all heat loss.

Air tightness: The loss of heated air from inside the building through any gaps and cracks in the external building envelope should be prevented. Air tightness is defined as the rate at which air escapes when the building is pressure tested. Poor air tightness can significantly increase fuel use.

Thermal mass: Thermal mass is a material's resistance to changes in temperature. Objects with high thermal mass absorb and retain heat, so may be useful in good passive solar heating design, especially in locations with large daily temperature ranges.

External heat gains: The impact of heat gain from the sun can have a significant impact on the internal heat

[2] More details are available from http://www.energysavingtrust.org.uk/Insulation/Energy-performance-certificates

demand of a house. Where a house has a high level of exposure to the sun, particularly through windows, internal temperatures can be significantly increased. In the winter, this may be desirable to reduce heating demand, but can lead to unwanted overheating in the summer.

Internal heat gains: Heat may be generated unintentionally within the building. The metabolic activity of a house's occupants can increase internal temperatures. An adult may produce up to 160 watts of heat while undertaking normal household activities. Similarly, services and utilities, such as lighting, cooking and appliances, may also result in internal heat gains.

The fabric standard (FEES) aims to ensure that a good minimum standard for building fabric is embedded in all new homes as shown in Figure 4. It is measured in kWh/m^2/year, which is the amount of energy a building uses per unit of floor area, representing the intensity of a building's energy use. This means that it is not affected by variations in the carbon emissions associated with different fuel types. It aims to achieve flexibility in the design approach and can be achieved in a variety of ways and with combinations of different materials or product specifications (ZCH, 2011a).

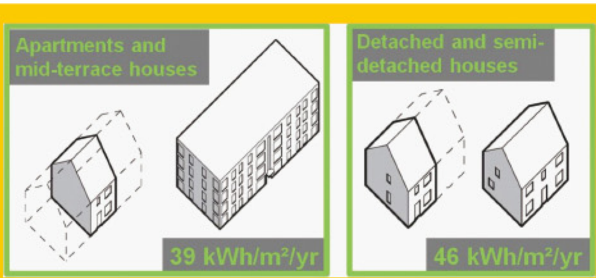

Figure 4 Fabric Energy Efficiency Standards - proposed levels

Carbon Compliance

The next part of the triangle is the 'on site heat and power' section, which when combined with the Fabric Energy Efficiency Standard, forms the Carbon Compliance Standard (Figure 5). This is a set of maximum limits on the permitted amount of CO_2 that arises from a home's regulated energy use. Included in this are the home's heating, cooling, hot water use, fixed lighting and ventilation systems, but not the emissions from cooking or 'plug-in' appliances as shown in Figure 6 (ZCH 2011a).

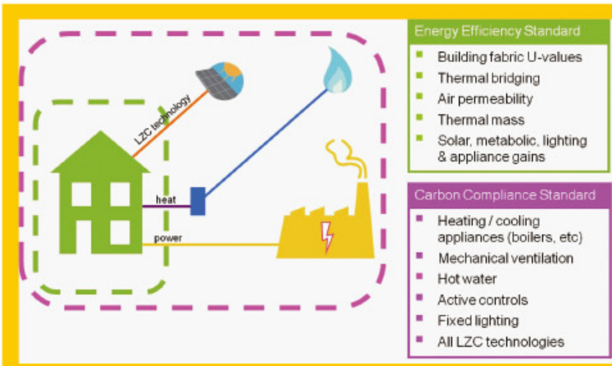

Figure 6 Carbon Compliance and the Energy Efficiency Standard

There are two ways to achieve the Carbon Compliance target. Firstly, by taking an energy efficient approach to building design, implementing fabric first measures for the Fabric Energy Efficiency Standard. Secondly, by reducing CO_2 emissions on-site through low and zero carbon technologies.

Note that when referring to 'CO_2 emissions', this comprises not just CO_2, but also other greenhouse gases expressed as equivalents. The Carbon Compliance Limit is expressed in $kgCO_2(eq)/m^2$/year, so that it links directly to the Government's carbon reduction strategy. This also means that it can be achieved when using a range of heating or fuel types.

The targets for Carbon Compliance proposed by industry have not yet been agreed by government. However initial government announcements suggest that they will be in line with the overall aim for 2016.

Allowable Solutions

The final part of the triangle is known as Allowable Solutions. For a house to qualify as Zero Carbon, any CO_2 emissions that remain after the Fabric Energy Efficiency Standard and Carbon Compliance limits have been met, must be reduced to zero.

There are two ways to achieve this, first by further carbon reduction on site. Second, where CO_2 emissions from regulated energy use cannot be met in a cost-effective manner or where solutions are not technically feasible on-site, they can instead be offset through off-site measures, referred to as 'Allowable Solutions' (Figure 7) (ZCH, 2011b, 2012b).

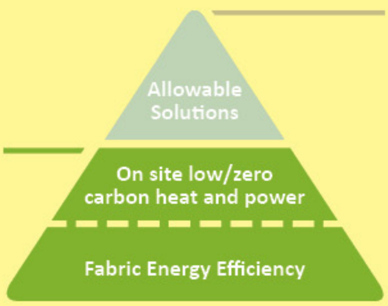

Figure 5 Carbon Compliance

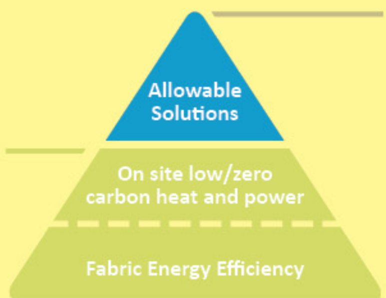

Figure 7 Allowable Solutions

The detailed framework under which Allowable Solutions will work has not yet been defined. There are a number of important questions concerning how it would be applied and the potential delivery routes, including what exactly would qualify as an Allowable Solution (Figure 8). The Hub will support the UK Government in undertaking further consultations to consider this.

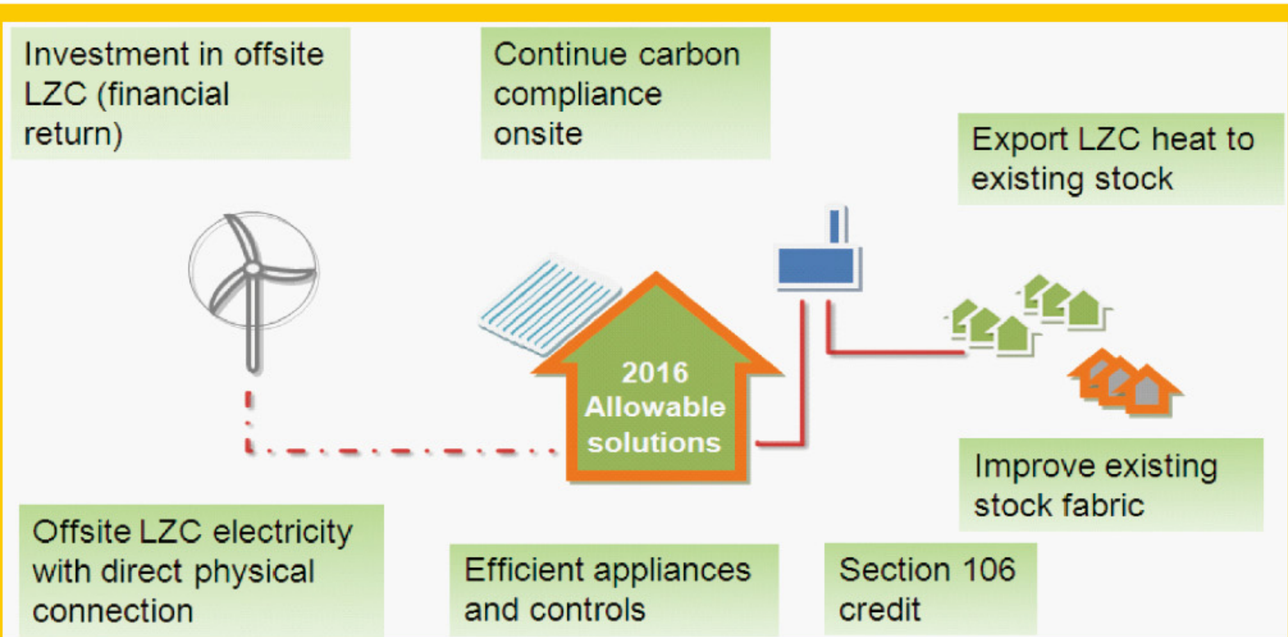

Figure 8 Potential Allowable Solutions delivery routes

Progress in implementing the Zero Carbon Standard in the UK

UK housebuilders are already learning to build low carbon, low energy homes. The Government has gradually raised energy performance standards in Building Regulations over time, maximising the industry's chance to prepare for the 2016 standard. This allows time for the industry to tackle any challenges and develop the skills needed to build zero carbon homes, for example, how to meet tougher air-tightness specifications.

This year, there is a further step in UK Building Regulations towards Zero Carbon: carbon emissions must now be reduced by a further 6% across the build mix compared to 2010 standards. A 'target Fabric Energy Efficiency' must also be met. This is similar to the definition in the Hierarchy.

The Hub plays a central role in helping the Government to trial, test, measure and advise on the realities of the Zero Carbon Policy, as well as disseminating the results. Some of this work is done through government initiatives to try and shift zero carbon principles into the mainstream. For example, the Homes and Communities Agency is funding development on their land ownership for a number of new ecotowns, which must meet higher energy efficiency standards. Through this, the Hub is helping developers trial the Allowable Solutions standard, and other developers have sought help from the Hub to build to the Fabric Energy Efficiency Standard. The Hub has an innovative and unique role in trialling proposals on site and sharing the results (ZCH, 2013a).

Factors Linked to the Zero Carbon Hierarchy

In preparing the industry for 2016, the Hub has aided the understanding of the broader economic, environmental and social context of Zero Carbon Buildings Policy. For example, the UK housebuilding industry is in a fragile recovery period, so it is really important to understand the costs of building zero carbon homes, as well as the benefits they bring. There is also significant concern that there is a gap in the energy performance of new homes—between design intention and the actual delivered performance. These issues and a number of other concerns associated with delivering Zero Carbon Homes are considered below.

Costs

Any extra cost to build zero carbon homes remains an important concern for housebuilders and policy makers. In the eight years since the zero carbon policy was first announced, there has been a consistent reduction in the building costs required for achieving these standards. At today's prices, the typical additional cost of building a semi-detached house to the Zero Carbon Standard could be less than £5,000 ($8,000 USD), compared to £40,000 ($64,000 USD) when the policy was first announced (ZCH, 2014a).

This reduction is largely driven by ongoing reductions in the cost of solar photovoltaics (PV), combined with a better understanding of the costs of delivering highly energy efficient buildings, and changes to the details of the standard itself.

Highly energy efficient homes can help to protect consumers against rising fuel prices by reducing the amount of energy people use consume to live comfortably. In terms of running costs, an analysis by the Hub has found that a new home built to 2013/14 energy efficiency standards costs half the price to run compared with a 120-year old house with modern improvements (Figure 9). Looking ahead to 2016, this saving is expected to become even greater.

While energy efficiency is only one of the advantages of buying a new-build house, the potential to accrue savings in running costs year after year could become a much more important factor in people's home purchasing decisions.

Figure 9 Spending on annual household energy

Overheating, Ventilation and Consumer Experience

Summertime Overheating

As the climate changes, cities grow denser and buildings become more 'airtight'. There is a growing concern that UK homes are at risk of overheating. This may make them unhealthy to live in, and in extreme cases represent a risk to life. Given that average temperatures are set to increase, and that more hot spells are anticipated, overheating could become more commonplace in the future. The challenge for the housebuilding industry is to provide energy efficient homes which stay comfortable throughout the year. To better understand the scale of this problem, and propose solutions to address it, the Hub is partnering with the UK government and industry experts to lead the debate on overheating.

Overheating comes from two sources:

External heat gains - sun shining through the windows and heat moving through the building fabric can heat interior surfaces and air. This can be useful in cold winters but this heat may accumulate in inadequately ventilated new houses. The extent of heat gain depends on factors including window area, orientation, and whether any blinds, shades or shutters are used.

Internal heat gains - internal gains can vary depending on the type or age of the home. For recently built airtight and insulated homes, heat gains from internal sources may have a significant effect. These can arise from occupants themselves, building services such as hot water systems, lighting and appliances.

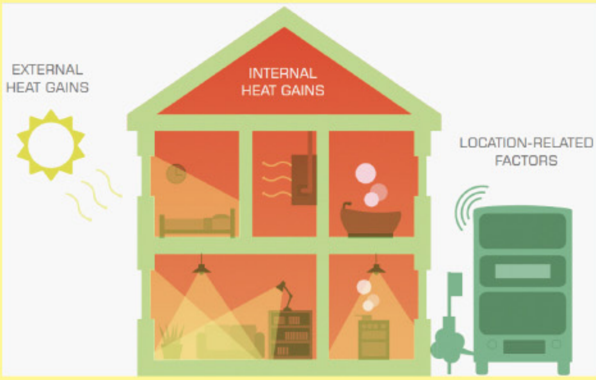

Figure 10 Internal and external heat gains

The location, construction type and layout of a home can have an impact. Overheating often arises when a number of causes or processes act together, such as the 'urban heat island effect', where air temperatures remain high even at night.

One difficulty in addressing this problem is being able to define overheating. It is difficult to agree on what constitutes 'too hot' because it differs from person to person, and depends on external temperature, humidity, duration and an individual's susceptibility and perception.

The Hub is evaluating a number of options for supporting and incentivising action by housing providers to tackle overheating, ranging from improving tools and guidance, through to mandatory legal standards. More importantly, the UK government, the housebuilding industry, and those involved in managing existing homes are closely engaged to ensure all proposals are both practical and commercially viable.

The subtropical climate in Hong Kong means that avoiding overheating in homes is a major concern. With new homes typically reliant on air conditioning, the cooling demand must be minimised as a means of reducing the carbon emissions of new homes.

Ventilation

With increasing numbers of low and zero carbon homes in the UK, strategies for adequate ventilation need to take into account more airtight construction, and to make sure that indoor air quality is not compromised. Good ventilation strategies, and the processes to implement them, must be clearly defined, developed and implemented. They can then be used to set future government policy and encourage housebuilders to adopt them.

The Hub is working with industry and government to understand how to guarantee the performance of ventilation systems at each stage of construction. This includes understanding what can go wrong; the impact if it does; who is responsible for assuring performance; and what the quality assurance processes are or could be. For example, who is responsible for ensuring that systems are properly installed? How can housebuilders be confident that mechanical systems will not create so much noise that occupants turn them off? Who is responsible for encouraging home users to replace filters in ventilation systems? The Hub will also showcase examples in which the process has worked well.

Hong Kong has a combination of factors that make ventilation and internal air quality an important concern: it is densely populated, it has high levels of air pollution and most buildings rely on mechanical ventilation. It is therefore crucial that suitable standards are set for ventilation and internal air quality, and that the installed systems deliver their designed performance. Compromised internal air quality could otherwise cause health impacts for occupants.

Consumer Experience

The way occupants use a low energy home can significantly impact the building's performance. To achieve best performance, the housebuilding industry must ensure that their customers understand how to properly use their homes. This is particularly crucial where relatively complex systems are installed—such as mechanical ventilation and heat pumps, which most users would not be familiar with. For example, homes with whole-house mechanical ventilation systems may best avoid overheating when the windows are kept closed so that the heat pump can control the air temperature. In the UK, this may be counter-intuitive to many users, who are accustomed to simply opening windows to cool their homes (ZCH, 2013b).

These interactions between low energy homes and their users is a critical area that requires more detailed understanding and analysis. This may also help housebuilders to be sure they are marketing homes to best effect.

High-Rise Apartment Buildings

Under the definition of zero carbon, the higher an apartment block, the more challenging it will become to achieve any given carbon compliance level. This is because there will be proportionately less roof space available per apartment, therefore increasing the need to find strategies that do not rely on roof-mounted solar solutions. In the UK, where the climate means that heating is the primary concern over cooling, this may drive the use of 'shared' solutions such as combined heat and power, biomass, or linking to a low carbon district heating scheme.

At the same time, high rise blocks use very different construction techniques and materials than typical UK homes and are diverse in their structural designs. They often use more complex building services than houses or low-rise developments, requiring specialised installation and maintenance. In some respects they have more in common with some types of non-domestic buildings and offer the opportunity for the use of technologies and design features being developed for the non-domestic sector. They may also be part of mixed-use schemes, including retail or other uses, that create specific needs (and opportunities) for infrastructure and services. To reflect this, the Hub intends to help the government undertake further research to set an appropriate carbon compliance level for high-rise blocks in the UK.

The Hub's soon-to-be-released 'Zero Carbon Compendium'[3] —a snapshot of some of the most sustainable cities and buildings across the globe – also highlights a number of exemplary low energy, high rise buildings. The 70-storey Torre Costanera in Chile is cooled using water from the local canal system, and has a curtain wall system that incorporates an insulating chamber to achieve high thermal efficiency. In the United Arab Emirates, Masdar City uses traditional Arab building techniques such as wind catchers and urban shading to keep buildings cool. High-rise apartments in Barangaroo Australia, feature high performance solar shading facades and use water from Sydney Harbour in their cooling systems. In Hong Kong, Singapore and across South-East Asia, many new and innovative solutions are being employed to tackle the challenge of high-rise buildings. The Hub hopes to share knowledge from these projects to help Hong Kong and other countries develop suitable standards and practical solutions for high-rise residential buildings.

The Performance Gap

The Hub's recent work has found extensive evidence of a considerable 'performance gap' between the energy use of new homes as-designed and actual use once the building is completed. This gap occurs when a completed home requires more energy than was predicted during its design before taking into account the behaviour of occupants.

This gap represents a significant risk to the UK's carbon reduction commitments. It has the potential to result in higher than expected household energy bills and undermine buyer confidence in new (low carbon) homes. As we approach 2016, housebuilders are producing higher performing homes and need to be confident that they truly perform as intended. Otherwise, they will find it challenging to proactively market this beneficial aspect of their homes compared to more inefficient existing homes (ZCH, 2013c).

The Gap between Calculated and Actual Performance of New Homes

Since January 2013, with government support, the Hub has carried out a length study involving over 160 professionals from across the industry, to help understand and tackle this performance gap problem. The project's aim is to close the performance gap, so that by 2020, a minimum of 90% of all new homes meet or perform better than their design intent.

At the start of this research there was a misconception that the Performance Gap was simply caused by inaccuracies within energy modelling software and poor construction practices on site. However, it was found that a gap can arise due to issues at various stages of the housebuilding process. Throughout this practice, a number of interlinked recurring themes were: unclear allocation of responsibility; poor communication of information; and a lack of understanding, knowledge and skills.

The Hub identified 15 'Priority for Action' issues to begin to address the performance gap as shown in Figure 11 below. These range from: planners failing to understand the energy challenges; current material and product testing protocols not reflecting 'real world' conditions when calculating thermal performance; procurement teams not considering energy related site skills when reviewing tenders; to site managers viewing energy related issues as comparatively low priority (ZCH, 2014b).

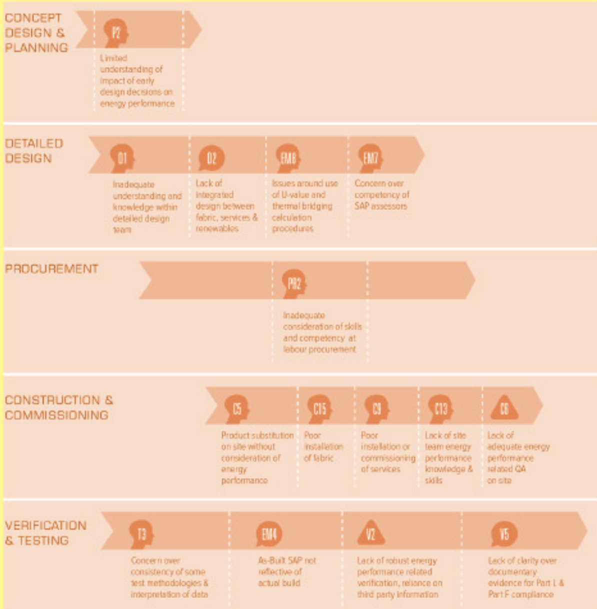

Figure 11 15 'Priority for Action' issues

Recommendations and Solutions

In July 2014, the Hub published the End of Term Report (ZCH, 2014d), setting out recommendations and solutions to help reduce the performance gap. Although the industry is capable of closing the gap itself, government also has a role to play in providing funding, support and refinements to the compliance regime. Collaboration is needed between government and industry. A number of priority actions—both for industry and for government were therefore identified:

Recommendations for the Housebuilding Industry:

- Carry out research and development to create innovative and commercially viable methods to test and measure the energy use of completed homes so that industry can understand their true performance;
- Embed energy literacy across the sector, with energy training and up-skilling of all professionals and operatives;
- Set up an industry owned and maintained 'Construction Details Scheme', to provide assured, as-built energy performance details for the most common major building fabric junctions and systems; and

[3] Available from http://www.zerocarbonhub.org/full-lib

- Support further evidence gathering and feedback to accelerate continued improvement across all sectors of the industry.

