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Towards zero carbon in a hot and humid subtropical climate

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Abstract

Hong Kong buildings account for 90% of total electricity consumption and over 60% of greenhouse gas emissions. Therefore buildings present both a challenge and an opportunity for reduction in energy use and greenhouse gas emissions. Net Zero Energy Building (NZEB) and Net Zero Carbon Building (NZCB) are recognised as feasible strategies to reduce energy use and carbon emissions leading to a more sustainable built environment. While there is a growing number of NZEBs and NZCBs in relatively cool or temperate climates, there are relatively few examples in the subtropical climate, and in a densely populated city such as Hong Kong.

This paper will examine the current progress towards a low carbon built environment in Hong Kong, zero energy/carbon design strategies and technologies applicable to building in a subtropical climate, and examines a case study of Hong Kong's first zero carbon building─ZCB. ZCB's energy and carbon performance, experiences and lessons learned, and future directions are discussed. The paper will conclude with the challenges and opportunities for wider adoption of NZEBs and NZCBs in the Hong Kong construction industry.

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Keywords: Net Zero Energy Building; Net Zero Carbon Building; Subtropical climate; ZCB; Building performance

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1. Introduction

The built environment has a key role in climate change mitigation. There is an urgent need to minimise the impacts of construction sector activity on the natural environment and to develop low carbon cities [1], [2]. Having reached an unprecedented first ever-binding agreement to combat climate change at the Paris climate conference (COP21) in December 2015, 195 participating nations are committed to actions and investments toward a low carbon and resilient future. The Paris Climate Agreement aims to limit global warming to well below 2°C with a long-term goal of net zero emissions for this century [3]. Net Zero Energy Building (NZEB) and Net Zero Carbon Building (NZCB) are recognised as feasible strategies to reduce energy use and carbon emissions [4], [5], [6], [7].

There are relatively few examples of NZEBs and NZCBs in a subtropical climate and in high density cities. As the first of its kind in Hong Kong, Zero Carbon Building (ZCB) aims to achieve zero carbon emissions through balancing the energy consumed with the energy generated from renewable energy sources on an annual basis. Surplus renewable energy generated is used to offset the embodied carbon of its construction process and major construction materials. The design, construction, and operation of ZCB is innovative in its application in the hot and humid subtropical high density Hong Kong environment. However, more widespread adoption of zero energy/carbon building principles and technologies in the Hong Kong construction industry would rely on demonstrable evidence of energy use reduction and carbon reduction potential, as well as their transferability from small scale use to highrise applications. The aim of this paper is to present a case study overview of ZCB's energy and carbon performance, experiences and lessons learned to date, with a view to examining strategies applicable to a subtropical climate and the feasibility of applying NZEB and NZCB approaches in a highrise urban environment.

2. Towards a Low Carbon Built Environment

In line with an urgent international agenda to reduce carbon emissions, Hong Kong has pledged to reduce its carbon intensity by 50%-60% by 2020 [8]. The Hong Kong SAR Government has also launched an "Energy Saving Plan for Hong Kong’s Built Environment (2015-2025)" [9], which outlines the Government's energy saving policy, strategy and targets. A target of this plan is to reduce Hong Kong's energy intensity by 40% by 2025 compared to the 2005 baseline. Policies and actions for carbon reduction are in place as part of Hong Kong's aim to become a low carbon liveable city.

The need to target climate change and abate greenhouse gas emissions has led to increasing awareness of the concepts of NZEB and NZCB among stakeholders in the Hong Kong construction industry as approaches to create a low carbon city. ZCB is an example of this shift in thinking. Recent times have also seen an increasing number of residential, commercial and institutional projects with BEAM and LEED Platinum ratings in Hong Kong. Examples include Welfare Road Residential Development, Hysan Place, Hang Sang Management College S H Ho Academic Building etc. [10]. More attention is also directed towards sustainable urban development in newly developed and existing developed districts. One example of a newly developed area is the Energizing Kowloon East development comprising a mix of government buildings, commercial areas, residential buildings, community facilities and open spaces with the integration of a district cooling system [11]. This development aims to be a new economically, environmentally and socially sustainable Central Business District in Hong Kong. These examples demonstrate Hong Kong's efforts to transition to a low carbon built environment.

