CONSTRUCTION
INDUSTRY COUNCIL
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FEASIBILITY OF DELIVERING HIGH-RISE LOW OR ZERO CARBON BUILDINGS IN HONG KONG

RESEARCH SUMMARY

Construction Industry Council
Feasibility of Delivering High-rise Low or Zero Carbon Buildings in Hong Kong
Research Summary

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FOREWORD

It is important to reduce environmental impact and incorporate the concept of sustainability into building design and management. With respect to construction industry, Low or Zero Carbon Building (L/ZCB) has been regarded as the most innovative and promising model of sustainable development in the built environment. It is a building with net zero energy consumption or net zero carbon emissions on an annual basis. In recent years, L/ZCB has attracted much attention in many countries because they are considered as an important strategy to achieve energy conservation and reduce greenhouse gases emissions. The Construction Industry Council (CIC) established the Zero Carbon Building (ZCB) in 2012 to serve as an exhibition centre, an education centre and an information centre for L/ZCB, and to promote low carbon living in Hong Kong. However, the feasibility of wide implementation of L/ZCB in Hong Kong is still to be thoroughly investigated. Therefore, the CIC initiated the research by engaging a research team from The University of Hong Kong to carry out a feasibility study, and to formulate the strategies for high-rise L/ZCBs in Hong Kong.

The research team led by Dr. Pan has done a remarkable work. The definition of L/ZCB for Hong Kong was first defined and then the feasibility of delivering high-ise public residential and private office L/ZCBs in Hong Kong was examined. Design strategies as well as scenario-based design solutions were proposed. The established Base Case is status quo green buildings, and the developed Quick-Win and Optimisation Scenarios have the potential of reducing energy use and carbon emissions by about 25% and 50%, respectively. Besides, non-technical feasibility aspects of high-rise L/ZCB were also explored in the report.

I would like to congratulate and thank the authors and all those who have contributed to the report, and look forward to the actions of the construction industry to move towards the L/ZCB.

Ir Albert CHENG
Executive Director
Construction Industry Council

PREFACE

Buildings worldwide account for over one third of energy consumption and carbon emissions and therefore stand out as the biggest contributor to anthropogenic climate change. In Hong Kong, buildings consume 92% of electricity and contribute 60% of carbon emissions in the city. Low or Zero Carbon Building (L/ZCB) has been regarded as a most innovative model of sustainable development in the built environment. Many countries and regions have seen policies and/or initiatives on L/ZCB, which, albeit varied in their contexts, present unprecedented challenges to both research and practice in identifying and implementing feasibility decisions on delivering L/ZCBs. First, there is a lack of consistent L/ZCB definition and methodology. Second, the vast majority of L/ZCBs to date are located in cold and temperate climates. Third, few high-rise L/ZCBs have been reported worldwide. This research project is therefore timely and significant as it fills the knowledge gaps.

This project has taken up the great challenge by examining the feasibility of delivering high-rise L/ZCBs in Hong Kong and developing scenario-based design solutions to delivering very low carbon and energy high-rise buildings. The research objectives are ambitious but well achieved. A Hong Kong definition of L/ZCB is established, with relevant design strategies. Scenario-based design solutions are developed to achieve quick-win and optimised energy use, and carbon emission reductions for two types of high-rise developments: public residential and private office buildings. The study focuses on the technical feasibility, while the socio-cultural preference, commercial viability, supply chain competency, statutory and regulatory acceptance of the strategies and solutions are also addressed to facilitate systems thinking. The methodology adopted is comprehensive, and the use of real-life cases for verification and sensitivity analysis is effective. It is an exciting exercise to deliver the project with the challenging time and resources constraints. This project is significant, the findings provide a useful definition of L/ZCB for Hong Kong, and meaningful strategies and roadmap for achieving very low carbon and energy high-rise buildings in Hong Kong. The findings will encourage the take-up of innovative low energy and low carbon technologies in the building sector. The findings also contribute to a better understanding of high-rise L/ZCBs in a systems approach. This contribution will have profound implications for the future design and delivery of low carbon and low energy buildings in Hong Kong.