Recommendations for the UK Government:

- The Government must clearly indicate that it expects the construction industry to act now to ensure that the performance gap is being addressed. Industry should then commit to demonstrating that this has been achieved by 2020;

- Provide funding to stimulate industry investment in a 'Construction Details Scheme' and to develop innovative testing, measuring and assessment methods;

- Strengthen the compliance regime, with refinements to energy modelling and verification procedures (a government group has already been set up to address this, with the Hub's help); and

- Stipulate that only energy-certified operatives and professionals be employed on public land developments from 2017. This would accelerate demand for industry developed qualification schemes.

Key stakeholders from both industry and the UK Government have been keenly involved with the performance gap project, reflecting their commitment to tackling this problem. To do so, they will need to collaborate closely – acting quickly and decisively – to implement these recommendations. Collaboration is also needed with the energy sector, which has an important role in delivering as-built performance. Failure to act on these recommendations could jeopardise UK carbon reduction targets and undermine the good work carried out by the industry (ZCH, 2014d).

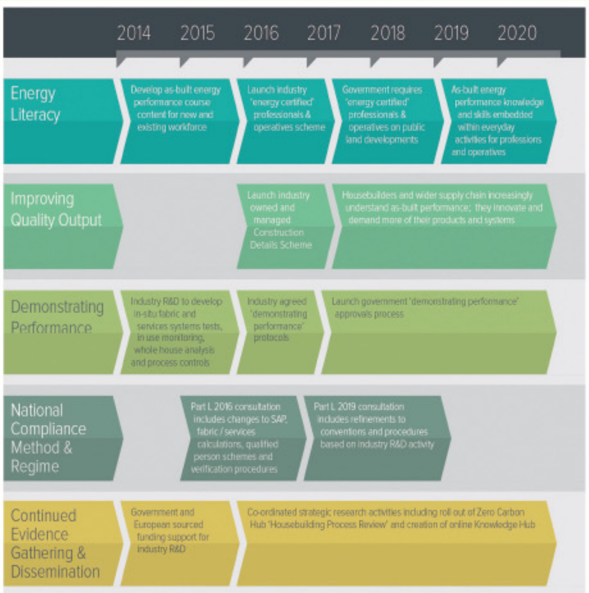

Figure 12 Road map to close the performance gap

Alongside these headline recommendations, contributors to the performance gap project identified a range of solutions with the potential to help close the gap. The Hub produced a 'road map' detailing these steps between now and 2020 as shown in Figure 12.

A performance gap between design stage and completion in homes in Hong Kong represents a significant risk for carbon reduction targets. The challenges and solutions could be quite different from the UK. There may be very different financial and process models of housebuilding, resulting in different building performance. The Hub is keen to collaborate and share findings from this study so that other countries can start to tackle the problem[4].

Conclusions

In 18 months time, the UK Government will put in place the final Zero Carbon Standard, with targets for non-domestic buildings and the EU Nearly Zero Energy Standard to follow. The UK is therefore entering the last stages of consultation to get the final details on the workings of zero carbon, to include the energy modelling software, compliance regime and ways Allowable Solutions and Carbon Compliance will interact with one another. In the meantime, continued effort and commitment are needed across the industry to make sure the targets can be achieved. To help understand our progress, less invasive performance testing and monitoring techniques must also be developed.

At the same time, rising energy prices can make the opportunity to save money year after year a much more important part of the decision process for homebuyers. Evidence suggests that home purchasers and the mortgage industry do not currently see significant additional value in the operational cost savings achieved by very low energy homes, compared to older properties. Supporting the industry in communicating these benefits to customers continues to be an important area of work for the Hub.

[4] This, along with all other Hub publications, is available from http://www.zerocarbonhub.org/full-lib

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Sustainable Building Façades Towards the ZCB Era

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The development of new sustainable buildings requires tactful manipulation of energy flows at the external façades. There are several basic principles in formulating the design strategy: to reduce air-conditioning and lighting loads without affecting occupancy health and comfort, to minimise the embodied energy in the material use life-cycle, and to optimise self-reliant power generation via façade-integrated renewable energy systems. The last point is crucial to facilitate zero-carbon building (ZCB) developments. In this article, a range of sustainable façade technologies are discussed. The merits of the green features for applications in the high-rise and high-density built environment of Hong Kong are highlighted. Compared with the cold climate region, the ZCB context is less remote in the subtropical region, however it is not easy to implement the concept for our unique urban environment. To realise the goal of zero carbon, a cross-disciplinary approach should be adopted, in which the building components and services systems are to be considered as a whole, from the project commencement stage.

Keywords: building façade, building sustainability, renewable energy, low-energy building, zero-carbon building

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Introduction

The development of a low-carbon building (LCB) needs in depth consideration of two main aspects: (i) an environmentally responsible and resource-efficient building structure throughout its life-cycle; and (ii) energy reduction measures for both embodied energy and operating energy. The coverage encompasses a range of technologies, such as:

- Passive solar design
- Efficient ventilation and airflow strategy
- Daylight utilisation
- High performance system equipment
- Energy management and optimisation
- Energy storage and power shifting
- Waste water and heat recovery
- Minimised material delivery and transportation
- Material recycling and minimum embedded energy

What is required is a whole-building approach that considers the above factors, along with their potential interactions and impacts on the occupants. Such an integrative approach departs greatly from the conventional approach, in which each building discipline in a fragmented process performs its own task, mostly in an isolated manner. Moreover, zero-carbon building (ZCB) technology can be taken as a combination of LCB technology with on-site energy generation. At its heart, this means that buildings with extensive improvements in energy efficiency are to meet their energy demands via various means of distributed renewable sources. On-site photovoltaic (PV), solar hot water, wind turbine, biofuel generator and fuel cell are among potential candidates. Innovative ideas derived from some of these can be incorporated onto the building façade for cost reduction and power output maximisation.

Traditionally, the building façade is a crucial element in architectural design. But now it has escalating importance in services engineering decisions, owing to its significant influence on engineering system performance and energy use. From this perspective, the following re-visits the multiple roles of façade design and construction, considered in the subtropical high-rise and high density urban environment of Hong Kong.

Requirements for Building Envelope

In an energy-efficient building, unwanted heat gain or loss through the building envelope should be minimised. Key design parameters include building aspect ratio, façade orientation, ventilation scheme, window-to-wall ratio (WWR) and construction material properties. Their level of influence can be readily explored by thermal analysis through building simulation programs (Chow and Chan, 2009a). A number of advanced simulation programs are available for the said purpose, such as EnergyPlus, DOE, ESP-r, etc. Computational fluid dynamics and environmental life-cycle analyses can also be applied on demand.

Façade Orientation

Façade orientation governs the amount of direct solar radiation falling on its surface at different times of the year. For a low-latitude location in the northern hemisphere, the south wall may not receive the highest solar irradiation over a year. In Hong Kong, between 4 June and 9 July every year, the sun above our heads is shifted to the north. Within this period, it is the north-facing walls rather than those facing south that receive more direct solar radiation. Nevertheless, the intensity is relatively low because of the high sun altitude (Chow *et al*., 2005). Figure 1 shows the variation of annual solar irradiation with façade orientation and surface tilt angle. The data is from ESP-r simulation results based on the Macao Typical Meteorological Year database (Chow and Chan, 2004). A surface azimuth angle of 0° refers to the direct south, whereas 90° and -90° are the west and east respectively. It can be seen that the southwest façade receives the highest solar radiation within a year. And during the summer months, the orientation with highest solar radiation shifts towards the west. So when considering air-conditioning load, the highly-glazed façade of an air-conditioned space should avoid facing west.

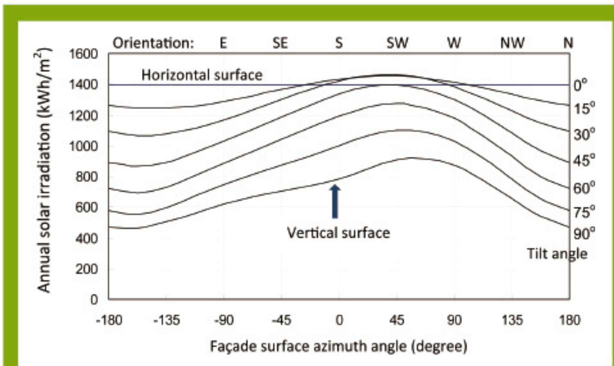

Figure 1 Simulated results of variation in annual solar irradiation with surface orientation and tilt angle (Chow and Chan, 2004)

For a commercial building in Hong Kong designed with absorptive glazing on the curtain wall, the increase in annual cooling load is 20% if the WWR changes from 0.2 to 0.8 (Chow and Chan, 2009a). However, for the same building the addition of 50mm thermal insulation at the opaque area can only reduce the annual cooling load by 3%. Hence in Hong Kong, more attention should be paid to the heat transmission characteristics of window glazing rather than on opaque walling. For envelope construction, the wastage of air-conditioning energy should be carefully considered in relation to imperfect air tightness and thermal bridging, which are affected not only by the envelope material and structure, but also by the construction process, such as the quality of workmanship.

Façade Conditions

The surface conditions of the external façade also affect solar absorptance. It is a well-known fact that a dark rough surface tends to absorb more near-infrared (NIR) radiation. If a dark appearance is preferred, then replacing the conventional pigment with a cool-colour coating with higher solar reflectance, that absorbs less NIR radiation may help.

On the other hand, more attention can be paid to building life-cycle performance. The reduction of embedded energy in imported construction materials can lead to a significant decrease in the overall carbon footprint (Zhang *et al*., 2014). In essence, durable materials and less complicated components are preferred. A component that is neither durable nor repairable should be recyclable or easily segregated into reusable pieces. When different parts of the assembly have different life expectancies, the design should consider the convenience of sub-component repair or replacement. The use of glues and chemicals should be avoided as far as possible.

Low-rise buildings offer more roof space per unit floor area for solar panel installation. The positioning of the solar panels should favour the year round energy conversion. Figure 2 shows the variation of annual solar irradiation with the panel tilt angle for different orientations within the southwest quadrant (Chow and Chan, 2004). It can be seen that as a general rule of thumb, the proper tilt angle should be close to the local latitude, i.e. 22.5°.

Solar Applications

In the high-rise built environment of Hong Kong, full use should be made of the building's vertical façades to accommodate the solar panels, because these have a larger available surface area than a flat roof alone. The disadvantages are the increased cost in maintenance work and reduced incident solar intensity. From Figure 2, it can also be seen that within the southwest quadrant, the annual solar irradiation on a vertical surface is only around 55-62% of that on the surface at the same orientation but with the best angle of tilt.

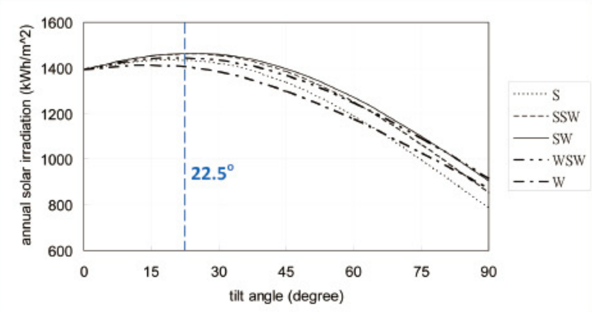

Figure 2 Annual solar irradiation on façade surfaces at different tilt angles and orientations within the southwest quadrant (Chow and Chan, 2004).

Greenery and Shading

Green roof as a leisure space offers the beauty of vegetation on a flat roof. There are two main types: extensive and intensive. The soil depth of an extensive green roof is usually 150mm or less. This is suitable for lightweight buildings. An intensive green roof is one with trees and shrubs which need regular garden maintenance. This is the same as for a rooftop farm. Factors like thicker soil layer, lower plant height and higher leaf area index (LAI) are favourable, to provide a roof system with better insulating capacity (Chan and Chow, 2013). Through evapotranspiration, it is possible to cool the ambient air at the roof. Hence, the merits are reducing indoor heat gain via the roof slab, and mitigating the urban heat island effect. Other benefits include removing CO_2 through photosynthesis, reducing sound transmission, controlling stormwater runoff, and prolonging the life of roofing materials. Climbing plants and shrubs growing directly along vertical façades or along plant supports such as trellises and wires provide very similar benefits (Susorova *et al*., 2014). They create a milder local microclimate adjacent to the façade and reduce the surface temperatures due to shading by plants in the daytime.

The provision of balconies on residential buildings is also useful. The merits are enjoyment of scenery, better ventilation, and increased planting space. A balcony also acts as an overhang and serves as a solar shading device. A case study of a living room with a southwest facing balcony and clear glass panes showed that the annual saving in air-conditioning consumption can reach 12% (Chan and Chow, 2010).

For solar shading, external shading devices are particularly useful. Fixed overhangs and side-fins can be used on clear glass windows to restrict direct sunlight penetration. The performance of external shading is affected by its physical dimensions and position. Generally speaking, a reduction of around 40% in window heat gain can be expected (Huang *et al*., 2014). As the depth of the overhang increases, the thermal performance is improved, but the daylighting performance drops. In Hong Kong, its overall performance on the south window is less than on windows facing east and west. The north facing glass receives little direct sunlight, so no external shading (or one with shallow depth) is required.

In comparison, interior shading devices like venetian blinds or vertical louvers are less effective in reducing the cooling load than external devices, since the solar heat gain has already been admitted into the room. But they can be adjusted by occupants and hence are more user-friendly, particularly from the glare control point of view. The overall performance of venetian blinds depends mostly on their surface reflectance and the slat angle. A higher surface reflectance will favour their ability to admit natural light and reduce space cooling load so this is the preferred option. Compared with a bare window, changing the slat angle from 90° (the horizontal position) to 30° (an inclined position against sunlight) may alter window heat gain reduction from 20% to 50%. However daylight performance will be affected accordingly. In Hong Kong, the overall performance of internal blinds on the south window is more or less the same as those facing east and west.

Ventilated Façade

In recent years, ventilated façade systems have become popular across various climatic zones. The reasons are their high energy performance, rich variety of available design solutions, reduced effect of solar radiation on indoor microclimate, good noise reduction properties, and possibility of rapid building repair and reconstruction (Nizovtsev *et al*., 2014). The performance of ventilated façades are influenced by both outdoor conditions (like solar irradiance, wind flow and outdoor air temperature), and indoor conditions (like room temperature and humidity) and façade design features (like air-layer configuration, other material properties, composition and layout).

Window Glazing Technology

The construction of extensively glazed buildings is a worldwide architectural trend. The positive aspects of this trend include transparency, natural brightness, modernity, and indoor-outdoor interaction. But the negative effect is, in principle, energy wastage. For a given window system, one of the key design parameters is the solar heat gain coefficient (SHGC or g-value), which is the sum of the direct solar transmittance of the glazing and the part of solar energy absorbed by the inner glass pane and reemitted inwards. The other two important parameters are thermal transmittance (U-value) and visible transmittance (VT).

Single-glazing

Single pane window glazing is widely used in subtropical climates. Clear glass, characterised by high visibility and solar transmission, is the basic and economical choice. Tinted glass, available in a range of colours like bronze and grey, is common for commercial buildings and classic apartments for its effectiveness in reducing solar heat transmission. Unfortunately the available daylight, as reflected by its lower VT value, is also reduced. It is also called 'absorptive' glass because of its high extinction coefficient, low transmittance and high absorptance. All absorbed radiant energy is initially transformed into heat within the glass, thus raising its temperature. If a higher reduction in solar gain is desirable, a reflective coating can be added. This consists of thin metallic or metal oxide layers, so the glass has a metallic colour like bronze, silver or gold. The mirror like reflective glass may be the preferred choice for a sharp reduction in solar transmission. But the visual pollution in the neighbourhood (like glare for road users) can be problematic. The SHGC value varies with the thickness and reflectivity of the coating, and its position in the glazing system. As with tinted glass, the VT of reflective glass usually declines more than its SHGC.

Multi-pane Window

With the growing popularity in LCB technology, double glazing is increasingly used. Double glazing is formed by two panes of glass separated by an air gap. This offers better insulation by reducing conduction and convective heat transfer, with a marked reduction in outside noise transmission and internal condensation. Choices available in the market include air-sealed, gas-sealed, low-e, and vacuum glazing. Triple glazed windows are also available for cold climate regions. The SHGC value of air-sealed double glazing with clear glass panes is around 35-78% of single pane counterparts (Huang *et al.*, 2014). This is in the range of 47-68% for U-value, but the VT value remains reasonably high. During summer, the buoyant-induced air current within the cavity carries absorbed heat to the window top along the outer pane, so a cool pool is developed at the bottom of the inner pane. The insulation effect can be improved by replacing the sealed air with an inert gas such as argon or krypton. Inert gas is more viscous (slow-moving) and less conductive. It minimises the convection currents within the window cavity.

In low-e glazing, a glass pane with low-emissivity coating is combined with other glass pane(s) to form multi-layer glazing. This is now commonly used in modern architecture all over the world. 'Low-e' refers to a low level of emissivity over the long wavelength portion of the spectrum. Low-e coatings in gold, silver or copper offer a range of solar control characteristics. For low solar gain applications, the low-e coating at surface 2 of the outer glass blocks most of the long wave radiation from the outside. To prevent space heat loss during winter time, the coating should be at surface 3 of the inner glass pane. And lastly, in the absence of convective heat flow, vacuum glazing theoretically provides the best insulation. The presence of spacers at the thin cavity keeps the glass panes apart, and provides a moisture barrier and gas-tight seal. It is advantageous for vacuum windows to use low-e glass panes (at surfaces 2 and 3) to reduce inner pane radiation heat transfer.

Glass type	SHGC	U-value ($W/m^2.K$)	VT	Room heat gain (W/m^2)
Single glazing (5.7mm glass pane)				
Clear glass	0.777	6.010	0.888	465
Tinted glass	0.524	6.017	0.534	361
Reflective on clear glass[1]	0.348	6.023	0.311	256
Reflective on tinted glass[1]	0.293	6.020	0.122	223
PV laminated glass[4]	0.280	5.701	0.106	213
Double glazing (5.7 mm glass panes and 12.7 mm cavity space)				
Clear + Air + Clear	0.596	3.035	0.793	380
Tinted + Air + Clear	0.388	3.037	0.476	256
Reflective on clear + Air + Clear[1]	0.273	3.038	0.286	187
Reflective on tinted + Air + Clear[1]	0.216	3.038	0.110	153
Low-e on clear + Air + Clear[2]	0.303	1.625	0.706	194
Low-e on tinted + Air + Clear[2]	0.209	1.636	0.450	138
Low-e & reflective on clear + Air + Clear[3]	0.121	1.625	0.274	85
PV laminated glass + Air + Clear[4]	0.177	2.700	0.095	127
Clear + Argon + Clear	0.598	2.883	0.793	380
Low-e on clear + Vacuum + Low-e on clear[5]	0.222	0.806	0.629	139

Table 1 Energy performance at the centre of the glass of vertical windows under steady-state thermal conditions: G=1000 W/m^2; $\theta=60°$; $T_a=33°C$; $T_r=25°C$; $h_o=22.7 W/m^2.K$; $h_i=8.29\ W/m^2.K$ (Chow *et al.*, 2010)

Notes:

1. Reflective coating at surface 1, i.e. outside surface;
2. Low-e coating at surface 2, i.e. inside surface of outer pane; $\varepsilon=0.04$;
3. Reflective + low-e coating at surface 1; $\varepsilon=0.04$;
4. 10.5mm PV laminated glass; electricity generation = 43W; and
5. Low-e coatings at surfaces 2 and 3; vacuum space 0.12mm.