3. NZEB/NZCB Strategies and Technologies for a Hot Humid Subtropical Climate

An evaluation of existing NZEBs and NZCBs shows that there are several main strategies to achieve net zero: (1) reducing energy demand through the use of low energy passive design measures; (2) increasing efficiency through using energy efficient building systems and technologies; and (3) using renewable energy sources to supply the remaining energy demand [12]. Different building types, countries, and local climatic conditions would affect energy conservation, the standards or values used to evaluate indoor environment quality, the types of renewable energy sources that could be adopted, as well as whether renewable energy is supplied onsite or offsite [13].

Hong Kong is characterised by a subtropical climate—hot humid summers and mild to cool winters [14]. The typical cooling season in Hong Kong is estimated at 2000 degree-hours, which differs quite significantly to London's 200 degree-hours for example. Meeting the cooling demand for buildings is therefore a significant challenge in Hong Kong [15]. Integrating NZEB and NZCB design strategies and technologies that perform effectively in a hot humid subtropical climate is therefore critical.

Passive cooling or using natural ventilation through optimal orientation can be the most effective design strategy in a hot and humid climate [16]. Air movement can enhance human thermal comfort through increased skin evaporation. Furthermore, 50% of the energy used for mechanical ventilation in buildings in a tropical and subtropical climate can be conserved. Building envelope design influences 55% of peak cooling loads for office buildings in Hong Kong. Building envelope design can reduce the amount of solar heat gain and also potentially integrate renewable energy technologies. The use of energy efficient technologies can further reduce the internal cooling load [17]. For renewable energy sources, studies have found that photovoltaics (PV) and wind power have potential applications in Hong Kong [18], [19]. These NZEB/NZCB strategies set the context for the following discussion on the strategies and technologies adopted at ZCB.

4. ZCB—First Zero Carbon Building in Hong Kong

Completed in June 2012, ZCB is a 1400m² building situated on a 14700m² site in the industrial and commercial district of Kowloon Bay. Developed by the Construction Industry Council (CIC), ZCB is an exhibition, education and information centre. The vision for ZCB is to showcase and disseminate information on sustainable site planning and low/zero carbon building design and technologies to construction industry stakeholders, both locally and internationally, with a view to promote more widespread application in Hong Kong. Four main principles underlie the development and operation of ZCB. ZCB aims to be: (1) experimental; (2) evolving; (3) educating; and (4) evaluating.

Fig. 1. An aerial view of ZCB

ZCB is a three-storey building with indoor and outdoor exhibition facilities, an eco-office, meeting rooms, an eco-home, a multipurpose hall, an eco-cafe and shop. The building is surrounded by a landscape area with an urban native woodland to promote biodiversity.

Over 2800 sensors installed throughout the building monitor and record key environmental performance parameters. This information, including carbon dioxide (CO_2) levels, temperature, humidity, renewable energy generation, energy consumption, energy import and surplus energy export to the electricity grid, is continually collected by the Building Management System (BMS). This data is extracted for evaluation, to identify areas for energy performance improvements, and to optimise building operational performance on an ongoing basis.

4.1. Energy strategy

ZCB's energy strategy comprises a combination of passive solar design, active systems and onsite renewable energy generation (Figure 2). ZCB aims to be carbon neutral and energy positive with feed-in to the electricity grid. Over eighty technologies based on principles of sustainable site planning and landscape, energy use reduction, low carbon construction and material selection, water use minimisation, building flexibility and adaptability have been integrated into ZCB. A vast open landscape area—Hong Kong’s first urban native woodland, contributes to improving the microclimate of a dense urban area by cooling the local environment and mitigating the urban heat island effect (lowering temperature by up to 1°C) whilst improving local air quality and comfort levels, enhancing biodiversity and providing a leisure place for the local community. Through passive design measures and active systems, ZCB aims to achieve a 45% energy saving over the Building Energy Code [20].