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RESEARCH HIGHLIGHTS

This study has established a L/ZCB definition for Hong Kong, examined the feasibility of delivering high-rise public residential and private office L/ZCBs in Hong Kong, and developed design strategies as well as scenario-based design solutions. The established Base Cases are status quo green buildings, and the developed Quick-Win and Optimisation Scenarios have the maximum potential of reducing energy use and carbon emissions by over a quarter and around half, respectively. The explored strategic Decarbonisation and Emerging Renewable Scenarios suggest the potential of achieving nearly net zero in the long term.

A L/ZCB definition for Hong Kong

To address the high-density, high-rise and hot-and-humid features of buildings in Hong Kong, the definition needs to regard L/ZCBs as complex socio-technical systems (Pan and Ning, 2015), and to recognise their multidimensional system boundaries and wide-ranging stakeholder engagement (Pan, 2014). A ZCB (or a LCB) is defined as a building within its defined system boundaries with net-zero (or very low) carbon emissions on an annual basis during its operational stage. The technical components of the definition, which should be interpreted within the relevant regulatory, geographic and social contexts, are energy scope, carbon scope, energy use estimation and/or measurement methods, carbon estimation methods, unit of balance, period of balance, measures and indicators, use of renewable energy, and grid connection.

High-rise L/ZCB feasibility and scenario-based solutions

The high-rise L/ZCB feasibility of two types of building was examined: public residential and private office building. Using two sampled typical real-life building projects, the Base Cases, Quick-Win and Optimisation Scenarios were developed.

The residential building used for study is a typical 40-storey public housing block adopting a modular flat design, completed in and occupied since 2013. The Base Case was established through an iterative process of energy simulation and verification, drawing from the Electrical and Mechanical Services Department (EMSD) released end-use energy data, metered energy use and engagement with professionals. The energy use intensity (EUI) is 106.6 kWh/(m^2-yr), and in order of significance covers cooling electricity (23.5%), cooking gas (22.41%), appliances (20.84%), domestic water heating (DWH) gas (16.22%), lighting for communal areas (4.71%), lighting for residential units (4.55%), lifts (3.24%), water pumps (2.59%), and other communal area usage (1.94%). The carbon emissions intensity (CEI) is calculated as 55.51kg/(m^2-yr).

The Quick-Win Scenario was developed through energy simulation using DesignBuilder software, and sensitivity analyses using jEPlus software of wide-ranging passive design features, energy efficiency measures and established renewable energy technologies, as well as verification by engaging professionals. This scenario reduces the Base Case EUI by 25% to 79.8 kWh/(m²-yr) (14% and 11% through efficiency and renewable, respectively), and in order of significance covers cooking gas (26.09%), appliances (24.26%), DWH gas (18.88%), cooling electricity (14.82%), lifts (3.77%), lighting for residential units (3.49%), lighting for communal areas (3.43%), water pumps (3.01%), and other communal area use (2.26%). The CEI is reduced by 28.5% to 39.71kg/(m²-yr). In the Quick-Win Scenario, the most energy-sensitive saving measures were found to be, in order of significance, cooling set point, gross rated co-efficiency of performance (COP) of air-conditioner, airtightness, window to wall ratio, window glazing properties, and solar absorptance of walls. Renewable energy technologies (PV and wind turbine) with standard efficiency are included, which together can provide electricity that may offset nearly 13% of the building's total energy consumption.

The Optimisation Scenario was developed through estimation on desk analyses and literature review. This scenario reduces the Base Case EUI by 49% to 53.88kWh/(m²-yr) (28% and 21% through efficiency and renewable, respectively), and in order of significance covers cooking gas (29.36%), appliances (23.23%), cooling electricity (17.73%), DWH gas (11.69%), lighting for residential units (4.17%), lighting for communal areas (4.11%), water pumps (3.61%), lifts (3.39%), and other communal area usage (2.71%). The CEI is further reduced by 58.3% to 23.12kg/(m²-yr). In this Optimisation Scenario, the most important energy saving measures adopted include the change in shower time along with improving the efficiency of the hot water boiler, the improvement in domestic appliance efficiency, cooking stove efficiency, lifts using regenerative power, and a more efficient water pump system. Renewable energy technologies (PV and wind turbine) with advanced efficiency are included, which generate electricity that may offset nearly 30% of the building's total energy consumption.