Table 1 lists the room heat gains together with the three key design parameters for a selected sample of vertical windows for ready comparison. The thermal analysis was carried out through steady-state numerical computation based on industrial-grade thermal and optical data sets (Chow *et al*., 2010). The idea was to simulate window performance in a typical hour of a sunny summer day, where strong incoming solar radiation is at an incident angle of 60°, with its direct and diffused components at 680 and 320W/m^2, respectively. Taking a ground reflectance of 0.2, the global irradiation is 617W/m^2 for normal incidence. Typical convective heat transfer coefficients are used. From the results, the good thermal performance of low-e glazing options is illustrated by low room heat gains, and better daylight performance (higher values of VT) than reflective glazing options. However, smart window options that make use of chromic technology to switch between clear and dark colour, depending on the level of sunlight, are not on this list. Their applications in Hong Kong are not attractive in view of the low response to colouring and high material costs (Yik and Bojic, 2006). It should also be noted that in a comprehensive evaluation of window energy performance, in addition to the glazing characteristics, the window frame dynamic behaviour and energy contents also combine to determine long-term performance.

Ventilated-glazing

Multi-glazed windows are widely used in buildings, including double skin façade (DSF) options. For some of these, the air gap between adjacent glass panes is ventilated by a natural or forced airflow stream that may cover one or more stories. An air-tightened façade provides increased thermal insulation and reduces heat loss in winter. A ventilated façade however, readily removes solar heat and reduces space cooling load. Other advantages are it acts as good ambient noise barrier and is effective in wind pressure reduction. But the disadvantages can be higher cost, increased fire risk, reduced usable floor space, and weakened room interior sound insulation. For an office building case in Hong Kong, the DSF system with single clear glazing as the inner pane and double reflective glazing as the outer pane can save 26% of the building cooling energy annually, compared to a conventional façade with single absorptive glazing (Chan and Chow, 2009).

PV-glazing

In order to reduce room heat gain, there are two basic principles in window design for a warm climate: (i) to filter out the infrared spectrum, but not visible light; and (ii) to utilise solar irradiation as a renewable energy source. In line with this is the introduction of PV glazing. The majority come as crystalline silicon (c-Si) wafer solar cells laminated within two clear glass panes. While c-Si cells are opaque to visible light, an alternative is the use of 'semi-transparent' amorphous silicon (a-Si) solar cells on glass. This 'see-through' solar cell technology incorporates a-Si cells in a regular pattern of tiny holes. The presence of these holes results in reduced power output, with a magnitude closely linked with the increase in daylight transmission. In other words, a higher level of transparency is accompanied by a corresponding reduction in electricity generation.

Renewable Energy Integration

Building-integrated Photovoltaic

For photovoltaic technology, the electricity produced by a PV module is in a form of direct current. This must be converted to alternating current by an inverter and adjusted to meet the power characteristics of the utility grid or the load. The circuit arrangement can be stand-alone or grid-connected. Apart from the roof-mounted option at the best angle of tilt, the wall-mounted option is also available, known as building-integrated photovoltaic (BiPV). Through the full integration of PV modules with the building envelope, the incremental cost of PV can be reduced, and its life-cycle cost improved. Hence, a BiPV system can have lower overall costs than a PV system that requires separate and dedicated mounting systems. However, the solar radiation falling on a vertical façade is less than on the correct angle of tilt.

Currently, the main obstacle to PV applications is still the lengthy cost payback period, which may be even longer than its service life. In Hong Kong, the PV electricity cost is several times higher than from the utility grid. Moreover, the solar cell conversion efficiency decreases at higher module operating temperature. The drop is more severe for the c-Si cell types than the a-Si types. In order to improve the conversion efficiency, the provision of a ventilating air stream behind the PV modules as a means of heat dissipation is desirable (Chow *et al*., 2003).

Building-integrated Solar-heating

In terms of the cost payback period, a solar water heating system is much more attractive than a PV system. The two common solar water heaters in use are the flat-plate solar collector and the evacuated tube solar collector. Theoretically, both can be incorporated as a part of the building envelope. Such façade integration allows more energy generation in association with reduced building thermal transmission (i.e. reduced air-conditioning load) and heat reflection (i.e. reduced UHI effect). For example, the potential application of a centralised solar water heating system in a high-rise residence has been evaluated (Chow *et al*., 2006). Arrays of solar thermal collectors, which occupied the top two-thirds of the south and west façades of a high-rise residence, were proposed to support the domestic hot-water (DHW) system. It was found that with a solar fraction of 53%, the payback period is around 9 years for hot water services, and in fact can be even shorter if the air-conditioning saving has been taken into account. More examples of innovative research work on ZCB technologies are discussed in the next section. These are experimental systems, including hybrid solar photovoltaic/thermal (PV/T) integration, PV ventilated glazing, and liquid-flow window system.

Innovative R&D Work

Hybrid-solar Technology

A PV/T system is the integration of PV and solar thermal collector components into a single device that simultaneously generates both electricity and heat energy. With solar cells as (part of) the thermal absorber, the hybrid design can maximise the energy output from an allocated space reserved for solar application. Either air or water, or both, can be used as coolant(s) to lower the solar cell working temperature. Comparatively, water cooling is more effective than air-cooling because of the higher heat capacitance and as a result, more favourable convective heat transfer. Those with flat plate collectors meet the low temperature DHW system requirements. They are also applicable as preheating devices for high temperature DHW services. Just like the building integrated solar thermal collector system, the BiPV/T provides additional thermal insulation at the external façade.

Figure 3 shows an experimental test rig, in which the PV/T collectors were mounted on the external wall of an air-conditioned chamber. Water circulation between the six collectors and the water tank above can be either by pump-driven (forced circulation) or by thermosyphon (natural circulation) mode. The experimental results showed that this BiPV/T system can be more energy efficient under the thermosyphon operating mode (Chow *et al*., 2009b). Through numerical analysis, it is shown that for office applications, the energy payback time and greenhouse gas payback time are around 2.8 and 3.8 years respectively (Chow and Ji, 2012). The cost payback period is about 14 years. These are more favourable than the BiPV option. Many research projects on PV/T technology are underway worldwide. One technical hurdle is how to improve the equipment service life to make the system more sustainable.

Solar-absorbing Windows

Figure 4 shows the configuration of a PV ventilated window for use in warm climates. The window system has two glazing assemblies. The inner one is simply a clear glass pane. The outer assembly carries a PV glass pane with vent openings at its top and bottom to provide the buoyant flow of ventilating air from the outside on sunny days. With the screening effect of the PV glazing, together with the cooling air stream in the cavity, the solar transmission to the indoor space is much reduced. The system also improves disability glare and local thermal discomfort caused by radiation asymmetry. For office building applications, the natural ventilated PV double glazing system can lower air conditioning power consumption by 28%, compared to the conventional single absorptive glazing system (Chow *et al*., 2009c).

From an investment point of view, one promising design is the replacement of airflow channel by liquid such as water. In the liquid flow option, a thermosyphon induced liquid stream flows up the cavity to the heat exchanger

Figure 3 An experimental BiPV/T system at the university campus

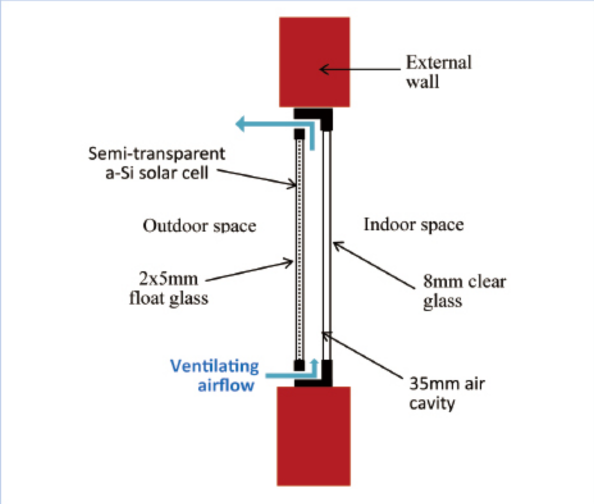

Figure 4 Cross sectional view of PV ventilated glazing

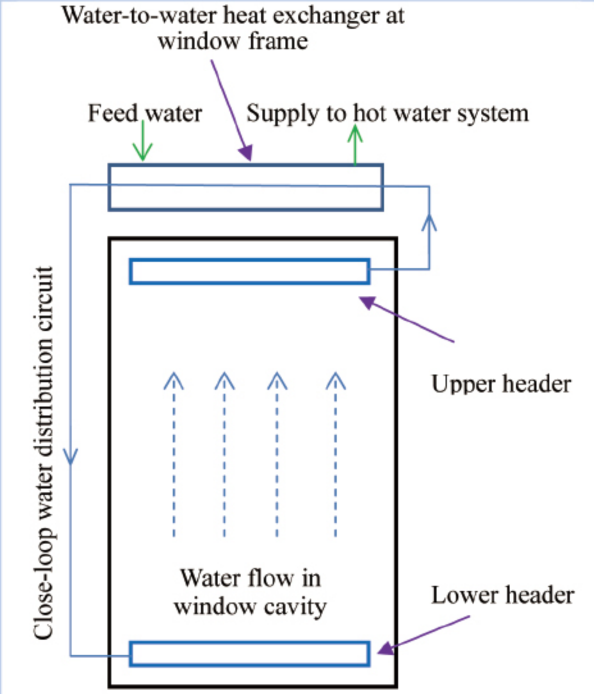

Figure 5 Flow circuit of thermosyphon water flow window

at the top for DHW preheating. Figure 5 shows an indicative water flow circuit. Solar transmission through glazing is then reduced and the space cooling load is lowered. Natural light is enhanced since the water layer has negligible effect on the visible light spectrum. The advantages are thermal load reduction, natural light preservation and utilisation, and useful heat gain for hot water supply.

Discussion and Conclusions

Adverse climate change leads to worldwide calls for the development of low-carbon buildings. In addition to further improvements in system energy efficiency, through statutory measures for example (Lau and Li, 2014), the tactful manipulation of energy flow at external façades is equally important. When faced with the more ambitious target of zero-carbon building development, the full incorporation of onsite renewable energy systems becomes indispensable. Compared to cold climate regions, the ZCB context is less remote in the subtropical region. But it is not easily implemented in the unique high-rise high-density urban environment of Hong Kong. The goal requires a cross-disciplinary approach that considers all the building components and services systems, notably at the project commencement stage. In other words, site planning, aesthetic design, system equipment and construction material selection, financing, construction, commissioning, and long term operation and maintenance have to be well coordinated. The final outcome can be a high performance building in terms of comfort, functionality, energy use, resource efficiency, economic return, and life-cycle value (Griffith *et al*., 2007).

ZCB or LCB?

The challenge is perhaps how much we wish to have ZCB models in our society, and whether an aim is to mainstream LCB as our ultimate target. On the energy use aspect, the Hong Kong BEAM Plus assessment encourages integrative design of building systems, as well as innovative elements that enhance energy efficiency and cost saving. Advanced computer simulation approaches are capable of examining coupled energy dynamics in a comprehensive manner.

Sustainable building façades with both active and passive design elements have been discussed in this paper. At one end, the target is to achieve a sharp overall reduction in building energy demand primarily in air-conditioning and lighting installations, while at the other end the opportunity lies in the development of façade integrated renewable energy systems to make up the balance. Examples of R&D efforts are introduced. The use of low carbon recyclable materials and construction methods is an emerging modern trend. More attention should be paid to advanced window glazing technology, as extensively glazed façades continue to be a favourable architectural option.

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The Application Potential of Building Integrated Photovoltaics in Hong Kong

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This paper examines the potential of solar photovoltaic (PV) applications in buildings in Hong Kong. A detailed case study of rooftop PV systems has been conducted. The potential installation capacity of rooftop PV systems in Hong Kong is estimated to be 5.97 GWp, and the annual potential energy output is predicted to be 5981GWh—equivalent to 14.2% of the total electricity use in Hong Kong in 2011. In addition, about 3,768,030 tonnes of greenhouse gas (GHG) emissions could be avoided yearly, by replacing the equivalent local electricity mix. These results demonstrate the immense potential of BIPV applications in Hong Kong. Although the current PV electricity cost is relatively high in Hong Kong, PV generated electricity is expected to be able to fully compete with traditional electricity modes in the near future, if appropriate subsidies are provided by the government and there are ongoing reductions in installation costs. The findings presented in this paper are expected to provide a theoretical basis for local energy policy makers to develop reasonable energy policies, development targets and subsidies for PV technology in Hong Kong.

Keywords: solar energy, building-integrated photovoltaics, potential of rooftop PV systems, greenhouse gas emission

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Status of Local Energy and Environment

In 2011, total energy end use in Hong Kong was about 278,618TJ, with renewable energy—including solar, wind, biogas and bio-diesel providing only 0.8%, and the remainder derived from fossil fuels (coal, oil, and natural gas) (EMSD, 2013). In 2009, the electricity mix in Hong Kong comprised 23% nuclear power imported from Mainland China and 77% traditional thermal power generated by local power plants (EBHK, 2010). About 71% of local thermal power was generated by coalfired power plants, and the other 29% was generated by natural gas power plants (ACHK, 2012). The extensive burning of fossil fuels has resulted in massive emissions of greenhouse gases (GHG), and is thought to be a major source of environmental pollution. Figure 1 presents the GHG emission trends in Hong Kong from 1990-2008 (EBHK, 2010). The total annual GHG emissions reached up to 42 million tonnes in 2008. Electricity generation ranked highest in terms of sectoral contributions to Hong Kong's GHG emissions. For instance, it accounted for about 67% of the total emissions in 2008. In 2010, thermal power plants accounted for 50%, 25% and 16%, respectively, of SO_2, NO_x and respirable suspended particulates (PM_{10}) emitted in Hong Kong (ACHK, 2012). Therefore, reducing the operation of fossil fuel power plants could effectively mitigate local environmental pollution and GHG emission issues.

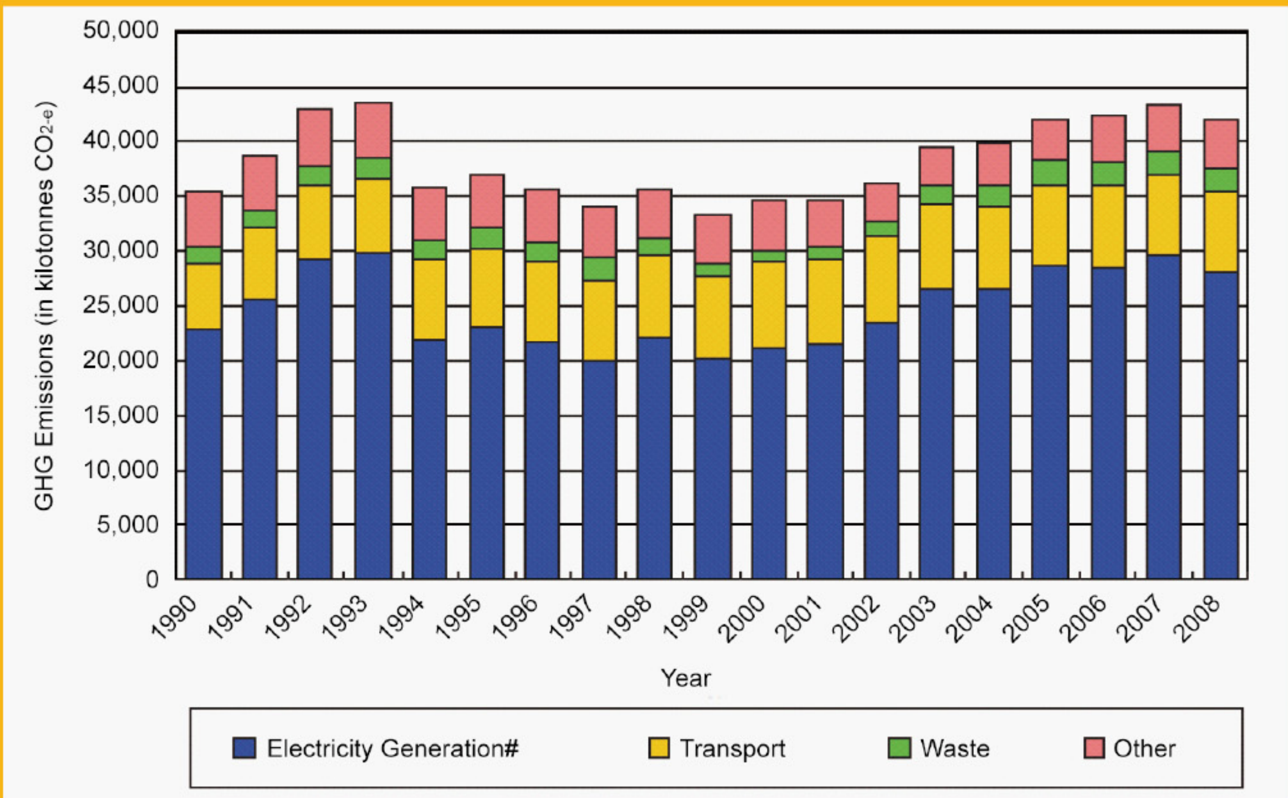


Figure 1 GHG emission trends in Hong Kong from 1990-2008 (EBHK, 2010)

In this context, and for a more sustainable future, the HKSAR Government issued a public consultation document on coping with the challenge of GHG emission and climate change in September 2010. This document proposed a target of 50-60% carbon intensity reduction by 2020, compared with 2005, as shown in Table 1 (EBHK, 2010). In order to achieve this ambitious goal in such a short timeframe, enhancing energy efficiency of electrical equipment, and the wide use of renewable and low carbon emission fuels for electricity generation were proposed. Thus, two options were proposed to revamp the fuel mix for power generation by 2023, as shown in Figure 2. In option 1, the fuel mix proportion of coal should be reduced to less than 10% by 2023, by increasing the share of natural gas to 40% due to its much lower GHG emissions per kWh electricity generated. At the same time, about 30% of electricity will be purchased from the Mainland China grid. Moreover, the proportion of renewable energy would increase from only 0.1% in 2011 to 3-4% by 2023. In examining how this renewable energy development goal can be achieved, this paper focuses on evaluating the potential of solar photovoltaic applications in buildings in Hong Kong.