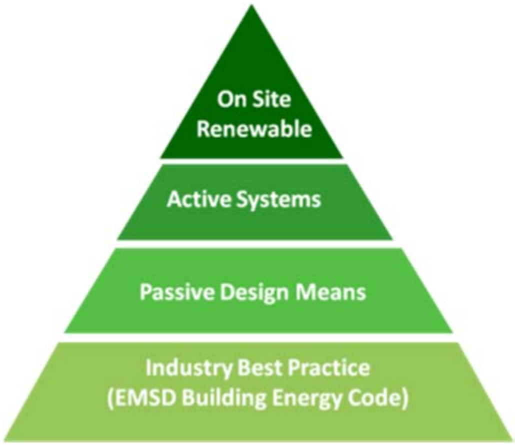

Fig. 2. ZCB's Energy Strategy

4.2. Designed performance

As shown in Figure 3 below, the energy demand for ZCB and its surrounding landscape area was expected to be 116MWh/year and 15MWh/year.

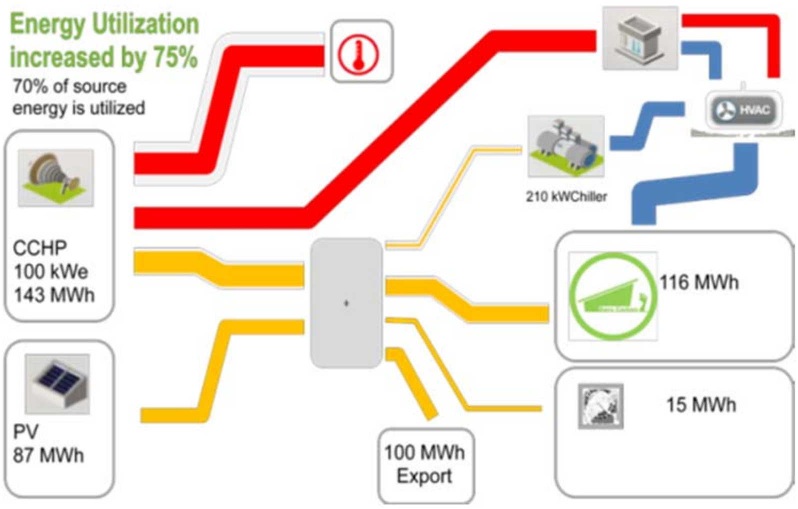

Fig. 3. Designed energy performance

The PV systems and the Combined Cooling Heating and Power (CCHP) system or tri-generation using biodiesel (B100 waste cooking oil) were estimated to produce 87MWh/year and 143MWh/year respectively. Approximately 100MWh/year surplus electricity would be exported to the city grid to offset the embodied carbon accrued during the construction process and for major construction materials. This equates to a carbon reduction of about 45-50 tonnes/year over an assumed 50 year building lifespan as shown in Figure 4.

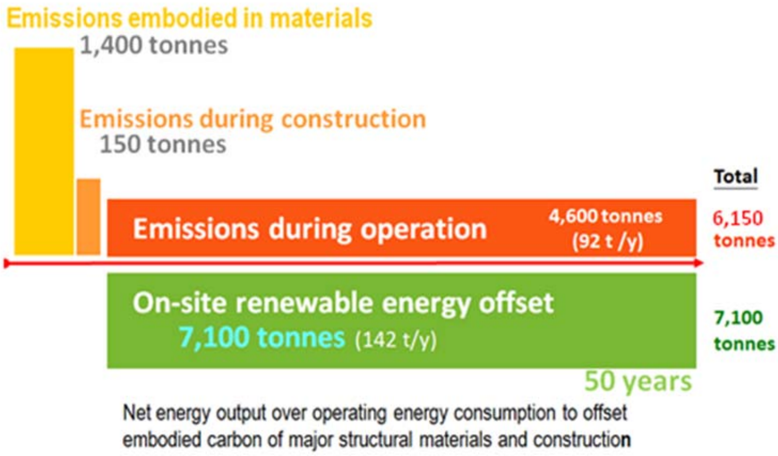

Fig. 4. ZCB's carbon strategy

4.3. Operational Performance

Three energy audits were conducted for ZCB over 2013-2014. These together with daily monitoring prompted continuous testing and commissioning to finetune the operation of different building services systems. In 2015, ZCB's total renewable energy generation (377MWh) exceeded total energy consumption (355MWh). This resulted in a carbon footprint of -16 tonnes for 2015. The carbon footprint display in Figure 5 below shows that as at 29 July 2016, cumulative energy generation (599,204kWh) since January 2015 exceeds energy consumption (524,889kWh).