The office building used for study is a 26-storey typical new private office block built using an in situ concrete method. The Base Case was established through an iterative process and energy simulation and verification, drawing from the EMSD released end-use energy data and engagement with professionals. The EUI is 282.4 kWh/(m²-yr), and in order of significance covers cooling electricity (41.9%), fans (23.6%), appliances (17.5%), interior lighting (16.5%), and pumps (0.4%). The CEI is calculated as 197.7kg/(m²-yr).

The Quick-Win Scenario was developed through energy simulation using DesignBuilder and TRNSYS software, and sensitivity analyses using jEPlus software, of wide-ranging passive design features, energy efficiency measures and established renewable energy technologies, as well as verification by engaging professionals. This scenario reduces the Base Case EUI by 38% to 175.5 kWh/(m^2-yr) (33% and 7.1% reductions through efficiency and renewable, respectively), and in order of significance covers cooling electricity (30.51%), appliances (25.15%), fans (23.39%), interior lighting (12.61%), pumps (4.58%), and heat rejection (3.76%). The CEI is reduced by 38% to 122.85 kg/(m^2-yr). In the Quick-Win Scenario, the most energy-sensitive saving measures were found to be the water-cooled chiller system, daylighting control and underfloor air supply, each of which can reduce the building's total energy use by around 10%. The most energy-sensitive design feature was found to be fan efficiency, a 0.9 value of which can reduce the fan related energy use by nearly 30% from that of a 0.3 efficiency. Renewable energy technologies (PV and wind turbine) with standard efficiency are included, which can however only offset around 7.1% of the building's total energy use.

The Optimisation Scenario was developed in the same way as the Quick-Win Scenario, along with desk analyses and literature reviews. This scenario reduces the EUI by 57% to 120.2 kWh/(m^2-yr) (47% and 19.65% reductions through efficiency and renewable, respectively), and in order of significance covers cooling electricity (28.28%), fans (24.92%), appliances (21.17%), interior lighting (16.58%), pumps (5.04%), and heat rejection (4%). The CEI is further reduced by 57% to 84.14 kg/(m^2-yr). In this Optimisation Scenario, the most important energy saving measures adopted include the District Cooling System (DCS), shortening the heating ventilation air-conditioning (HVAC) operation time, switching off unoccupied equipment, and other social aspects. The most important design features or parameters used include raising the equipment efficiency, and reducing heat gain by better building orientation. The impact of the energy saving measures on energy savings was found to be far greater than that of the building design features or parameters.

To sum up, the developed Quick-Win and Optimisation Scenarios have the maximum potential of achieving 49% EUI (52.72 kWh/(m^2-yr)) and 58.3% CEI (32.39 kg/(m^2-yr)) reductions, and 57% EUI (162.2 kWh/(m^2-yr)) and 57% CEI (113.56 kg/(m^2-yr)) reductions from the Base Case, for public residential and private office building, respectively, which represents very low energy and low carbon emission high-rise buildings, particularly in a hot-and-humid climate. The solutions require the systems integration of passive design, efficiency, behavioural changes and renewable energy use, thus facilitate systems thinking addressing political, economic, social and technological perspectives.

High-rise L/ZCB design strategies

A wide range of design strategies have been developed, and these are grouped under ten elements of building energy use and carbon emissions. Underlying all the strategies is dynamic systems integration, which is required for the possible achievement of net zero carbon in the long term. Systems optimisation is required for achieving different levels of low carbon while addressing socio-technical trade-offs.

Strategic scenarios and way forward

To achieve high-rise net zero carbon in the long term, more efficient or emerging renewable energy technologies and/or decarbonisation technologies must be explored and adopted, of which two strategic scenarios are developed:

Emerging Renewable Scenario which is based on the Optimisation Scenario and takes into account emerging renewable energy technologies such as combined cooling heating and power (CCHP), DCS and Fuel Cells (FC) that together further reduce the net energy use (hence net carbon emissions) of the building towards zero or negative;

Decarbonisation Scenario which is also based on the Optimisation Scenario but takes into account solutions such as decarbonised electricity generation, changing fuel mix, carbon capture & storage (CCS) and tree planting that together further reduce the net carbon emissions of the building towards zero or negative.