	2005	2020	Reduction
Carbon intensity (kg $CO_{2\text{-}e}$/HK dollar)	0.029	0.012-0.015	↓50-60%
Total GHG emissions (million tonnes)	42	28-34	↓19-33%
Per capita GHG emissions (tonnes)	6.2	3.6-4.5	↓27-42%

Table 1 A proposed GHG emission reduction roadmap for Hong Kong from 2005 to 2020

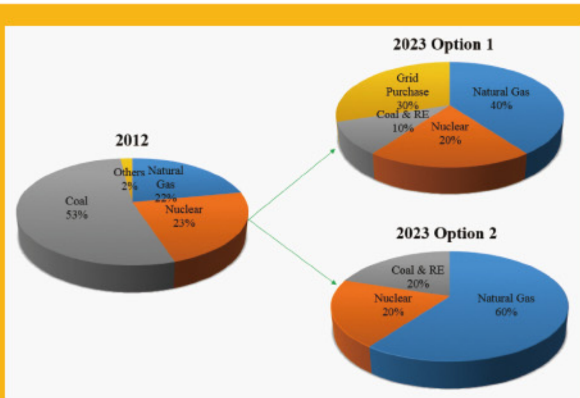
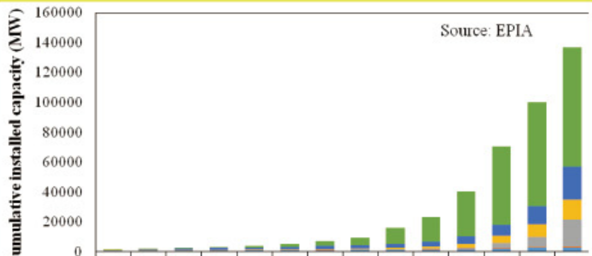


Figure 2 Hong Kong's electricity mix for power generation in 2012 and 2023 (EBHK, 2014)

Trends in the Global PV Market

Global Installation Capacity

Solar photovoltaic technologies have been developing rapidly with great support from governments around the world. By the end of 2013, the global PV cumulative installed capacity reached up to 137GWp, representing a 110-fold increase over 2000, as shown in Figure 3 (EPIA, 2014). Germany is the most aggressive country in the utilisation of solar PV systems, even though its solar energy resources are not abundant. Its cumulative installed capacity reached up to 36GWp by the end of 2013, accounting for about 5.3% of the country's total electricity consumption. Italy is the country with the highest penetration of solar PV electricity. PV-generated power accounted for approximately 9% of Italy's net electricity consumption in 2013. China's PV installed capacity reached 19GWp by the end of 2013. Moreover, China's National Energy Administration (NEA) has set the 2014 target for new solar PV capacity installations as 14GWp, two thirds of which would be building-integrated photovoltaic (BIPV) systems (REN 21, 2013).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Europe	116	249	381	580	1283	2264	3258	5274	1097	1677	3035	5246	6969	7995
APAC	368	496	686	916	1198	1502	1827	2098	2628	3373	4951	7513	1215	2199
AMERICA	21	24	54	102	163	246	355	522	828	1328	2410	4590	8365	1351
China	19	24	42	52	62	70	80	100	140	300	800	3300	6800	1810
MEA	0	0	0	0	1	1	1	2	3	25	80	205	570	953
ROW	751	807	887	964	993	1003	1108	1150	1226	1306	1590	2098	2098	2183

Figure 3 Evolution of global cumulative installed capacity, 2000-2013 (MWp)

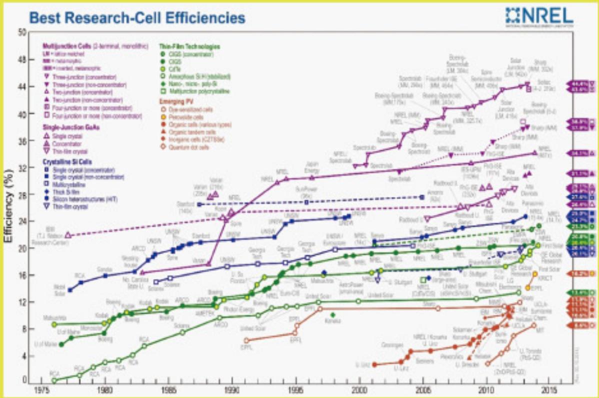


Figure 4 The evolution of the world's best research-cell efficiencies (NREL, 2014)

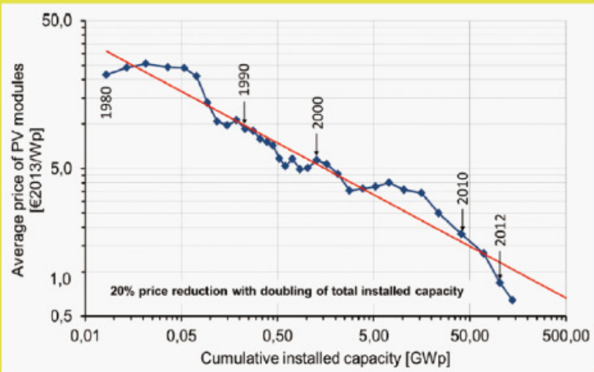


Figure 5 Historical price trends of PV modules varying with the installed capacity (Wirth, 2014)

The Latest Energy Conversion Efficiencies

In recent years, great progress has been made in material science research related to solar cells, leading to continuous improvements in efficiencies of solar cells and PV modules. Figure 4 illustrates the evolution of best research-cell efficiencies (NREL, 2014). As of March 19, 2014, the best efficiencies of commonly used solar cells, viz. mono-crystalline, multi-crystalline, amorphous silicon, copper indium gallium selenide (CIGS) and cadmium telluride (CdTe), were 25%, 20.4%, 13.4%, 20.8% and 20.4%, respectively.

The Costs of PV Systems

With worldwide applications of PV systems in recent years, there has been an ongoing reduction in PV module prices arising from technological progress and economies of scale. Figure 5 shows the historical price trends of PV modules with increasing global installed capacity (Wirth, 2014). The price of PV modules has been reduced to approximately €0.6/Wp from the previous €4/Wp in 2006. The trend indicates that the PV module price would be reduced by 20% if the cumulative installed capacity is doubled. Provided that significant efforts continue to be made to develop products and manufacturing processes, prices are expected to continue to fall in accordance with this rule. At the same time, the PV installation costs have fallen significantly—from €5/ Wp in 2006 to €1.64/Wp in 2014 for rooftop installations in Germany with rated outputs of up to 10kWp (BSW, 2014).

According to a recent report from Deutsche Bank (Vishal *et al*., 2014), the sharp decline of PV installation costs has resulted in PV generated electricity becoming competitive with conventional electricity from the grid in at least 19 markets around the world, even without subsidies as shown in Figure 6. Although Hong Kong is not included in the 19 markets, the levelised cost of electricity (LCOE) of solar PV is rapidly approaching parity with conventional electricity in Hong Kong (Peng *et al*., 2013a), and modest subsidies now could accelerate the adoption of solar PV and stimulate an entirely new industry.

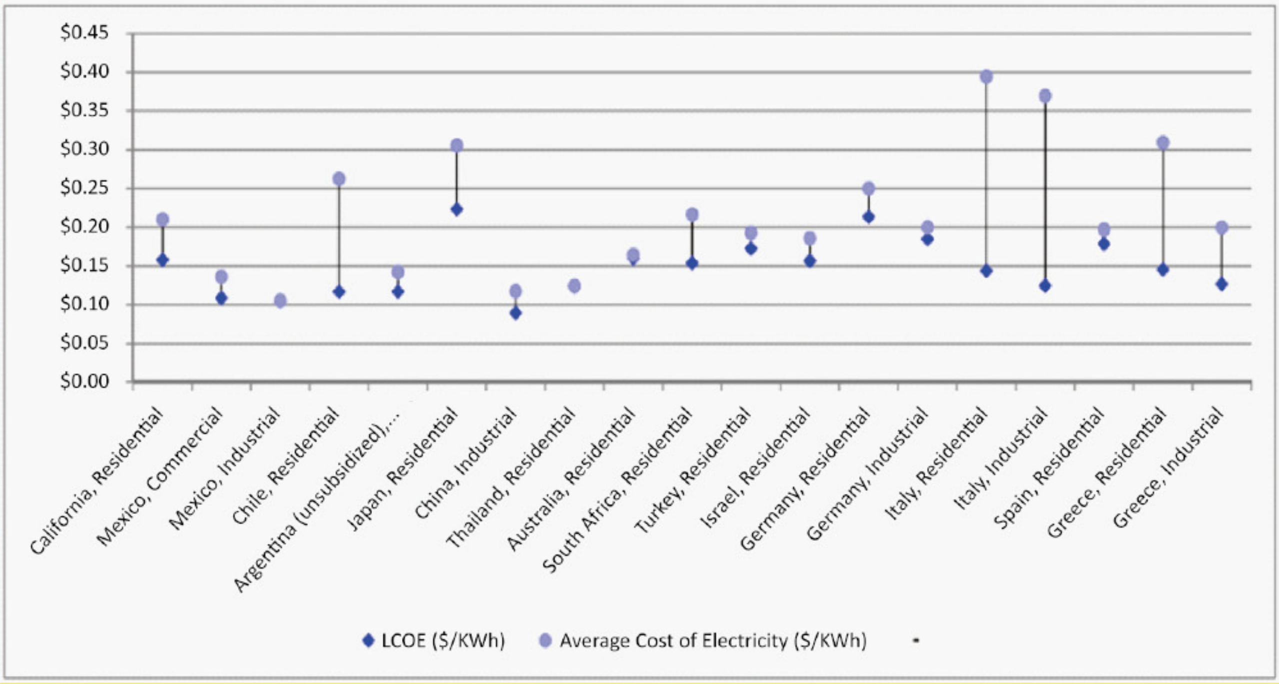


Figure 6 PV achieved parity with grids in 19 markets worldwide (Vishal *et al.*, 2014)

Potential of Building Integrated Photovoltaics

Building Integrated Photovoltaics

Building-integrated photovoltaics (BIPV) refer to using photovoltaic materials, viz. solar cells and PV modules, to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades. These PV modules simultaneously serve as building envelope material and generate power, thus can provide savings in material and electricity costs (WBDG, 2011). Compared with common ground mounted PV systems, BIPV systems do not occupy any land resources, so are very suitable for use in cities that are short of land but have high-density buildings, such as Hong Kong.

Estimating the PV-suitable Rooftop Area

An assessment of rooftop PV potential usually starts with determining the rooftop area available for installing PV systems. However there is little direct statistical information regarding PV-suitable rooftop areas. In recent years, some research methods have been reported for estimating the PV-suitable rooftop area (Denholm and Margolis, 2008; Gutschner *et al*., 2002). In this study, the PV-suitable rooftop area was estimated from buildings' ground floor areas. The details of the procedure are illustrated in Figure 7. Firstly, the ground floor area is transferred into the gross roof area by using a 'gross roof area to ground floor area' ratio. The potential PV suitable rooftop area can then be calculated based on the gross roof area by using solar suitability and architectural suitability factors. Usually, the 'gross roof area to ground floor area' ratio and the solar suitability and architectural suitability factors can be determined by rule of thumb. In this paper, these three factors were assumed to be 1.2, 0.55 and 0.7, respectively, to estimate the potential PV-suitable rooftop area in Hong Kong. The total ground floor area of all buildings in Hong Kong is about 117 km² (PDHK, 2011). Based on these figures, the potential PV-suitable rooftop area in Hong Kong can be easily calculated. The results are presented in Table 2.

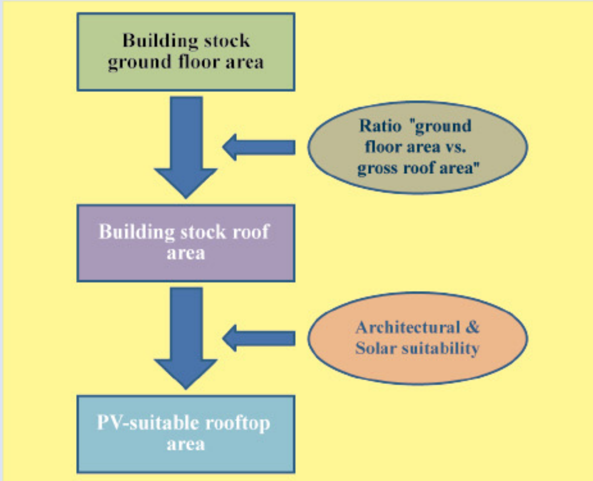


Figure 7 Procedure for estimating potential PV-suitable rooftop area

Ground floor area	117 km²
'Gross roof area to ground floor area' ratio	1.2
Gross roof area	140 km²
Architectural suitability factor	0.7
Architecturally suitable roof area	98 km²
Solar suitability factor	0.55
The potential PV-suitable rooftop area	54 km²

Table 2 The potential PV-suitable rooftop area in Hong Kong

Application Potential of Rooftop PV Systems

In order to maximise the energy output of rooftop PV systems in limited PV-suitable roof areas, high efficiency PV modules should be used. In this study, a STP260S mono-crystalline PV module made by Suntech, China, was chosen as an objective module. After taking the reserved array distance into account, installing a single objective PV module would occupy about 2.35m² of a rooftop. The total active area of the rooftop PV modules can be calculated by Eq.1:

$$A_{act.} = \frac{A_{pot.}}{A_{occu.}} \times A_{pv} \quad (1)$$

Where, $A_{act.}$ is the potential total active area of PV modules; $A_{pot.}$ is the potential PV-suitable rooftop area in Hong Kong; $A_{occu.}$ is the installation occupancy area of a single PV module; A_{pv} is the area of a single PV module. For rooftop PV application, the potential total active area of PV modules installed with the optimum tilted angle of 23° was calculated to be 37.4km². Thus the potential installation capacity of rooftop PV systems is estimated to be 5.97GWp in Hong Kong. The potential of annual energy output of rooftop PV systems can be briefly estimated by the following equation:

$$E_{potential} = A_{act.} \times G_{optimal} \times \eta_{stc} \times \lambda \quad (2)$$

Where, $E_{potential}$ is the annual potential energy output of rooftop PV systems in Hong Kong; $G_{optimal}$ is the annual total solar radiation received by the PV modules installed with the optimum tilted angle. This is about 1332.7 kWh/m²; η_{stc} is the PV module's energy conversion efficiency in the standard testing conditions (STC), and the efficiency is 16% as declared by the manufacturer; λ is the performance ratio of PV systems. This ratio considers all losses from converting solar energy into direct current electricity and then inverting the direct current into alternating current electricity. It is assumed to be 0.75 in this study.

The result of calculating $E_{potential}$ is about 5981GWh per year, which is equivalent to 14.2% of the total electricity use in Hong Kong in 2011 (CSDHK, 2011). This proportion is much higher than the target set for renewable energy development (3-4%) in Hong Kong. According to this result, policymakers could develop a more ambitious target for developing renewable energy in future, and PV technology certainly has the potential to meet the target. In addition, every year about 3,768,030 tonnes of GHG emissions can be avoided annually by replacing the equivalent local electricity mix with potential PV electricity (5981GWh) generated by rooftop PV systems in Hong Kong. Thus, it appears possible that rooftop PV systems can play a significant role in saving energy and reducing GHG emissions in Hong Kong.

Energy and Environmental Benefits

In order to thoroughly investigate the life cycle environmental effects and energy payback performance, a life cycle assessment was conducted in our previous study to evaluate PV systems' sustainability and environmental friendliness (Peng *et al*., 2013b). Figure 8 presents the results of energy payback time for various PV systems. It was found that the average energy payback time of the five commonly used rooftop PV systems ranged from 1.4-2.7 years, which is far less than the lifespan of PV systems, which is usually about 25 years. The GHG emission rates of PV electricity generated by various PV systems are summarised in Figure 9. They ranged from 10.5-50g CO_2-eq/kWhe. The mono-Si PV system has the highest GHG emission rate due to its high life-cycle energy requirement. Nevertheless, its GHG emission rate still had an order of magnitude less than that of fossil-based electricity in Hong Kong, which is about 700g CO_2-eq/kWhe. Thus, from the perspectives of both energy payback time and GHG emission rate, solar PV electricity is definitely sustainable and environmentally friendly.

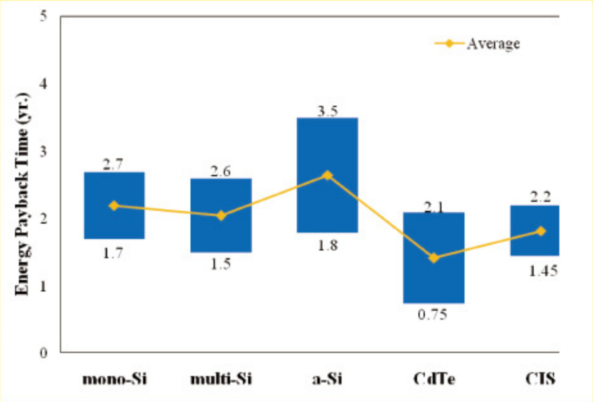


Figure 8 Review of the energy payback time of various PV systems

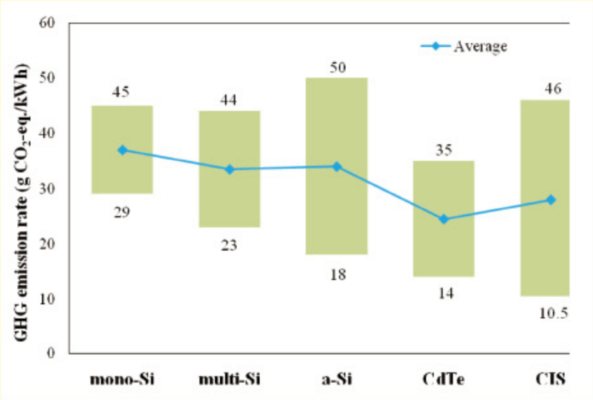


Figure 9 Review of GHG emission rates of PV electricity generated by various PV systems

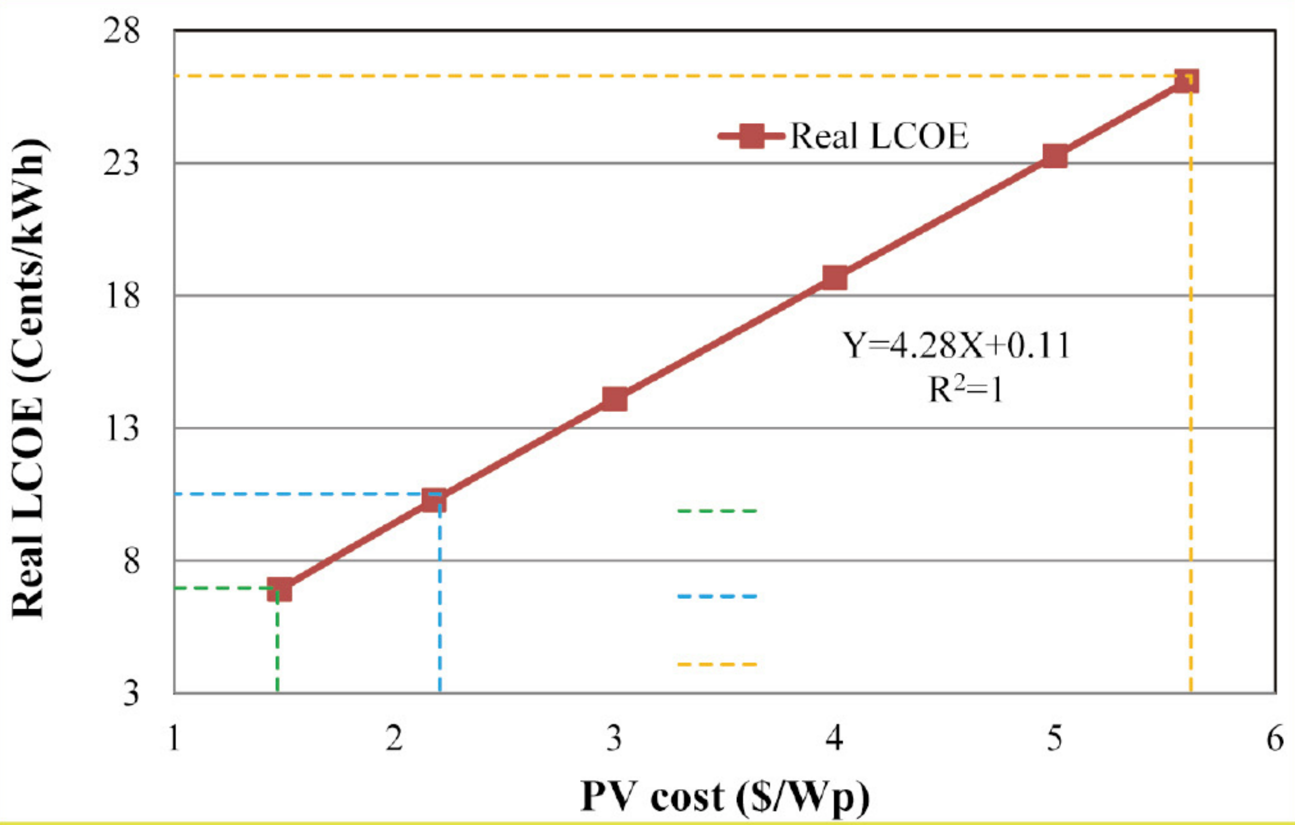


Figure 10 Relationship of PV installation costs and LCOE of PV electricity in Hong Kong

Levelised Cost of Energy

Figure 10 presents the relationship between PV installation costs and the LCOE in Hong Kong. It is shown that the LCOE of PV electricity is proportional to installation costs and it decreases with the reduction of installation costs. For every $1/Wp decline in installation costs, the LCOE will drop about 5 cents/kWh. In order to further understand the impact of installation costs on the PV systems' LCOE in Hong Kong, the potential LCOEs according to installation costs in Mainland China, Germany and Hong Kong were analysed and shown in Figure 10. Case 1 shows the potential LCOE of rooftop PV system in Hong Kong assuming the installation cost is equivalent to that in Mainland China ($1.48/Wp), it is about 6.9 cents/kWh. Case 2 indicates the potential LCOE is about 10.3 cents/kWh assuming the installation cost is equivalent to that of Germany ($2.18/Wp).