Fig. 5. Carbon footprint display as at November 2016

The average yearly energy consumption for 2013-2015 was 339MWh/year─160% over the design estimate of 131MWh/year. Figure 6 shows the designed and actual energy consumption for 2013, 2014 and 2015. The following factors can be seen to contribute to the performance gap:

- ZCB is currently operating 7 days a week resulting in an approximate 40% increase in energy consumption over the designed estimate for a 5 days operation week. It has been estimated that 90MWh/year of electricity is consumed for the 2 extra days per week;
- Minor energy consumption was assumed for non-operation hours (19:00 to 08:00) for lighting and power however actual energy consumption accounted for 22% of total daily energy consumption in summer and 30% in winter. A base load of 18-20kW was measured for a typical daily lighting and power load profile;
- Larger than expected energy consumption related to non-essential services such as landscape lighting, basement floor energy consumption, and plumbing and drainage.

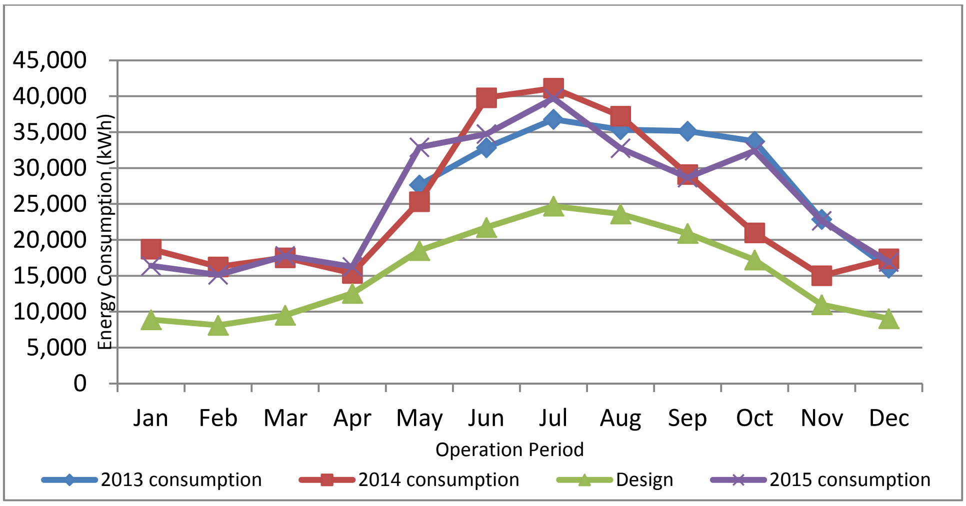

Fig. 6. Monthly energy consumption

Although renewable energy generation was 14% below the design target in 2013-2014, overall generation at the end of 2015 was 11.5% above the design target. This was primarily due to extension of operation of the CCHP system beyond summer months (May-September) to all year round and to smooth operation of the system. The CCHP system suffered a number of major breakdowns from May-June 2013 and from August-November 2014. As a result, energy generation by the system was short of the original design target (Figure 7).