More realistic should be the integration of some solutions proposed for the two strategic scenarios in order to more effectively achieve energy use and carbon emissions reductions, while addressing the non-technical feasibility aspects. Government, industry and university should work together to further explore these two strategic scenarios, as well as their underlying technologies and solutions for addressing the socio-technical aspects of their feasibility.

CONTENTS

1 INTRODUCTION

1.1 Background

Buildings worldwide account for as much as 45% of energy consumption and carbon emissions (Butler, 2008), and therefore stand out as the biggest contributor to anthropogenic climate change. L/ZCB is regarded as the most innovative model of sustainable development in the built environment. Many governments have adopted the L/ZCB model as an important strategy for addressing climate change, achieving a low carbon economy and improving the quality of people's life (Wilford and Ramos, 2009, Pan and Garmston, 2012). For example, in Europe, there are legal requirements set by the Energy Performance in Buildings Directive (EPBD) for all new buildings to be 'nearly zero-energy' by 2020 (EU, 2010). In the US, the Energy Independence and Security Act of 2007 authorizes the Net-Zero Energy Commercial Building Initiative to support the goal of net zero energy for all new commercial buildings by 2030, and further specifies a zero-energy target for 50% of US commercial buildings by 2040 and net zero for all US commercial buildings by 2050 (Crawley *et al.*, 2009). In the recent Paris Agreement, low greenhouse gas emissions development has been set as a fundamental climate change strategy (UN, 2015). These goals, although varied in the context of their policy and implementation, are creating unprecedented challenges in both research and practice to identify and implement feasibility decisions on delivering L/ZCBs.

Alongside government policy promotion, L/ZCB has also attracted much attention in both research and practice within the areas of building energy and carbon. Several observations have been made. First, there exists a diversity of L/ZCB-related concepts worldwide (Pan and Ning, 2015), e.g. zero carbon homes (UK), net zero energy building (US), nearly zero energy building (EU) and zero emission building (Australia). Secondly, the vast majority of L/ZCBs (or initiatives with similar names) to date are located in western countries or regions and in cold or temperate climatic zones, with far less being located in the other regions and in subtropical climatic zones (Pan and Li, 2016). Thirdly, most of such L/ZCBs are of special typology (e.g. hotel, hospital and sports hall), educational buildings, office buildings, and small residential buildings, but with very few apartment building blocks. Few high-rise L/ZCBs have been reported in the world to date. Fourthly, despite the promotion of L/ZCB by many governments, there exist perceptions among developers, builders and customers that a L/ZCB may not be achievable, or may prove to be economically or socially unsustainable (Davis and Harvey, 2008; Pan *et al.,* 2017; ZCH, 2011). All these reflections, taken together, suggest an urgent need for research into high-rise L/ZCBs in subtropical climatic zones, in not only concept but feasibility of delivery.

In Hong Kong, buildings consume 92% of its electricity and contribute 60% of the city's carbon emissions (EMSD, 2015a), which are much higher than the worldwide averages (Pan and Garmston, 2012). The HKSAR government has pledged to achieve a reduction in carbon intensity of at least 50% to 60% on the 2005 baseline by 2020 (ENVB, 2010). At the end of October 2014, there were roughly 2,671,900 stocks of living quarters in Hong Kong (HKCSD, 2014), with a substantial increase annually. Tackling carbon emissions from buildings is therefore a critical component in the government's achieving its goals for substantial carbon reduction and long-term sustainability in Hong Kong. The Hong Kong Green Building Council (HKGBC, 2012) proposed the 'HK3030' vision, based on demand side management, to reduce the absolute electricity consumption in buildings by 30% by 2030 as compared to 2005 levels. The Chief Executive (2013) of the HKSAR Government has committed in its 2013 Policy Address to promoting green building. The Construction Industry Council (CIC, 2012) constructed the first 'ZCB' in Hong Kong in 2012, as a signature project to showcase state-of-the-art green design and technologies to the construction industry, and to raise community awareness of sustainable living. These contextual factors together suggest an unprecedented opportunity for L/ZCB, as a cutting-edge model of green building, to help drive the transition of the Hong Kong built environment towards low carbon and sustainable development.