Case 3 represents the current real LCOE of PV system in Hong Kong. It is about 26.1 cents/kWh, which is calculated by the current average installation cost of $5.6/Wp. Currently, the domestic electricity price in Hong Kong is about 14-23 cents/kWh depending on the amount of electricity consumption (HKE, 2013). With the rising prices of fossil fuels, the tariff would rise by about 4% annually. Thus, even calculated with the current installation cost, the LCOE of PV systems in Hong Kong is probably lower than the retail electricity price 2 years later. If the installation cost is reduced to equal that in Germany in the coming few years by reducing the soft costs, the LCOE of 10.3 cents/kWh would be lower than the current retail tariff by 26-55%. With the costs of PV modules and inverters further decreasing, the installation cost in Hong Kong would probably be reduced to equal that in Mainland China, hence the LCOE of 6.9 cents would fully compete with other traditional energy sources without subsidy. If the environmental benefits of PV electricity, such as much lower GHG emission rates are considered, the advantages and competitiveness of PV electricity would be strengthened.

Recommendations for PV Development in Hong Kong

From the above analysis, policy makers should develop related measures or policies to further reduce the soft costs of PV systems as well as provide a suitable subsidy or feed-in tariff. Based on the above installation costs and comparisons for different countries and regions, the following suggestions to facilitate the reduction of installation costs and promotion of PV application in Hong Kong, are proposed:

- The government should provide appropriate subsidies and preferential feed-in tariff to increase users' enthusiasm in installing PV systems as well as expand the PV application scale when the LCOE of PV electricity is higher than the retail tariff. The effects of large-scale application is beneficial to further reduce hardware costs and non-hardware costs. After PV systems have developed to a certain cost scale, the subsidies could be gradually reduced year by year.

- Introducing more intense competition mechanisms, such as opening up to PV companies and labour in Mainland China to install PV systems in Hong Kong.
- Training workers and engineers to improve work efficiency and developing more efficient installation methods.
- Simplifying the processes of grid-connection and reducing the relevant soft costs as much as possible.
- Effectively attracting private capital and foreign investment (well established PV suppliers or investors from Mainland China) to develop rooftop PV power plants in Hong Kong by the way of energy management contract (EMC).

Conclusions

This paper investigated the potential of solar PV applications in buildings in Hong Kong. The potential installation capacity of rooftop PV systems in Hong Kong was estimated to be 5.97GWp, and the annual potential energy output was predicted to be 5981GWh. This is equivalent to 14.2% of the total electricity used in Hong Kong in 2011. Hence policymakers could develop a more ambitious development target for renewable energy in the future. PV technology certainly has the potential to meet the target. Although the current PV electricity cost is relatively high, PV generated electricity is expected to fully compete with traditional electricity modes in the near future, if appropriate subsidies are provided by the government and there are ongoing reductions in installation costs. Therefore, the government should pay more attention to this development, by introducing new policies for encouraging private companies and building occupants to install more BIPV systems.

Acknowledgements

The authors sincerely appreciate the financial support from the Public Policy Research (PPR) Funding Scheme 2013/14 (PPR Project: 2013.A6.010.13A) of the Hong Kong Special Administrative Region (HKSAR).

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Challenger, Bouygues Construction and Dragages Head Office: A Zero Energy and Low Water Usage Building Renovation

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Challenger, the emblematic headquarter of Bouygues Construction, first opened in January 1988 in Guyancourt, France. Twenty years later a complete renovation program was undertaken with an ambitious objective: enhancing the energy and environmental performance whilst upgrading the working environment for 3,200 employees.

Completed in July 2014, after 4 years, Challenger is one of the first ever tertiary buildings renovated to an energy positive level. Challenger is a showcase of the group's expertise and leading know-how in sustainable construction, and achieved LEED® Platinum, BREEAM® Outstanding and HQE® Exceptional.

The aim of this paper is to present the main environmental features of this major renovation in terms of energy, water, ecology and indoor quality. The results and benefits of first year performance after renovation are also reported in this article.

Key features:

- ***Super insulated buildings: 88% of the glass cladding replaced by a double-skin façade***
- ***Ground (ground-source) and air (air-source) heat pumps***
- ***VRF air conditioning system with variable water flow***
- ***25,000m² of photovoltaic panels***
- ***Wastewater and rainwater is treated and reused on site through artificial wetlands - zero water goes to sewers, and water consumption is reduced by more than 60%***
- ***Individual LED Lighting to reduce energy consumption***
- ***Renovation on an occupied site***
- ***Positive impact on biodiversity***

Keywords: Zero Energy Building, geothermal, artificial wetlands, LEED®, BREEAM®, zero water building, positive biodiversity

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Roland Le Roux is the Open Innovation Manager of Bouygues Construction. Prior to joining the innovation field, Roland worked as a Green Building Consultant. He also co-founded 360Efficiency, a US based company specialised in energy audit software, and led the technical team of the National Energy Leadership Corps—a nation-wide program aiming at retrofitting low-income family homes to enhance their energy performance.

Devani Perera, a Project Manager at Elan, a subsidiary of Bouygues Construction, is a Green Building Consultant and Civil Engineer. With over 8 years of diverse experience in the construction industry, Devani also worked as a civil engineer in structural construction work in Asia, and as a Building Cost Estimator and Construction Project Manager in North America before joining Elan in France.

Introduction

Challenger was built in 1988 on a 30-hectare wooded site near the headwaters of the Bièvre River, a short distance from the Château de Versailles. The final project was the result of a close and trusting collaboration between Francis Bouygues and Kevin Roche, which took the architect's preliminary design through to its final form—a building complex with vast common facilities to promote communication, well being and progress.

The campus is composed of a main building consisting of a central part as shown in Figure 1 with three vast atria (11) on which converge four large curved office wings (3,4,5,6). The central part provides the main services for occupants of the office buildings (restaurants, gymnasium, conference room, shops etc.) and represents less than 30% of the total gross floor area. Two triangular buildings (2 and 7) are connected to the main building by a central driveway, flanked by two reflecting pools and a new underground parking (1 and 10).

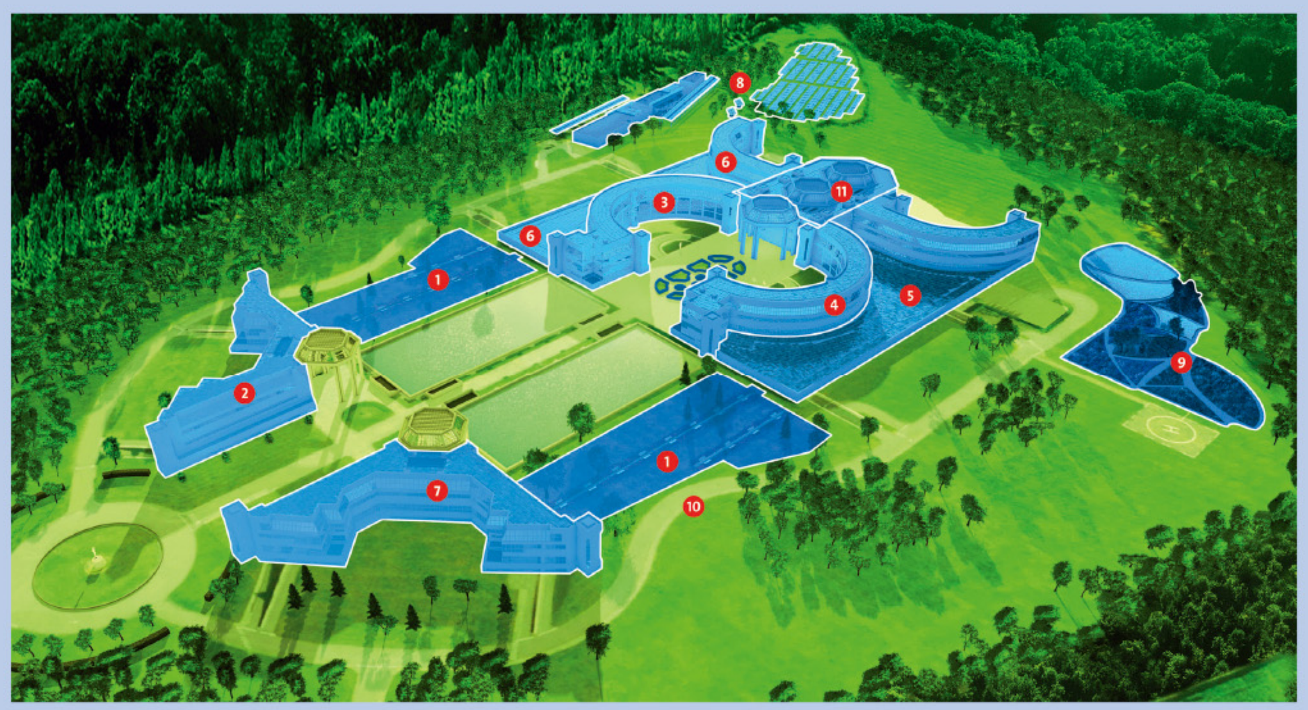

Figure 1 Challenger site – Scope of renovation

Renovation of Challenger included the following works and phases (see figure 1):

1. Pool and South Triangle ground-level carparks
2. North Triangle
3. Northwest wing of Main Building
4. Southwest wing of Main Building
5. Southeast wing of Main Building
6. Northeast wing of Main Building
7. South Triangle
8. Energies and services building/Solar farm/Geothermal probes
9. Jardin Filtrant®: constructed wetland
10. Finishing of carparks and grounds
11. Renovation of atrium

The Project Team

Owner	SNC Challenger (Bouygues Construction)
Project manager and green building consultant	Elan
Architect	SRA
Main contractors	Bouygues Construction (DV/Bouygues Energies & Services)
Façades consultant	Emmer Pfenninger partner AG
Building services consultant	Ferro Ingénierie
Energies & photovoltaic consultant	Amstein et Walthert
Structural engineering consultant	CEBAT 2000
Acoustics consultants	CIAL et LASA
External works consultant	LMP Conseils
Design & construction of filtering gardens	Phytorestore
Health & safety coordinator and building control body	Bureau Veritas
Fire safety coordinator	Eurocoord
Renovation of concrete façades	Tollis
Signage	Alto
Earthworks	Screg
Gutting of buildings	Colas
Roofing	Smac

Project Planning

2008	Energy and environmental audit of the existing buildings
2010	Start on site
September 2011	Handover of the filtering gardens (artificial wetlands)
November 2011	Handover of the solar farm - start of the test period
February 2012	Handover of the first building (North Triangle) - which became the world's first building to achieve triple environmental certification including LEED Platinum, BREEAM Outstanding and HQE (High Quality for Environment) Exceptional
March 2012	Handover of the cockpit building which achieves three main purposes: Building management system (BMS) – to monitor and control all buildings; installation of the main plant room for the heating and cooling systems (thermal loop, ground source and air source heat pumps, solar farm); and showroom
April 2012	Commissioning and connection of the solar farm (6,500m² photovoltaics)
July 2012	Handover of the second building (South Triangle)
February 2013	Handover of the Northwest part of the Main Building
July 2013	Handover of the Southwest part of the Main Building
January 2014	Handover of the Southeast part of the Main Building
July 2014	Handover of the Northeast part of the Main Building
September 2014	Environmental certification of the campus - HQE/LEED/BREEAM

Zero Waste Water Building

Wastewater And Rainwater Management By Phyto-Purification

Water management is a key feature for Challenger. The very innovative solution adopted consists of a phyto-purification system - filtering gardens. The system works by creating a wetland environment which naturally purifies rainwater and wastewater.

As shown in Figure 2, filtering gardens® are landscaped treatment areas ($2270m^2$) which purify wastewater and stormwater on site. After treatment, the wastewater is fed to a storage pond and can be used for irrigating the grounds. All the stormwater collected on site goes through a series of treatments in order to be stored and reused for the building's toilets as well as in its six adiabatic towers and two cleaning stations.

The aim of this natural treatment plant is to achieve the following three goals:

- To reduce the municipal water demand by more than 58% using treated wastewater and rainwater on site, i.e. a saving of about $60,000m^3$ of water per year;
- To send zero stormwater or wastewater to the sewage system; and
- To irrigate all green spaces with $34,000m^3$/year.

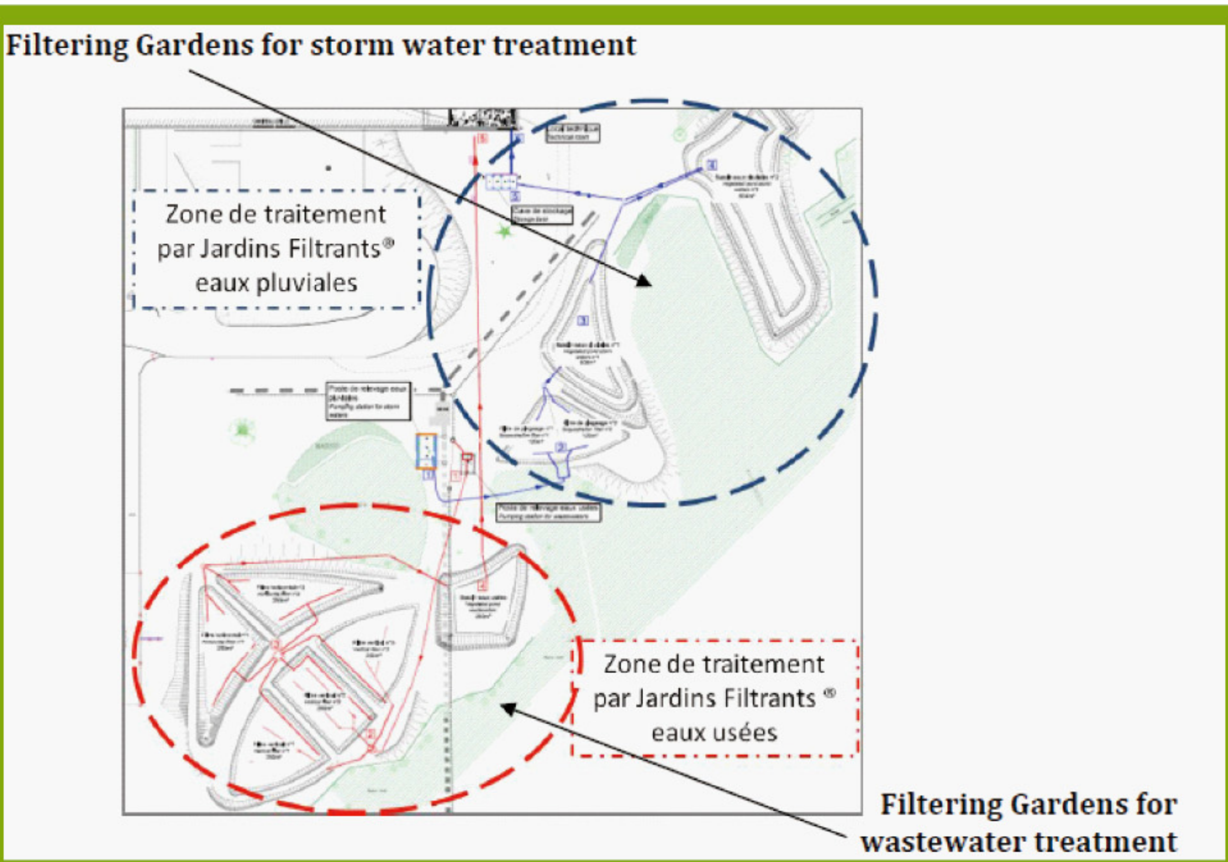

Figure 2 Filtering areas

The achievements include:

- Reduction of water consumption;
- Preservation of the environment by creating a wetland with biodiversity;
- Creation of a unique landscape; and
- Demonstration of the highest level of performance for 3 international certification tools: HQE, LEED, BREEAM.

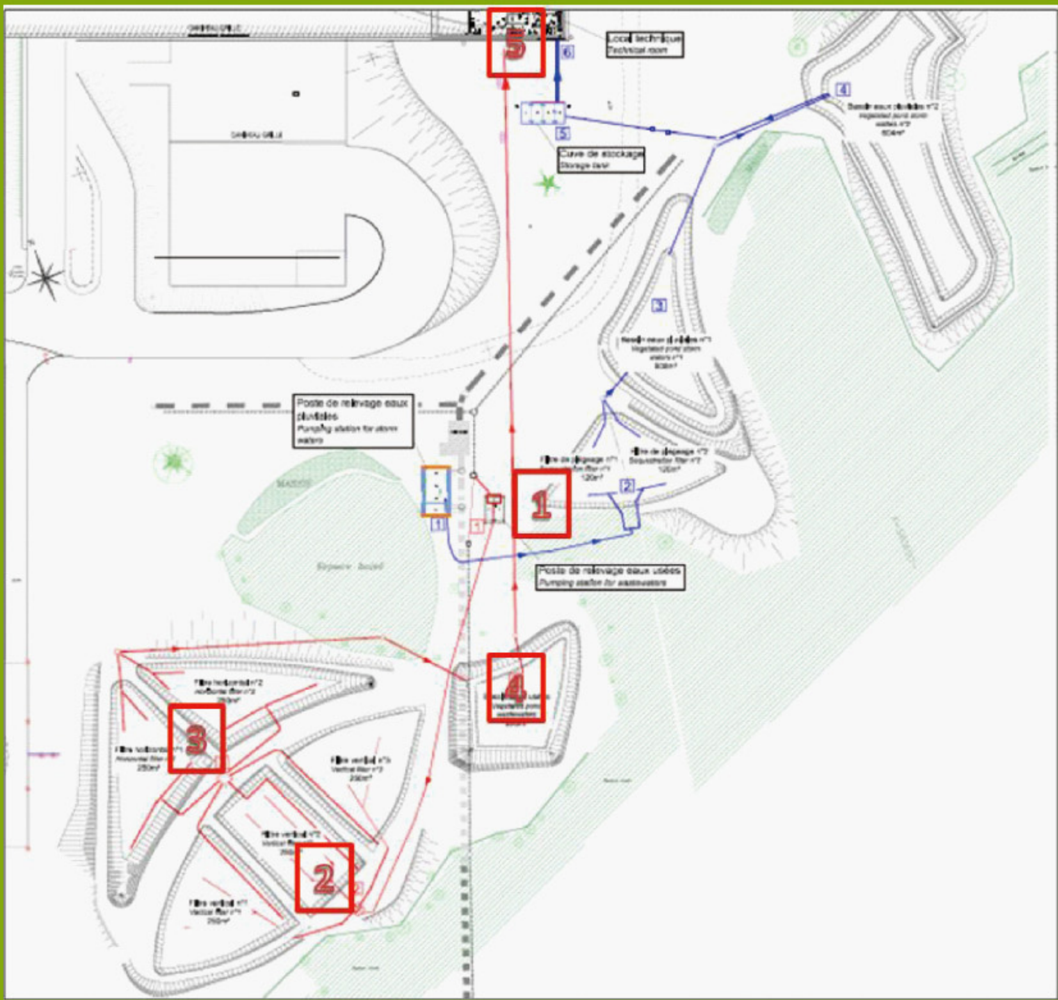

Figure 3 Wastewater treatment system

The wastewater treatment system consists of the following process, as shown in Figure 3.

Step 1 Collection Station

A station collects all the wastewater from the Challenger site estimated at 125kg per day (equivalent to a village of 850 inhabitants). Two crushing pumps with capacities of 75m³/h send wastewater into vertical filters for treatment.

Step 2 Vertical Filters

Vertical filters are the first step of phyto-restoration treatment for Challenger wastewater. 3 vertical filters each with an area of 250m², are geo-membranes composed of several layers of material with different granulations (bigger at the bottom and finer above) in which aquatic plants were planted.

These filters are called vertical filters because untreated wastewater, after being collected by an underground station, arrives through a supply line above substrata and is then collected at the bottom of the filter after crossing three layers of substrata as well as plant roots.