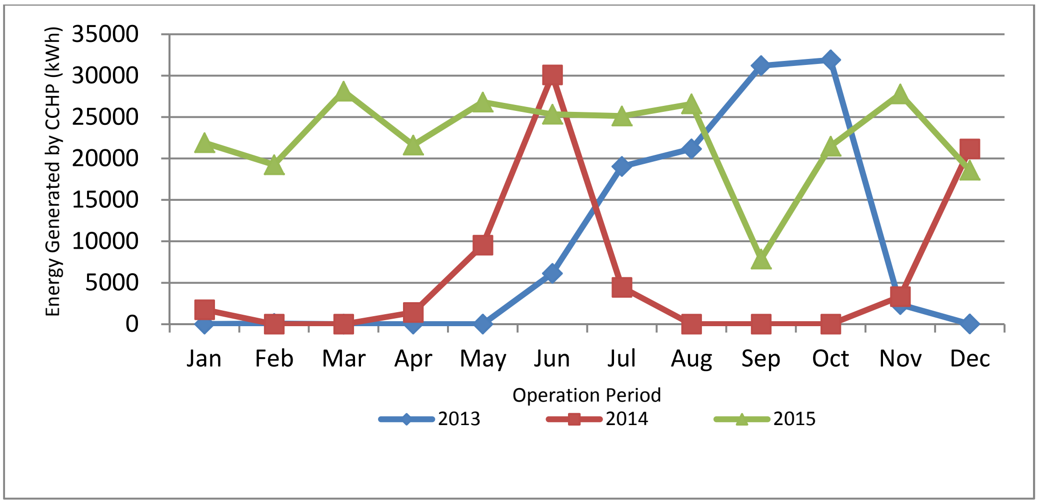

Fig. 7. Monthly energy generation by the CCHP system

Figure 8 depicts energy generation by the PV systems. The performance of the three PV systems (polycrystalline, BIPV and CIGS) was consistent and generated 106MWh of electricity in 2013, 107MWh in 2014 and 105MWh in 2015. This exceeded the designed annual output of 87MWh by 22%, 24% and 21% respectively.

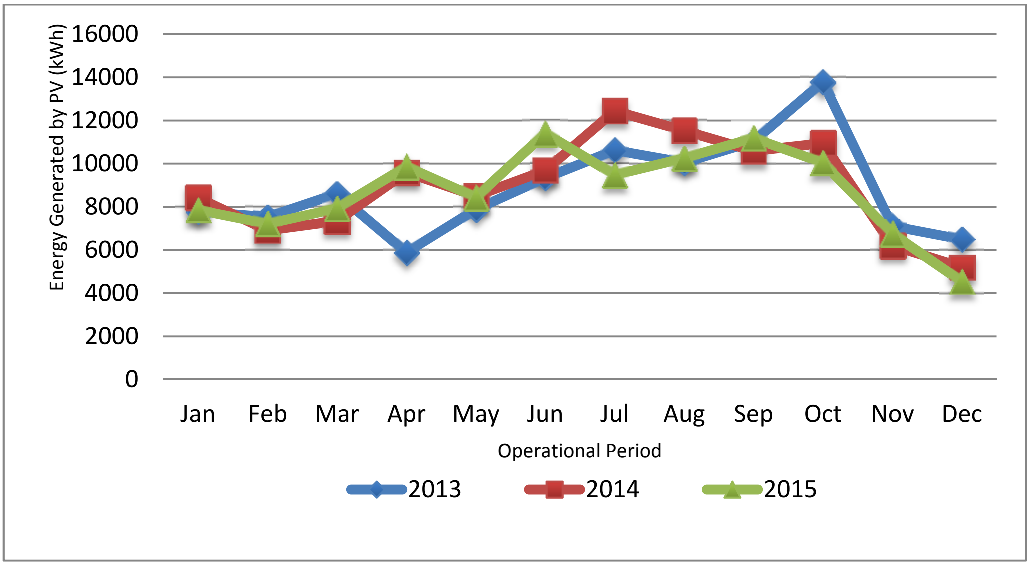

Fig. 8. Monthly energy generation by the PV systems

5. The Challenges to Achieving Zero Carbon and Lessons Learnt from ZCB

5.1. Designed target vs. operating target

A major factor that contributed to the current energy performance gap is the disparity between the intended and actual use of the facilities at ZCB. A 5 day operation schedule was assumed in the design of ZCB. The demand for services offered by ZCB as an information, education and exhibition centre led to an underestimation of the days, operation hours and the resultant level of energy consumption required to meet operational requirements. A critical challenge arising from the evaluation of ZCB is how to accommodate increased activities and changes in operational needs over time while striving to achieve the objective of zero carbon.