The presence of aeration chimneys along the filters prevents the creation of obnoxious smells by bringing oxygen needed to keep the filter in an aerobic condition. This filter has several roles: organic matter in the form of particles is filtered at the surface of the filter and then degraded by microorganisms that develop at the roots of plants. Nitrogenous matter, which are abundant in toilet effluent, undergo a chemical process-nitrification. In aerobic conditions, nitrogen present in ammoniac form (NH_4^+, NH_3) is oxidised and transformed into nitrates (NO_3^-) or nitrites (NO_2^-).

95-98% of organic matter is removed from effluent via exit of this filter. To obtain a proper 'digestion' of these substances, with the help of bacteria and other microorganisms, there are multiple filters in order to alternate between process and rest periods. Mineralisation processes are most efficient during this second step because microorganisms develop with an excess of these substances.

Step 3 Horizontal Filters

After vertical filters, water arrives by gravity into horizontal filters—the second step of filtering gardens®

treatment. There are 2 horizontal filters, each with a surface area of 250m^2. Water crosses these filters horizontally. The waterproof horizontal filters comprise two layers of materials with different granulations. By crossing one side of the filter to another, water stays in contact with roots longer than with vertical filters. This enables a complete degradation process of nitrogenous compounds called de-nitrification. Oxidised nitrogen is 'reduced' (in chemical terms) and transformed into gaseous nitrogen N_2 which is released into the atmosphere. The plants will consume organic molecules and phosphorus present in the water for their growth.

Step 4 Vegetated Ponds

Vegetated with decorative or oxygenating plants, landscaped water banks serve as habitats for dragonflies and other insects. This waterproof pond is the final step of treatment-disinfecting effluents. With the help of UV on water and microorganisms, germs are destroyed and the purified water is ready for irrigation.

Figure 4 Vegetated ponds for wastewater treatment

Step 5 Technical Station

Treated wastewater is collected at a technical station, where the water is sent for irrigation. This station facilitates the management of water reuse for irrigation of green spaces, saving 34,000m^3 of potable water or ground water per year.

Stormwater Treatment by Filtering Gardens®

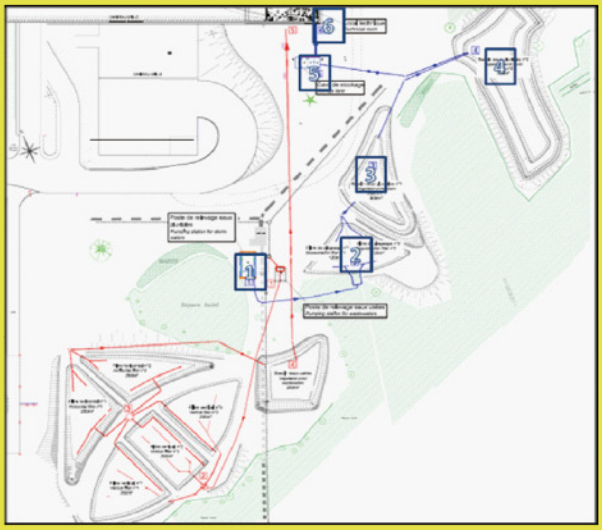

Figure 5 Stormwater treatment process

As illustrated in Figure 5, the renovation of the campus included the following changes:

- Underground parking access through the north and south ponds (560m^2 of impervious area added);
- Creation of the 'cockpit' building (810m^2 of new impervious area);
- Addition of solar panels on roofs of the three buildings - North Triangle (#1), South Triangle (#2) and Main building (#3). Pre-development roof areas were covered by gravel with a low runoff coefficient (C=0.6). Post-development roof areas are covered by solar panels with a higher coefficient (C=0.9);
- Addition of a solar farm increasing the imperviousness of the site by 6,500m^2.

The Challenger campus site occupied a pre-development active area of 7.02ha and occupies a post-development area of 8.06ha. The renovation of Challenger included the creation of several ponds with phyto-remediation and storage capacities in order to treat and keep 100% of stormwater and wastewater on site (based on 10-year storm events).

Step 1 Collection Station

All stormwater from the site arrives by gravity into an underground collection station with a 75m^3 capacity. Two pumps send this water into filters. The estimated volume of a storm varies from 200m^3 for an average rainstorm, to 850m^3 for an annual peak, and up to 2000m^3 for a once in a decade event.

Step 2 Trapping Filters

The treatment system is composed of two filters with areas of 120m^2 each, to rid suspended matter in stormwater, biodegrading grease from vehicles in water from roads, and trap heavy metals. Trapping filters are composed of several layers of materials with different granulations (gravel, compost, pozzolan[1]) in which aquatic plants were planted. The substrata in filters allows phyto-degrading of hydrocarbons with the help of plant roots that destroy long carbon chains present in hydrocarbons and trapping metals by chemical phenomena.

[1] Pozzolan: Siliceous material

Steps 3 and 4: Vegetated Ponds

Finally, water is stored in two ponds with a total capacity of 1110m³ before being reused on site (Figures 6 and 7). Two other existing ponds provide an additional storage capacity of 1000m³. The proposed treatment system is a wetland capable of preserving natural resources as well as recreating an environment rich in animal and vegetal biodiversity.

Steps 6 and 7: Rainwater Ponds

Purified stormwater is sent to a storage tank for reuse in toilets, cleaning and cooling towers. These two zones facilitate the management of water volumes for recycling to achieve the objective of a 'zero discharge' site for Challenger. The sizes of the natural treatment plant and ponds were determined based on a 10-year storm event (higher than average annual storm events). 100% of stormwater volume is collected and treated in the 'filtering Gardens'. 60,000m³ water is saved per year (29,000m³ stormwater and 34,000m³ of treated wastewater for irrigation).

Figure 6 and 7 Rainwater ponds

Stormwater Quality Control

The treatment system takes into consideration the fact that only stormwater from roads presents a real source of pollution, with 600kg/year of COD or 1800kg/year of suspended matter. It functions as shown in Figure 5.

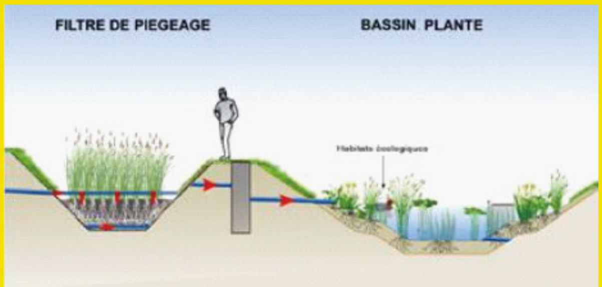

Figure 8 Storm water quality control

The filtering gardens have been created in order to capture the total suspended solids (TSS) and other types of pollutants and metals. According to manufacturer calculations and data, the filtering garden efficiency for TSS removal is 91%,

A variety of plants used for phytoremediation tend to thrive in hot and humid climate. Therefore, as cited in the article "The potential for bioremediation in Hong Kong waters" (Man *et al*, 2001), this technique can be used in Hong Kong although the lack of space could be an issue.

Positive Biodiversity

Challenger will also obtain the new BiodiverCity Label—an innovative tool which recognises the effort and commitment made to enhance biodiversity in the built environment.

Figure 9 BiodiverCity® Label

Before its renovation, Challenger already featured a 24ha park with 139 species of plants, 50 species of birds, 31 species of insects and many mammals, reptiles and amphibians. To further enhance this habitat diversity, a wetland and meadows were created. This not only helped to diversify the ecological environment but also helped in the overall stormwater and wastewater treatment.

An ecological audit carried out before and after the project confirmed that the rich biodiversity that was present on this site is maintained. The new wetland for waste and rain water treatment, and change in landscaping management practices (e.g. reduction of landscape waste), have contributed greatly in producing positive biodiversity on site.

A comparison of the ecological potential before and after renovation based on the audit demonstrates a substantial increase in ecological value as shown below.

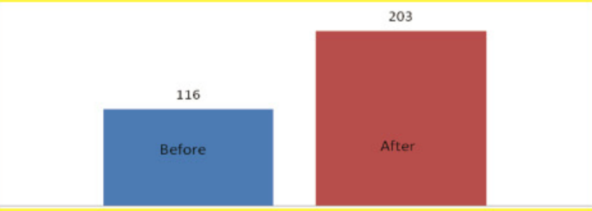

Figure 10 Comparison of the ecological value before and after the construction works

This is translated in the third axes of the certification Biodivercity: Ecological Potential, that the project obtained a level A thanks to the quality, capacity and functionality of the eco-systems of the project.

As clearly stated in the *Economics of Biophilia*[2], evidence based research has established a direct correlation between the impact of green and open areas on human health. A promenade surrounding the gardens with picnic tables and benches was created to enhance the relationship between building occupants and the natural environment around them. The 3,300 employees working on this site have the opportunity to relax and take a break in a clean and soothing environment.

The natural environment surrounding the building is also dotted with information panels and educational events, to inform and educate not only building occupants, but also the general public who visit the site. One of the many interesting features enjoyed by visitors are the bee-hives that are located on site, which help bolster the bee population that is affected by pollution and pesticides.

Figure 11 Educational panels along the footpath

Last but not least, green landscape maintenance practices have been adopted to avoid the use of chemical pesticides and other such products.

BiodiverCity rewards the efforts taken to account for biodiversity throughout the building and its gardens. By obtaining the BiodiverCity label for the project, Challenger demonstrates that even a building that already had rich flora and fauna can still go further and make an impact to boost biodiversity.

Figure 12 Bird boxes

Figure 13 Insect hotel

Figure 14 Hives in Challenger's park

The biodiversity issue can be applied to Hong Kong projects with other types of species. The BiodiverCity Label acquired by Challenger uses an international scheme that can be applied worldwide (www.biodivercity.fr).

[2] The Economics of Biophilia has been recognised with the Environmental Design Research Association (EDRA) 2014 Achievement Award

Energy

The Challenger building has undergone multiple modifications related to its energy retrofit. The following discussion presents the key renovation attributes that drastically enhanced the building's energy performance. Challenger reduced its energy consumption and incorporated systems to generate energy from local resources.

Reducing Consumption

Reducing Challenger's energy consumption and demand was a priority for the renovation. Achieving the target particularly involved improving the thermal performance of the building façade.

Double-Skin Ventilated Façades and Automated Blinds

The renovation of Challenger started with an audit of existing buildings, to identify the insulation work required to improve thermal performance. Thus the insulation and impermeability of external walls and roofs were upgraded. In addition, 88% of the 24,150m² of curtain walling was replaced by a ventilated double-skin façade. By allowing natural air circulation between the inner glazing and the outer single glazing, as shown in Figure 15, this new façade – chosen from among ten different kinds – results in better building insulation:

- In summer, the sun heats the air sandwiched between the two skins, and by thermal convection, this hot air is discharged from the top of the façade;
- In winter, the air circulating between the skins is the first to cool down, which limits the effect the outdoor temperature can have on the building interior.

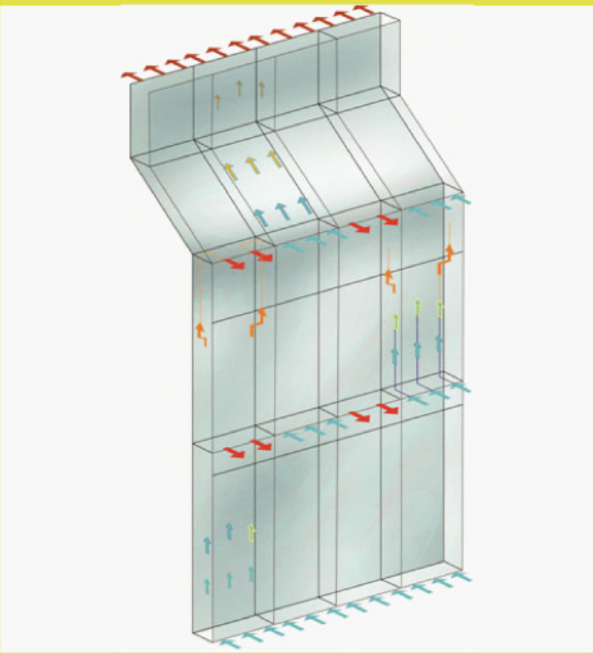

Figure 15 Double-skin ventilated façade

Blinds are installed between the two skins of the façade. These play an essential role in the enhancement of the buildings' thermal performance without introducing any detrimental effects to the site architecture. Above an energy value of 100 W/m² striking the façade, the blinds are automatically lowered to provide shading. During winter nights, the blinds are completely lowered to retain as much of the heat stored in the building during the day as possible.

Figure 16 Installation of the double skin façade

Referring to 6 Hong Kong examples, Haase *et al*. (2007) clearly stipulate that this kind of façade is highly suitable for hot and humid climates.

Renovating Concrete Façades

Challenger's concrete façades were renovated, and restored to their original colour, to regain their solar reflection performance. Black marks on the concrete were due to the presence of micro-organisms (Figure 17). Treatment was applied in several steps:

- A biocide enabled the micro-organisms to be removed;
- The concrete was deep-cleaned to restore its original colour (colorimetric tests were performed to verify it); and
- A waterproof coating was applied to protect the concrete.

Figure 17 Concrete façade renovation

External Lighting Monitoring

External lighting is commanded by the BMS. Lights are controlled according to signals from an external light meter installed on the technical building; and by a timer which turns lights off from 10pm to 5am.

The external lighting network is divided into zones (monitored by the BMS). These several zones are fed to the SDB situated in the south triangle, the technical building, the northwest wing, the southwest wing and the main entrance gatehouse.

Using Natural Resources

To harness electricity and heat from the sun and to use ground-source energy for climate control, Challenger maximises the use of natural resources at the site to produce green energy necessary for its operation.

Photovoltaic Energy

The annual solar production of the different installations on the site is 2,187MWh/yr with a maximum power production of 1,908kW.

Solar Farm

The solar farm can be seen in Figure 18. Located on the northeast of the site, it consists of 3,850 x 230Wp solar panels. The total power amounts to 885kWp.

Figure 18 Solar farm and technical building zone

Technical Buildings and Cockpit Roofs

Solar production on the roof of the technical buildings (Figure 19), located on the northeast of the site, consists of 437 x 230Wp solar panels. The total power amounts to 100kWp. The solar production on the cockpit roof, located in the northeast of the site, consists of:

- 466 x 230Wp solar panels on the roof of the cockpit building with 107kWp;
- 520 x 220Wp solar panels on the Ombrière' (covered walkway in front of the cockpit building), with power amounting to 114kWp; and
- 2 x 9 x 220Wp solar panels on two trackers, the power amounting to 4 kWp.

Figure 19 Cockpit and technical building

Two trackers have been installed in front of the cockpit building for two reasons. The first is to compare instantaneous production and the annual production between solar panels installed with different inclines:

- 30° for the fixed orientation tracker (on the right of Figure 8)
- 5° for the Challenger solar farm
- 20° on the covered walkway 'Ombrière'
- 10° alternated (10° south and 10°north) on the roof of the cockpit and technical building.

The second reason is to compare instantaneous production and the annual production between the fixed orientation tracker and the active sun tracking tower.

Figure 20 The two trackers – one is fixed and one is actively tracking the sun

Lower Terraces of Triangles and the Main Building

The solar production on:

- The lower roofs of the north triangle (terraces level 1) consist of 2 x 70 x 230Wp solar panels - the total power amounts to 32kWp;
- The lower roofs of the south triangle (terraces level 1) consist of 2 x 70 x 230WP solar panels - the total power amounts to 32kWp;
- The lower roofs of the north car park (terraces level 1) consist of 3478 x 230WP solar panels - the total power amounts to 800kWp.
- The lower roofs of the south carpark (terraces level 1) consist of 3478 x 230WP solar panels - the total power amounts to 800kWp.

Solar Heating

The system heats more than half the domestic hot water required by the complex, assuming 15,000L/day. This equates to the consumption of the staff restaurant and gymnasium.

With an average of 1690hrs/yr of direct sunshine in Paris and 1836hrs/yr in Hong Kong, solar photovoltaic applications will tend to have a shorter return on investment in Hong Kong than in northern France. Numerous projects in Hong Kong are referenced on HK RE Net (http://re.emsd.gov.hk/).

Water Rings

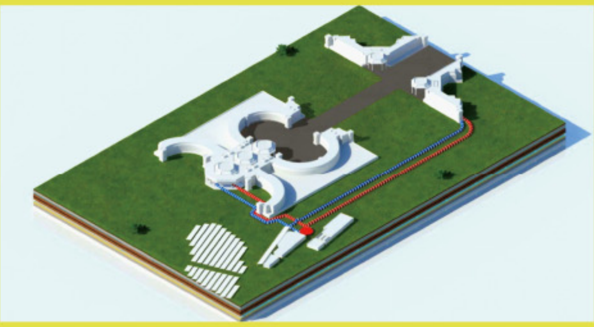

Figure 21 Water rings

Figure 21 illustrates the two low temperature water rings installed on the Challenger site. The two water rings transfer energy from the energy plant room to the buildings (one for the two triangles and one for the main building). The triangles and the wings are connected to a water ring. The energy plant room produces hot or cool water from the earth geothermal probes, geothermal groundwater or adiabatic coolers.

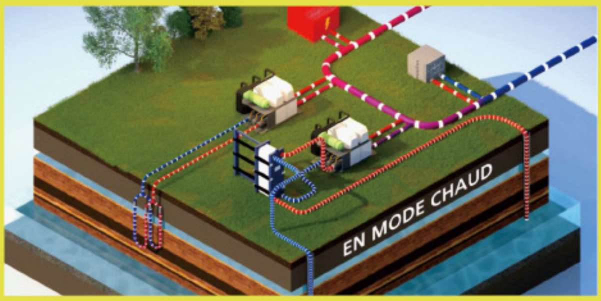

Figure 22 Hot water production mode

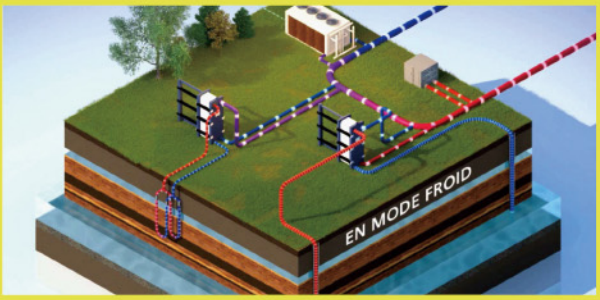

Figure 23 Cold water production mode

The hot or cool water product is stored in 5 x 50m³ tanks located in the technical building. The temperature of the 250m³ water in the rings is maintained between 17-32°C by discharging the water from the tanks into the water rings. The temperature of the water stored in the tanks depends on the weather report for the next day. A correction will be done in case of abrupt weather change during the day.

Geothermal Energy

Two ground-source energy systems were installed for heating and cooling the energy ring: 70 vertical dry borehole probes and one groundwater doublet.

Earth Geothermal Probes

Seventy vertical dry borehole probes descend to 100m beneath the solar farm. In addition, 5 vertical temperature probes were installed around the production probes to control variations of the earth during a long period. Six collectors concentrate the probes to the energy plant room. The heat pump of the earth geothermic circuit is equipped with a Turbocor® centrifugal compressor with magnetic bearings. This heat pump was chosen for its high efficiency and low noise emission.

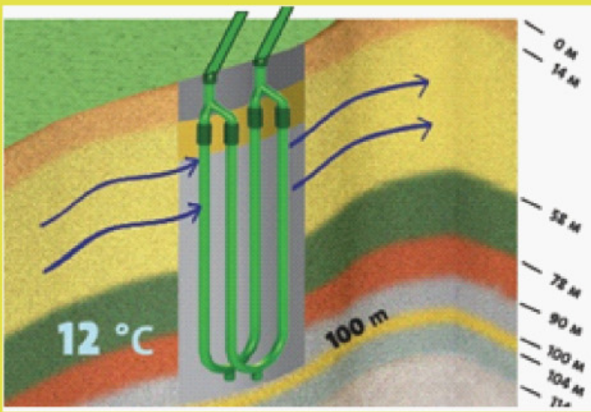

Figure 24 Vertical dry borehole probes

Groundwater Geothermal Wells

Two wells are located on site. One drilled to 135m to pump groundwater and a second, on the other side of the site, to reject the same water 152m below ground level after the thermal exchange (Figure 25).

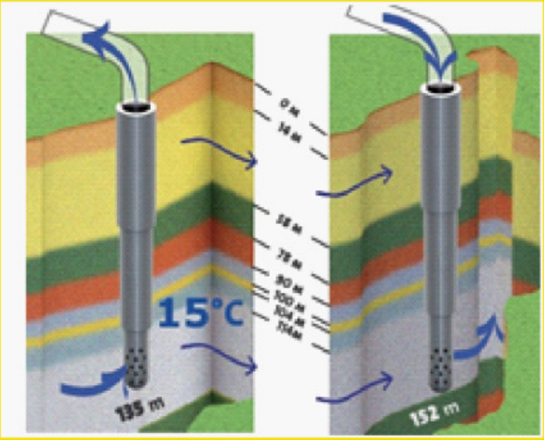

Figure 25 Groundwater geothermal wells

As described by (Li *et al*., 2006), geothermal energy production could be applied in Hong Kong. However, considering the lack of space, the need for cooling and the proximity of the sea in Hong Kong, heat exchange systems and water based heat pumps using the ocean water as a cooling medium could be a suitable and more applicable technology.

Adiabatic Coolers

Adiabatic coolers rely on the physical principle that occurs when the pressure on an adiabatically isolated fluid (i.e. no heat transfer with its environment) is decreased - the fluid expands, thus causing it to do work on its surroundings - the volume increases and the temperature falls as internal energy decreases.

Five adiabatic coolers were installed. The 3C JACIR-MULLER adiabatic cooler (Figure 26) is a heat exchanger where energy is rejected to the atmosphere through a dry process. As soon as the outside temperature increases, this heat exchanger uses the evaporation of the water. In complete safety (no Legionella risk), and without treatment of water, it dissipates energy by maintaining a temperature for cold water lower than that of the ambient air.

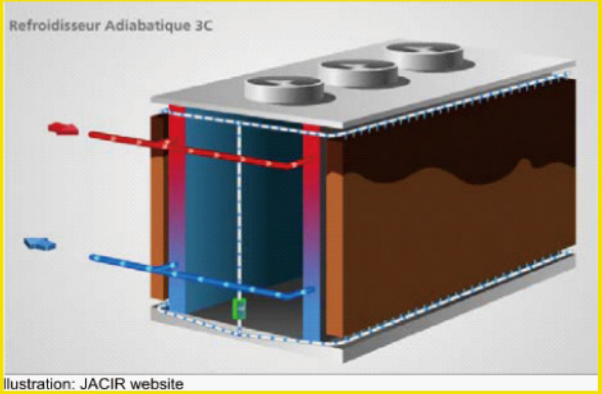

Figure 26 Adiabatic cooler 3C

This adiabatic cooler associates a dry cooling tower and a section of adiabatic pre-cooling: the role of this section of media cooling is to lower the temperature of ambient air by water evaporation on a medium specifically conceived for this use.

Dry mode - The fluid is cooled in the dry battery through which the ambient air flows. This air is pulled by ventilators. The medium at the entrance is dry. The ventilation is regulated according to the thermal load in order to maintain the outflow at a constant. The air is then evacuated upwards.

Adiabatic mode - When the cooling in dry mode becomes insufficient, the medium is humidified. The ambient air flowing through the medium cools by evaporation. The pre-cooled air then flows through the battery in order to cool the fluid. The surplus water is collected and recycled in the phyto-purification system.

Adiabatic coolers are suitable for high cooling demand climates such as Hong Kong. Although this technology is not widely adopted, Yang *et al*. (2009) show the interest in adiabatic pre-cooling for Hong Kong.

Other Energy Sources

Data Centre

The Data Centre at the basement of the northeast wing building is connected to the energy water-rings. The global consumption is 300kW. In heating mode, it represents a source of energy, and during cooling mode an additional consumption.

Generator Sets

In case of a default with the HV power supply, the generators would operate. During winter, a recuperation of energy is attained through plate exchangers.

Energy Balance

Table 1 below shows the energy balance of the site – all buildings are monitored.

Table 1 Energy balance

	Real values from 2014 (January to October) and extrapolated values (November and December)	Simulation Values
Considered buildings	All	All
Units	kWh primary energy/m²	kWh primary energy/m²
HP and VRVs	40.34	15.1
Water ring heating	3.28	1.2
Water heat cooling	3.39	0.37
Auxiliaries (water ring)	25.8	15.62
Auxiliaries (ventilation)	9.36	10.44
Lighting	20.68	19.64
PV production local use	103.25	86.04
PV production grid feed-in	0.12	0
Regulatory Subtotal	**-0.41**	**-23.67**
Computers	26.65	23.11
Total	**26.24**	**-0.56**

The discrepancies between the two columns are due to the following:

- Differences between simulation and reality - cooling and heating temperatures, lighting, store automation enhancement; and
- Temporary malfunctioning of systems - VRVs, balance of systems

Conclusions

This article focused on the renovation of the Challenger building and more particularly on the water and energy retrofit aspects. The environmental performance of these two facets are:

	Before	After
Energy consumption (regulatory conventional scope):	310kWhpe/m²/year	-0.41kWhpe/m²/year
Photovoltaic energy production	0mWh/year	2,500MWh/year
CO_2 emissions	22kg/m²/year	0kg/m²/year
Water consumption	59,000m³/year	28,000/m³/year
Waste water discharge (Grey and Black Water)	40,000m³/year	0m³/year

Figure 27 Challenger site

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Acronyms

VRV	Variable Refrigerant Volume
PV	Photovoltaics
VRF	Variable Refrigerant Flow
LED	Low Emitting Diodes
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
HQE	High Quality of Environment
COD	Chemical oxygen demand is used to measure organic matter in wastewater, treated effluent, and receiving waters
SDB	Sub Distribution Board
HV	High Voltage

Qingdao Net Zero Building Practice

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The construction industry accounts for 40% of global energy consumption. One of the key considerations of the sustainable building industry is to continuously lower building energy consumption—from low energy to zero energy building. Apart from the sustainable design concept, energy planners, equipment suppliers and material suppliers are also investigating the application of renewable energy as a key contributor to a zero energy building project. Bayer Material Science initiated The Eco Commercial Building Program to share best practices with the China construction market and demonstrated that net zero energy building can be achieved through a collaborative network. This paper will present the Qingdao net zero energy building project as a case study to illustrate the steps involved to realise a net zero energy project, with an emphasis on zero energy building techniques, and energy performance monitoring. The paper concludes that the annual energy performance of the Qingdao project validates the net zero energy building design concept, which has been awarded a Gold rating by Leadership in Energy and Environment Design (LEED).

Keywords: net zero energy building, ground source heat pump system, thermally active building system, renewable energy, online energy monitoring

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Introduction

As the fifth demonstrative project of the Bayer EcoCommercial Building Program, the project team planned for the first time, a net zero building located in the hot summer cold winter climate zone. The project involved a two-storey office building with a total floor area of 1163m^2. It serves as the administrative building of Bayer Material Science plant in Qingdao. With 60 workplaces and 1 cafeteria, the building was officially opened on October 16, 2012 and it was awarded a LEED GOLD rating in 2013. The office's energy needs are covered by long term efficiency gains and renewable energy generation. The project represents a model of world class best practice and feasible zero energy techniques applicable to Qingdao city and to the Chinese construction market in general thus helping to fulfil the demand for greener and more energy efficient buildings in China.

Located in northern China, Qingdao city belongs to a hot summer cold winter climate zone. According to typical meteorological data calculations based on Meteonorm Version 6.1, the sustainable solutions applied to this project can be grouped into three categories: passive building solutions, active building solutions and renewable energy. Passive building solutions include the installation of polyurethane roof insulation and floor insulation. Active building solutions include a ground source heat pump system, heat recovery wheel, and light emitting diode (LED) lighting. Renewable energy is supplied by a photovoltaic system. Other building solutions include a polyurethane flooring system and a low volatile organic compound (VOC) wall coating system for a healthy interior environment.

Figure 1 Passive and active energy saving technologies of the Qingdao building

Definition of Net Zero Energy Building

There are different definitions of net zero energy building. According to the International Energy Agency (IEA)'s "Towards Net Zero Energy Solar Buildings" programme, a net zero-energy building is an energy efficient, grid connected building that can generate energy from renewable sources to compensate for its own energy demand (IEA, 2014).

The Qingdao project (Figure 1) is a net zero energy building which fulfils the above definition—its energy consumption is equivalent to its generated energy on an annual basis. In fact, according to its energy management records, the Qingdao building produced surplus electricity over 2013-2014. The actual performance is beyond original design aspirations—it is now an 'energy plus building' (Rainer, 2002).

Steps to Realising Zero Energy

Figure 2 shows that there were four steps in the roadmap to realising the Qingdao net zero energy building.

Figure 2 Roadmap to net zero energy building

Setting the Sustainability Target

Achieving a zero energy building is one of the ways to show the corporation's commitment to sustainability. The project owner/investor has to set the sustainability target, including baseline clarification, scenarios for local climate, locally available technologies, and target identification. The Qingdao location was chosen due to its representative climate zone and suitability to demonstrate energy efficient building technologies.

Two energy planners provided the baseline clarification and simulation support for the Qingdao project: one European technology services company and one local Shanghai energy planning office. During the initial energy simulation work, the project was divided into ten internal temperature zones: office, open office, meeting room, canteen, show room, managers' office, etc. The designed interior temperature for the office area was 26°C in summer and 20°C in winter. Relative humidity calculations were based on 40-65% in summer and 30-60% in winter (Saracevic, 2011).

Monitor Execution

The second step involved monitoring detailed energy design based on the identified target as well as project execution. At this stage, the energy plan and the optimisation of the energy plan are equally important. By using an ordinary office building which is compliant with the China national energy efficiency code as the calculation base case (100%), 62.4% of the initial energy demand reduction could be achieved through selected sustainable design techniques. For example, high performance polyurethane roof insulation, floor insulation and a high performance glazing window system contribute to energy savings. In other words, initial energy demand reduction can be achieved through passive design solutions. The remaining energy demand could be met by on-site renewable energy generation. This is illustrated in Figure 3. Figure 4 shows the final energy balance sheet.

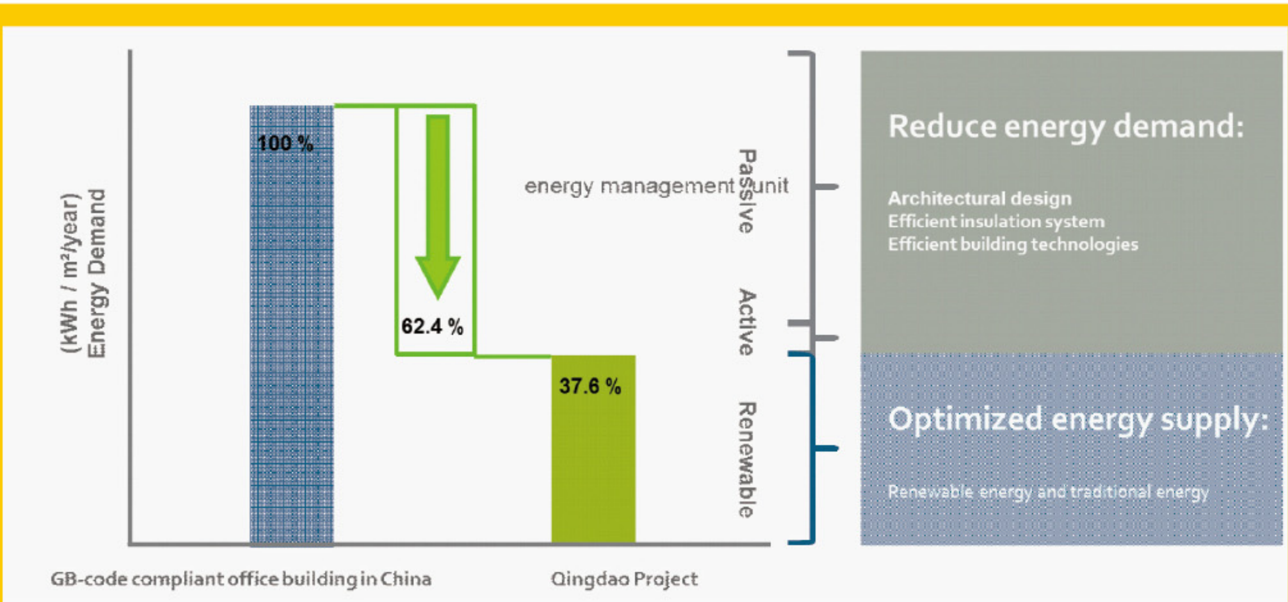

Figure 3 Energy saving performance - route to zero energy

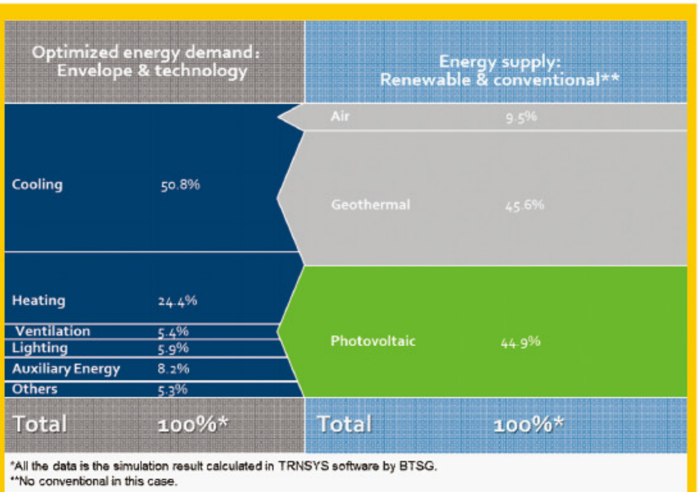

Figure 4 Energy balance sheet of Qingdao net zero energy building (percentages)

Monitor and Verify Results

The third step is to monitor and verify results. Since the building opened, the operational data has been collected on a monthly basis. The building has a trained on-site engineer to operate the energy management system. All staff have been informed on how to operate and work in an energy efficient building via training and user handbooks (see Figure 5). With a data sample of 365 days, from September 1, 2012 to August 31, 2013, the Qingdao building exhibited an annual energy balance of +8.3% per year, which means the building generated 8.3% more electricity than it consumed. Figure 6 shows the energy consumption dashboard monitoring results from September 1, 2012 to January 31, 2014 with monitored annual energy consumption kWh/(m²•a), key performance indicator (KPI as 100% calculation base), and surplus energy kWh/(m²•a) presented as a percentage.

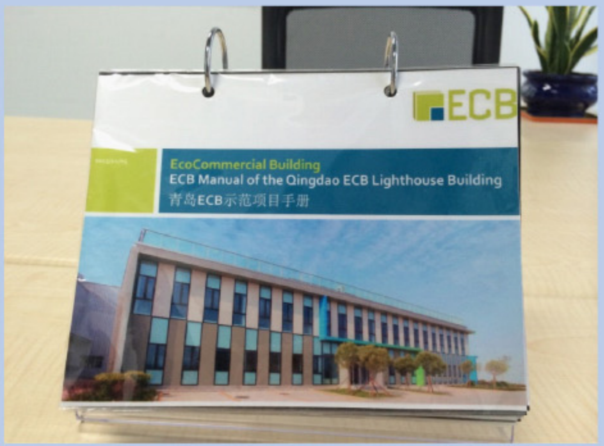

Figure 5 User manual for Qingdao net zero energy building

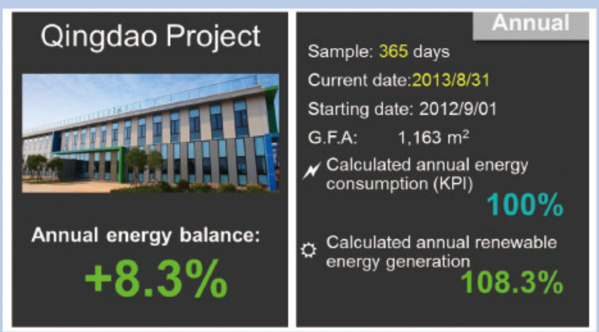

Figure 6 Consumption dashboard from September 1, 2012 to August 31, 2013, with surplus energy expressed as a percentage

Continuous Improvement

An annual review process is carried out to analyse the results compared with the target for further operational improvements.

Key Zero Energy Techniques

This section presents four key zero energy techniques in the Qingdao project. Some of the technologies are already known and applied in the China market for some time. The project management team placed a great deal of effort, to integrate both new and existing technologies into the Qingdao project, to fulfil the building owner's needs and requirements for this climate zone.

Heating Ventilation and Air Conditioning (HVAC)

Ground Source Heat Pump System

An electronically driven ground geothermal heat pump was selected as a preferable energy generator for this project. The scale of the geothermal heat pump was determined based on the building's simulated heating demand. In the summer, an additional cooling device is required to meet the cooling needs. However, given the geological conditions at the building site as reported in a Geotechnical Investigation Report dated October 25 2010, common heat exchangers with earth probes cannot be applied. To solve this problem, Bayer Technology Services Germany specially engineered a heat exchanger that can be used in the project. This heat exchanger was built on site. The ground source heat pump system includes 12 holes with depth >=100m and φ=150mm and two sets of water cooled heat pump units with total cooling capacity of 110kW for heating 50kW.

According to a Thermal Simulation Report conducted by Shanghai Jian Ke Building Energy Saving Evaluation Office, the inlet/outlet mass flow circulation temperature was designed at 18/21°C in the cooling season and 28/25°C in the heating season. Table 1 shows the zones in which the different systems are applied and how much of the total ceiling area is occupied by the heating and cooling system (Ding, 2011).

Zone Name	Zone Total Area (m^2)	% of Total Area
1st floor open office	19.635	23.38%
1st floor manager office	8.085	27.5%
1st floor meeting room	15.96	54.29%
2nd floor meeting room	14.85	68.75%
2nd floor manager office	24.255	27.5%
2nd floor open office	73.755	23.78%

Table 1 Zones with radiant heating and cooling ceiling - area and percentage of total construction area

Thermally Active Building System

A thermally active building system with prefabricated piping embedded in the centre of the concrete slabs reduces the energy consumed by air conditioning. As mentioned in the introduction, there are ten internal temperature zones in this project. Each required very different heat and cooling load considerations in the design phase. Two different types of radiant heating and cooling were adopted: the structural cooling panels for the office area; and the false ceiling panels designed for the reception area and meeting rooms.

Quick Element Ceiling

Quick metal elements enhance the cooling and heating capacity of an area (see Figure 8). Radiant cooling takes advantage of the fact that it is more efficient to remove heat from water than it is to remove it from air. To remove the same quantity of heat, more energy is needed to pump air than water. Since the floor slab does not retain heat, the heating loads are reduced. With radiant cooling, the sunlight hits the floor, and heat is taken away by water circulating in the embedded pipes. Because the slab never warms up, the solar energy never becomes a load in the space.

Figure 8 Radiant heating and cooling ceiling in the reception area

Heat Recovery System

For heat recovery for the air handling unit, a wheel type was chosen rather than a heat recovery panel due to its higher recovery efficiency.

The four main HVAC system elements—ground source heat pump, thermally active building system, quick element ceiling, and heat recovery wheel are shown in Figure 9.

Figure 9 Four main HVAC system elements

Highly Efficient Polyurethane Insulation Materials

One of the most important pre-requisites for achieving low heating and cooling loads is an efficient building envelope comprising walls and windows, roof and basement.

Polyurethane foam insulation contributes to high energy efficiency over the whole life cycle of the building. Huafeng Puren, a customer of Bayer Material Science, provided 3 insulation systems for the project. The project applied a Huafeng Puren 100mm rigid polyurethane insulation system for roof insulation, a 50mm rigid polyurethane insulation system on the floor slabs, and 100mm rigid polyurethane insulation underneath the ground slab. Polyurethane foam insulates so well because of its low thermal conductivity, moisture resistance, temperature resistance and chemical stability.

Furthermore, the reduced space required for the insulation resulted in a larger usable floor space and hence a considerably higher value for the building. Figure 10 shows how to achieve the same insulation effect with different insulation materials and varying thicknesses. This affects the area of usable floor space for users.