Studies into the performance of NZEBs and NZCBs show that there is often a wide gap between design objectives (simulated building energy use) and actual measured performance (actual energy consumption). Measured energy consumption can be up to 3.5-5 times initial design estimates [21]. This is often attributed to buildings rarely having a realistic design stage energy use prediction against which operational energy use could be compared. A number of technical factors (e.g. operational efficiency, ease of use etc.) and non-technical factors (e.g. socio-economic context, attitudes etc.) that could influence adoption decisions and user behaviours for NZEBs and NZCBs have also been identified [22]. This points to a need to shift from the heavier focus on design intent to following through with systematic studies of the performance of NZEBs and NZCBs in-use. Post occupancy evaluation and feedback is critical to improve building performance and to the development of future energy use models. Corney et al. [23] advocate that net zero energy and carbon is 'more about designing a building to an operating energy target and then achieving that target'. Further analysis to examine the effects of different types of activities or uses on ZCB's energy and carbon performance will be carried out.

5.2. Ongoing testing and commissioning and re-commissioning

As a demonstration project, ZCB went through an extended testing and commissioning period since its official opening in January 2013. The testing and commissioning of various building services systems affected building energy performance. Most notable was the continued testing, finetuning and performance optimisation of the various components of the CCHP system (including the biodiesel generator, pumps, cooling towers and adsorption chiller). Delays in procurement of replacement parts and contractor inexperience in rectifying the problems contributed to lengthy gaps in operation resulting in a shortfall in renewable energy generation─36% for 2013-2014. Rectifications led to operation of the CCHP system for a period of only 7 months from July 2012 to December 2014.

Contingencies should be provided for building systems not operating as designed and re-commissioning is necessary to maintain and improve the performance of systems over time. Facility management staff has an important role in understanding how to operate, periodically review, and maintain the building fabric, structure and building services systems to ensure optimal performance and reliability of systems and technologies. A strategic maintenance strategy should be established at the outset with preventive measures, ongoing commissioning to align with changes in the operating environment, and improvement measures for smooth and effective operation of building systems to reduce energy use and carbon emissions.

A number of hurdles to the collection of quality BMS data for the performance evaluation of ZCB also had to be overcome. These included issues of data discontinuity, data inconsistency, faulty data and errors in data display. This issue of BMS data quality has been found to be a problem in the evaluation of low/zero carbon buildings and in the post occupancy evaluation of buildings generally [24]. ZCB is working with the BMS contractor to improve the quality of data collected on an ongoing basis.

5.3. Occupant behaviour, comfort and satisfaction

Balancing the goal of zero carbon with the provision of a comfortable indoor environment is a significant challenge. ZCB relies on natural ventilation during the cooler spring, autumn and winter months. Natural ventilation accounted for 40% of the year in 2013, 50% in 2014 and 40% in 2015. However, staff showed dissatisfaction with the level of thermal comfort in the building when indoor temperatures on occasion reached a low 9-10°C in winter and a high of 28-29°C in summer while the postulated internal comfort range is 18-25°C. Windows opened for natural ventilation in winter occasionally created uncomfortable workspaces. Even with windows closed, air leakage via openings and the raised floor plenums contributed to low temperatures. The addition of unanticipated plug loads, including portable heaters in winter and portable fans in summer to attain the desired level of thermal comfort, alludes to discrepancies between individual preferences and the building's automated controls and temperature set points.

As user behaviour (for example, occupants opening windows even when the air conditioning system is operating in the summer time), or individual control of systems (for example, task lighting, ventilation fans, operable windows etc.) affect energy performance, more effort is needed to align user expectations with the zero carbon objective. Periodic user feedback, further education, and behavioural changes are critical to achieve a more optimal balance between the zero carbon objective, a more comfortable indoor environment, and sustainable building operations.

5.4. Reliable renewable energy generation

For ZCB to meet its zero carbon objective, reliable renewable energy generation is critical. As discussed in section 4.3, the CCHP system underwent trouble shooting and rectifications thus energy generation by the biodiesel generator was short of the original design target for 2013-2014. With smooth operation of the system in 2015, the system generated 272MWh of energy, which almost doubled the designed figure of 143MWh. A great deal was learnt about the maintenance procedures for the biodiesel generator, such as the frequency for refueling, optimal water temperatures etc. The performance of the three PV systems exceeded the designed annual output of 87MWh by 22%, 24% and 21% for 2013, 2014 and 2015 respectively with minimal maintenance. However, significant overshadowing from surrounding tall buildings limits energy generation by PV, particularly during the winter time.