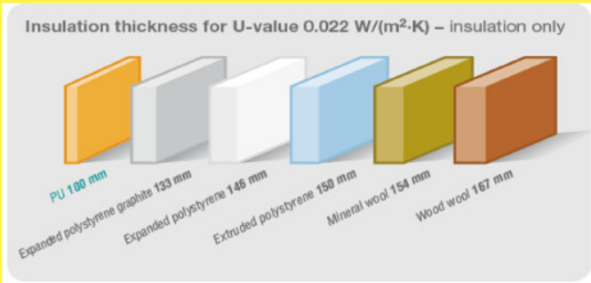

Figure 10 Comparison between 100mm Polyurethane @U-value 0.022W/(m^2.K) and other insulation materials to achieve the same level of energy efficiency

Polyurethane has an outstanding energy balance. When used to insulate a building (see Figure 11), polyurethane saves over 70 times more energy during its lifecycle than it is to manufacture it. In other words, polyurethane based insulation solutions offer great potential for attaining energy efficiency objectives, like the European Union Energy Efficiency Directive and Energy Performance of Buildings Directive, or the United States EPA National Action Plan for Energy Efficiency.

Figure 11 Roofing insulation application

Renewable Energy Solar Photovoltaic System

All available renewable energy options were considered in the initial design stage back in 2010. The owner finally chose a solar photovoltaic system from Kyocera (Figure 12). The surplus electricity is transferred to the service building and the production plant.

Figure 12 Roof top solar photovoltaic application

Light Emitting Diode (LED) Lighting

After considering all options for the passive use of daylight, LED lighting systems were selected (Figure 13). LED is energy efficient and offers a short payback period, longer durability, and is made with environmental friendly materials. LED lighting can save up to 50% electrical energy compared to fluorescent lighting. The technology allows for different colour renderings and provides pleasant lighting for the human eye. Another important advantage is the absence of mercury, used in the production of fluorescent lamps for example, which poses a major environmental threat if not properly disposed of at the end of its useful life. Especially in China, a proper disposal system of hazardous materials and products is not yet in place.

Figure 13 LED application in the reception and office area

Building Technologies - Real Time Energy Monitoring System

The project features a real time energy monitoring system to display the energy consumption and renewable energy generation of the building on a daily basis. The real time energy monitor is located in the reception area where it is easily accessed by staff working in the building. It has become a successful communication tool, available to visiting delegations, as well as internal employees. This tool has created an awareness of how individual behaviour can affect the Qingdao building energy performance.

By making real time energy monitoring data available (Figure 14), staff showed a thrifty attitude change in their own workplace energy consumption. After lunch, there is always a group of staff standing around the energy monitoring screen observing daily energy gains or losses: “Today is cloudy, we didn’t get enough sunlight”, “We have to switch off artificial lights so that we can generate more energy today!”. It also created some fun in the workplace.

By utilising a real time energy monitoring system, the energy management unit achieved three objectives:

- Increased transparency of the energy consumption of building operations: what, where and how much;

- Demonstrated the success of the zero energy concept and continued verification of the design; and

- Encouraged attitudinal change of individual users, increased awareness of their energy consumption, and educated them on how to be good Zero Energy Building users.

Figure 14 Real time energy monitoring system (dashboard)

Miscellaneous Building Solutions

Other building solutions include a polyurethane flooring system (provided by Nature) and a wall coating system (provided by Hempel) that ensured a low Volatile Organic Compound (VOC) interior environment. A key consideration was to use water based materials rather than solvent based materials, to reduce VOC coatings and create a joyful, healthy working environment as a shown in Figure 15.

Figure 15 Low VOC interior office environment

LEED Rating of the Qingdao Project

This building portfolio has been awarded the prize for 'Best Practice of Global Green Building', presented by the Global Forum on Human Settlements (GFHS) at the 'Conference on Sustainable Human Settlements', held during the Rio +20 climate conference in June 2012. It also achieved LEED GOLD rating in 2012, with 69 certified points.

Figure 16 LEED Certificate

Conclusions

Bayer Material Science opened the Qingdao Net Zero Energy Building in October 2012. After 365 days of energy monitoring, the building was found to generate more photovoltaic electricity than it consumed, which proved its original Net Zero Energy Building design concept. It also successfully created awareness on actively reducing building energy consumption in the industry, fulfilling Bayer Material Science's commitment to environmental protection through responsible management of its business activities.

Acknowledgements

The author would like to thank all network partners who worked together to realise the building. Efforts from Dr Michael Voigt, Varun Malpani, and Bayer technology services' hard work in project initiation and execution are also gratefully acknowledged.

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Opportunities and Challenges of Zero Carbon Buildings

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As worldwide carbon emissions set another record high, it is more urgent than ever to formulate and execute plans for carbon reduction. The building industry contributes around 40% of the carbon emissions worldwide and 67% in Hong Kong, with its high urban density. While existing technologies contribute to the realisation of many zero carbon buildings and developments around the world, there are opportunities for wider use, and further advancement of such technologies. Aside from the challenges of adopting technologies suited to local climate conditions, the energy needs of high-rises differ from that of low-rises, thus requiring different solutions. Apart from individual building performance, energy efficiency can be further increased through the development of district energy and micro grid systems. While the design of buildings and energy systems can help to reduce carbon emissions, the actual usage patterns stemming from occupant behaviour contribute significantly to the actual energy performance. There are also additional opportunities to adopt technologies at the broader city level. Together with all other available strategies for carbon reduction, the feasibility of attaining zero carbon building is demonstrated, and there is great opportunity for more wide spread application of technology at the city level.

Keywords: high-rise, building performance, district energy, micro grid, occupant behaviour, smart cities

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Introduction

In recent years, strategies have been adopted around the world to create energy-positive buildings, as well as to achieve zero-carbon performance through the whole lifecycle of buildings. Ever since the first energy-positive building was completed in Masdar, Abu Dhabi in 2010, several developments have taken place in Europe. However, the main focus has been on low-rise buildings. High-rise buildings that are being constructed around the world, particularly in major cities, have additional challenges to overcome in order to achieve zero-carbon performance. In recent high-rise projects, the application of strategies with an integrated optimisation approach, has made it possible to improve building energy performance. As a result, the energy use intensity (EUI) of most high-rise commercial buildings are being reduced from around 250-350kWh/m^2 to about 140kWh/m^2 in the latest designs, however these buildings are not yet approaching zero carbon (Cheng *et al*., 2014).

The objective of this paper is to present the zero carbon strategies implemented in existing projects as the current baseline and reveal the challenges still present in low-rise applications as well as adoption in high-rises. The paper also explores opportunities for using district energy and microgrid to attain zero carbon performance beyond the building level and at the city level. The scope of this paper not only covers application in highly dense cities like Hong Kong, but also in developing cities, particularly in China and Asia.

Beddington Zero Energy Development (BedZED), United Kingdom

Zero carbon/energy development can be traced back to around 2000. The Beddington Zero Energy Development (BedZED), shown in Figure 1, is a residential and workspace prototype constructed in 2002, to provide an attractive sustainable development with an affordable budget. It is situated in the London borough of Sutton—creating a carbon neutral community with 82 houses, 17 apartments, and a 1405m² workspace.

BedZED met very high environmental design standards and achieved zero net carbon dioxide emissions, through a combination of a substantial reduction in energy consumption using passive design strategies, together with the use of a centralised wood-fuelled combined heat and power plant to provide electricity and hot water. The BedZED community was designed as high-density housing with nearby workspaces with an aim of promoting green transportation. Walking, cycling, the use of public transport, and carpooling were integrated into the initial planning. Furthermore, BedZED used construction materials located within a 35-mile radius of the site when possible, to reduce the embodied energy and carbon footprint of the development. General Information Report 89 (2002) summarised the lessons learnt from the project and presented it as best practice. As for actual performance, Yudelson (2009) cited the carbon footprint of the BedZED resident as 3.5ton CO_2/year compared to 12ton CO_2/year for a typical UK resident.

Figure 1 Beddington Zero Energy Development (BedZED), UK (Courtesy of Raf Makda/VIEW)

Kingspan Lighthouse, United Kingdom

At the building level, the first net zero carbon house was built in 2007 in response to the UK government's commitment for all new homes to be zero carbon by 2016. In 2006, the UK government introduced the Code for Sustainable Homes. The Kingspan Lighthouse was the first house in the UK to achieve a design rating of Level 6 prescribed in the Code for Sustainable Homes.

Kingspan Lighthouse, depicted in Figure 2, is a two-and-a-half storey, two-bedroom detached house. It achieved net zero carbon by using a biomass boiler, building integrated photovoltaic (BIPV) on the roof, and a solar thermal system as renewable sources of energy. Other features include structural insulated panels, a wind catcher for passive cooling, mechanical ventilation with heat recovery (MVHR), and smart metering and monitoring. All are components of an integrated high-efficiency system for the building. A summary of the design is presented in an assessment report by Senel *et al*. (2010).

Figure 2 Kingspan Lighthouse, UK (Courtesy of Kingspan)

Samsung Green Tomorrow, Korea

In Asia, a zero energy house (ZEH) 'Green Tomorrow' was designed and built by Samsung in Yongin, Korea, in 2009, to serve as a design showroom and educational tool for the community (Schuetze and Hodgson, 2014). Green Tomorrow, shown in Figure 3, demonstrates zero energy, zero emissions, and green information technology.

The building adopted passive design features including natural ventilation and daylight utilisation. It also has active design features including a membrane bio-reactor that allows grey and black water to be reclaimed for irrigation, toilet flushing, and cleaning purposes. With these energy and water-saving fixtures, Green Tomorrow demonstrates how technology can be applied to achieve energy performance targets.

Figure 3 Samsung Green Tomorrow, Korea (Courtesy of Samoo Architects & Engineers/Samsung C&T)

Zero Carbon Building (ZCB), Hong Kong

The Construction Industry Council designed and built the first zero carbon building (ZCB) in Hong Kong. Completed and commissioned in July 2012. The project overcame challenges of the local climate and employed the latest advanced technologies for energy consumption reduction. The building feeds excess renewable energy to the local grid to offset the embodied carbon/energy. The picture of the building is shown in Figure 4 and further details of this project has been covered in other papers (Ng *et al*., 2013; Yau, 2014)

Figure 4 Zero Carbon Building, Hong Kong (Courtesy of Marcel Lam Photography)

Design Strategy - Passive, Active, Renewables and Low Carbon Technologies

As demonstrated by the aforementioned projects, recent zero carbon developments were created through using a sustainability framework applied to various stages: demolition, design, construction and operation. To achieve zero carbon building performance, various strategies are required, and their integration at the design stage is particularly important in affecting implementation in downstream processes.

At the design stage, typical design strategies include both passive and active systems for reducing energy usage in the building, and the use of renewable sources to supply energy without increasing the carbon footprint of the building.

Passive design focuses on building form and façade optimisation. Areas of concern include building massing, core location and layout, impact of neighbouring buildings and context on ventilation, solar shading, daylight, sunlight, glare and effectiveness of high performance glass and insulation. For active design, Mechanical, Electrical, Plumbing (MEP) energy optimisation is achieved through designing heat rejection systems on the water and air side, vertical transport, efficient lighting systems, controllability (such as daylight and noise control), and considerations of indoor air quality (IAQ). Active and passive design can substantially reduce energy consumption. However, energy is still required to attain human comfort in a building. On-site renewable generation plus waste-to-energy systems can help achieve this goal.

Several building integrated renewable energy solutions are available. Common sources of renewable energy include solar, wind, bio, geothermal, hydro and marine. These vary at different levels of technological maturity in terms of building application. Among these common energy sources, solar and biofuel are more suited for high-rise applications given their flexibility and scalability. Efficiencies of commercial solar cells are expected to increase by 67% in the next 5 to 20 years. Outputs of biofuel generators are expected to increase from about 100kW to 200kW, even as their footprints become smaller.

Challenges of Moving Toward Zero Carbon High-rises

Asia's urbanisation rate is expected to increase, with China being home to the highest proportion of the world's high-rise building developments. The Council on Tall Buildings and Urban Habitat (2011) states that "Asia now contains 56.8% of the world's 200m+ buildings and 57.5% of the global population. China, with 200 buildings at the 200m+ level, has nearly seven million citizens for every 200m+ building." Since high-rise buildings with large numbers of occupants will account for a large share of building energy use, achieving zero carbon in high-rises will be a great challenge for the future.

With most zero carbon buildings in the form of low-rises, moving towards zero carbon high-rises poses a great challenge. Even if known passive and active design strategies are used, energy usage is still required in order to provide indoor comfort for occupants. Since the energy generation from most types of renewable sources is directly proportional to the surface area, and extra surface areas from high-rise building are not enough to offset the required energy use for each additional floor, further improvements in power production efficiency and further reductions in energy use are needed for achieving a zero carbon high-rise.

Beyond the Built Environment

Furthermore, efforts to achieve zero carbon should go beyond buildings to improving the overall efficiency of a community. This can be achieved through integrating a district energy system. A micro energy grid enables systems to work together between buildings and district energy systems to create smart cities. These emerging smart cities are expected to develop in every part of the world.

Moreover, better building design alone will not make a long lasting impact. Energy management, energy audits, measurement and verification are required to ensure building operations are energy-efficient while delivering satisfactory human comfort. Incremental changes can also prompt occupant behavioural change to further reduce energy use. Changing the behaviour of the next generation, which appears to be more eco-conscious, could lead to design changes for even better building. This forms a complete loop for integration.

District Energy Systems

District energy systems contribute to the overall energy efficiency of a community by increasing economies of scale. By centralising energy conservation systems, higher systems efficiency can be achieved as better technologies can be employed at a larger scale. District energy systems can provide heating, cooling, or both. Aside from the benefit of higher efficiency, maintenance can also be managed more effectively through a single professional entity. As individual buildings do not have to accommodate the required equipment within their premises, prime space can be freed up for higher value usage. Further reasons for using the systems have been proposed by UNEP (2014).

In Hong Kong, two developments with district cooling systems (DCS) are underway; one is in the West Kowloon Cultural District Development; and the other is in Kai Tak (Figure 5). The Kai Tak DSC is planned to be completed in 2021. The maximum annual saving (final year) for electricity is expected to be about 85 million kWh, which is equivalent to HK$76.5 million on the electricity bill, and a reduction of 59,500 tonnes of carbon dioxide emissions.

Figure 5 Kai Tak District Cooling System (Courtesy of Arup)

Micro Energy Grids

With more and more on-site or distributed energy generation from individual buildings or communities and district energy systems in place, micro energy grids can meet urban energy demands with higher efficiency, reliability and security. A micro energy grid facilitates energy balancing between local supply and demand, as well as energy balancing between the loads from individual locations. A typical micro energy grid consists of renewable power generation systems, energy storage, energy demands from commercial, residential and industrial buildings, as well as monitoring and control systems, with possible connection to the main grid structure.

As a micro energy grid only focuses on a local community, higher security from cyber and physical attacks can be achieved through special measures incorporated into the local system. Balancing energy with a community of manageable size is easier than doing the same at the entire city level. Many micro energy grid examples are in operation, demonstrating the operational feasibility of this technology. Case studies have been documented by Quiggin *et al*. (2012). Beyond developing more robust systems through technological advances, policies and regulations are also needed to foster wider application of micro energy grids, in order to multiply their benefits.

Occupant Behaviour

Even with advances in building technologies, the building industry still faces challenges in continuing to reduce energy use while maintaining satisfactory services for occupants. One common observation from studies around the world of benchmark building energy use is the deviation between design values and actual operating measurements in existing buildings. Occupant behaviour in buildings is one of the major factors influencing operations and energy consumption. It has been treated as deterministic in design rather than stochastic in nature. In a conventional design process, the operation condition is often treated as deterministic, where the model is uniquely determined by parameters and the initial conditions. Therefore, the same parameters and initial conditions yield the same output from the model. On the other hand, occupant behaviour involves inherent randomness and is more appropriately described by stochastic models, which allow different outputs to be generated from the same parameters and initial conditions.

Not only is occupant behaviour important during building operation but the decisions and actions of all parties involved early in the design process will affect subsequent energy use in the building. For instance, the willingness to apply new technologies in the design, improving the commissioning protocol for design verification, and attitude change towards preventive maintenance all play a big role. Peschiera *et al*. (2010) for example, have reported significant energy reduction through addressing occupant behaviour.

The City as an Entity

Sustainability is more than green buildings—it also encompasses energy, transportation, safety and security, the natural environment, people and culture. Beyond growing our cities sustainably with eco-focused technologies, we also need to make our cities resilient to external risks and be responsive to people's needs.

First, being eco-focused means having technological solutions to harvest and use energy in a greener way, as well as manage our water and waste more sustainably. For example, we have numerous design best practices and industry guidelines to drive our buildings toward carbon neutral performance.

Second, with the pressures of climate change and urbanisation, cities will be required to be more resilient to unpredictable external events in the future, such as natural disasters. Big data allows us to monitor, correlate and predict trends that might interrupt the normal functioning of a city, specifically in the areas of transportation, safety and security, local economy, and housing.

Finally, urban residents are looking to city governments to better meet their needs. A city that is responsive to its citizens in the areas of health, social welfare, community service and education can attract more talent by creating better living standards for them.

In the area of energy and building, for instance, incorporating local consumption patterns and human behaviour into building design strategies will be necessary for energy reduction and low carbon living. This aligns with China's 'New Type of Urbanization,' launched March 2014, which proposed a 'Sustainable and People Oriented Approach' as a guiding principle. In many parts of the country, energy benchmarking has been established, and through increased regulation targeting energy use, data collection and reporting, individuals can monitor and adjust their energy use accordingly. This type of benchmarking will not only help to reduce individual usage, but also overall energy management on both supply and demand sides.

According to Bloomberg news (Roberts, 2014), a 42-trillion-yuan (RMB) price tag for China's 'New Type of Urbanization' is a large investment. This investment will be focused on clean technologies to support the scale of urbanisation in a sustainable manner. In addition, there needs to be a greater focus on improving the efficiency and effectiveness of current systems.

Discussion

In this paper, several pioneering zero carbon building projects were presented. Key lessons from these experiences include the need for: integrated multi-disciplinary city planning; expansion to higher density community and to different building types; adoption in different climate conditions; establishing key performance indicators for sustainability; and accounting for occupant behaviour into different design stages.

A number of opportunities exist for conceptualising zero carbon buildings in the city as a system through step changes. As a start, the city's master planning should integrate energy, water, waste, transportation, safety and security, local economy, and housing as one solution. Then building technologies (passive, active, renewable, and low carbon technologies) can be applied to more high-rises and mixed-use buildings. Most of these technologies can be further adopted and potentially adapted for application from one design climate condition to another local one.

A further opportunity is to bring the design to people through responsiveness to their daily living needs. A city and its buildings should be designed for residents to enjoy urban living, with key performance indicators for sustainability built into the system at an early stage. The feedback data collected can then form the basis for understanding and facilitating occupant behaviour for further carbon reduction.

Conclusions

The cases presented in this paper show various ways in which zero carbon can be achieved in individual buildings as well as at the community level. Challenges remain in terms of wider implementation at the city scale, as well as attaining zero carbon for high-rise buildings. There are future opportunities to further enhance existing technologies and strategies through greater investment in the area. Finally, working from the individual building level to the community and city scale to achieve higher levels of energy efficiency would lower carbon emissions on a larger scale.

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隨著世界各地經濟發展的同時，也破壞了週遭的環境。

溫室效應、空氣污染、冰川溶化等等，已經是現今社會最關注的問題之一。作為建築業一分子，我們應出一分力，發揮所長的同時，也可對地球作出貢獻。 這想法正正是**綠集團**及其關聯公司發展至今的初衷。

過去10年，經歷了300多個綠化項目，從不斷研發、嘗試、改良的過程中，正正反映了香港的**垂直綠化**、**屋頂綠化**及**綠化建築**帶來低碳生活的演進。

設計上不再局限於四四正正的一套綠化牆系統；到如今，我們已自家研發及從世界各地引進十多種種植系統，適合室外高空、室內大型商場、甚至於小康家居；設計由方正到曲線、弧度、圖案拼湊設計等等；更可配合鐵藝、燈光效果、石材、環保木以及流水效果。

我們確信，綠色建築這個產業，要用心去做，而且要不斷地去研發、實踐，從中學習和改良，循環求進。我們更深信這個產業可以有更大的發展空間，令"低碳生活"和"香港減一度"這個夢想得以進一步實踐。

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ISSN 2311740-0