A significant challenge for NZEBs/NZCBs is balancing the risk of applying innovative and experimental systems and technologies with more tried and tested methods to achieve zero carbon emissions. The suitability and effectiveness of renewable energy systems for a specific context is critical.

5.5. Ongoing monitoring, evaluation and performance improvements

An extensive monitoring and data collection system has led to complexity in data analysis and interpretation. Ease of BMS data extraction with frequent reporting and feedbacks for immediate actions are necessary for operational improvements for facility managers and building users. A new data extraction and analysis system is being installed at ZCB, to provide more detailed analysis of separate systems and technologies, to diagnose and improve the sensor and metering system, and to improve the quality of BMS data for ongoing performance evaluation. Careful consideration should be given to the scope and level of detail for performance evaluation at project outset such that the BMS framework and electrical systems are set up to align and facilitate this process.

6. Challenges and Opportunities for Wider Application of NZEB/NZCBs in Hong Kong

The insights and lessons learned at ZCB may not be unique but they can contribute to the development of strategies that could facilitate the effective delivery and operation of similar future projects. ZCB provides a platform for learning and knowledge transfer. As one of the first of its kind in Hong Kong, ZCB brings forth a number of issues that pose significant challenges for the wider application of NZEB/NZCB principles, systems and technologies. One issue is whether natural ventilation is a widely applicable strategy in Hong Kong's subtropical high density environment given the potentially high levels of humidity, air and noise pollution in Hong Kong. Another is the feasibility of large scale application of PV systems when overshadowing is prevalent in a highrise environment.

The legislative and policy framework, and energy infrastructure, presently limit the wider application of NZEBs and NZCBs in Hong Kong. In Europe and North America, two-way grids with tariffs are available. The lack of ready infrastructure and incentives for grid feed-in of electricity generated by renewable sources pose a challenge for wider adoption. Another significant challenge is how the principles, systems, technologies and lessons learned could be transferred to highrises. More exemplar zero energy/carbon building projects for different building types are needed. The ZCB experience has also identified the need to upgrade contractor skills, facility management knowledge, and user understanding for effective building delivery and operations.

The Hong Kong Construction industry remains skeptical of the NZEB and NZCB concepts without more operational and economic performance data for a solid business case. Explicit methodologies, data collection, quantification, development of appropriate metrics and benchmarking are needed. This needs to be coupled with rebates for NZEB and NZCB technologies and incentives for feed-in to the electricity grid. The Hong Kong SAR government plays a significant role in the development of the necessary regulations, infrastructures and incentives to create markets for NZEB/NZCB systems and technologies.

7. Conclusions

The performance evaluation of ZCB over its first 3 years of operation from January 2013 to December 2015 found that actual energy consumption was significantly higher than the design estimate. Major factors that contributed to this increased energy consumption included higher usage of ZCB facilities, higher than expected energy consumption during non-operation hours, and higher than expected energy consumption by non-essential services such as landscape lighting, basement floor plant rooms and plumbing and drainage for irrigation, grey water recycling and wastewater recycling. Renewable energy generation from the 3 types of PV systems exceeded design prediction. One the other hand, the CCHP system experienced periodic breakdowns resulting in below optimal energy generation. However, smooth system operation since 1 January 2015 indicates that the CCHP system is capable of generating the designed energy output. This led to renewable energy generation exceeding the designed target by 11.5%. With reliable renewable energy generation, ZCB achieved zero carbon emissions in 2015.

The insights and lessons learned from the performance evaluation of ZCB as a demonstration project, and attempts to identify design solutions and technologies applicable to the subtropical climate, constitute a noteworthy contribution to Hong Kong's efforts to transition to a low carbon built environment. While the implications of ZCB for highrise buildings remain to be seen, the issues raised and potentially applicable solutions, is a significant point of departure for further development of strategies for highrises. Further projects and research should investigate the concepts of NZEB and NZCB beyond the current narrow focus on carbon and energy parameters to include broader environmental, behavioural, social and cultural criteria, and to further investigate the applicability of more recent concepts of net positive energy buildings and regenerative design.

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