1.2 Aim and Objectives

This project aims to examine the feasibility of delivering high-rise L/ZCBs in Hong Kong, and to develop scenario-based design solutions to enable the delivery of high-rise buildings towards zero carbon in the long term. The research objectives are:

1) To establish a Hong Kong definition of, and design strategies for achieving, L/ZCBs in dense high-rise developments in Hong Kong;

2) To develop scenario-based design solutions to achieving low or zero carbon for normative high-rise buildings in Hong Kong;

3) To systematically examine the feasibility of such solutions, considering not only the technical feasibility, but also socio-cultural preferences, commercial viability, supply chain competency, and statutory and regulatory acceptance;

4) To verify such solutions by examining the sensitivity and dynamics of actual, real buildings in relation to uncertainties and missing or unknown information.

1.3 Scope and Limitations

This project was kept within the following scope:

- The L/ZCB definition is established, with explicit system boundaries;
- The L/ZCB scenarios and design solutions are developed for two building types, namely, public residential and private office building (care should therefore be taken in interpreting the results within the context of other types of buildings);
- For these two building types, only new-build is considered, the retrofitting of existing buildings not being included in this study;
- Also for these two building types, the research is based on case studies of carefully sampled typical building projects in Hong Kong (care should therefore be taken in interpreting the results within the context of other buildings);
- The scenarios and solutions developed are at the building level, i.e. without considering their interaction with any surrounding buildings or facilities, which is considered to be a necessary boundary for facilitating the development of generalisable strategies and solutions for the benefit of the industry;
- The technical feasibility is the primary focus of this study, and is investigated in detail with both simulated and empirical results, while the non-technical feasibility aspects are of a secondary nature, due to the project's time and resource constraints.

2 RESEARCH METHODOLOGY

2.1 Overall Research Design

The study adopted a multiple-method research design to examine the feasibility of high-rise L/ZCBs that have been regarded as complex socio-technical systems (Pan, 2014). The research design was shaped to allow the five-fold feasibility examination in an analytical and integrated manner.

The recommendation of the L/ZCB definition and design strategies was initially based on a comprehensive and critical literature review, and theoretical analysis within the international context, and then verified through focus groups with case project teams, and interviews with relevant professionals. The recommended definition and strategies embrace systems theory and promote an integrated approach to achieve L/ZCB.

The L/ZCB scenarios cover two types of high-rise buildings in Hong Kong, public residential and private office. The design solutions draw on representative building shape, orientation, number of storeys, design specifications, construction methods, energy fuel mix and solutions in order to maximise the potential take-up of L/ZCB practice in the Hong Kong building industry. The development and verification of scenario-based design solutions and feasibility examination were conducted using two real-life cases of building projects. Parametric simulation and sensitivity analyses coupled with engagement of professionals substantiated the quantification of the impact of wide-ranging design measures on the buildings' energy consumption.

2.2 Methods for Studying Public Residential Building

A 40-storey public housing block located in Kai Tak area was selected as the reference building for the examination of delivering high-rise public residential L/ZCBs. This building adopts the HK Housing Authority (HKHA) Modular Flat Design with the gross floor area (GFA) of 36,286 m², and represents the status quo of typical public residential building designs in Hong Kong. The building was completed in and has been occupied since late 2013.

A detailed energy model with precise building configuration was developed using energy simulation software DesignBuilder. As there was a lack of standard energy modelling input for residential buildings in Hong Kong, focus groups were held with the project teams and interviews with relevant professionals were carried out to identify the typical building construction materials, envelope technologies and user behaviours for public residential buildings in Hong Kong. The input of building geometry, occupancy schedule, and equipment load were thoroughly investigated through literature reviews and site visits. The final energy modelling inputs were determined through careful calibration of these parameters using the measured energy use data. However, due to limited access to individual householders' electricity use data, a top-down approach was adopted to estimate the cooling and lighting energy consumption of the residential units, using the measured town gas consumption and the overall energy consumption distribution reported in the EMSD Hong Kong end-use energy report. A procedure to generate a reasonable schedule setting for the energy simulation of the residential building was proposed. A series of schedules for the four basic unit types were generated based on the demographic data and number of units of the building. By combining these settings with the building envelope information and equipment specifications, a Base Case building energy model was developed.

Using the Base Case energy model, sensitivity analyses were then conducted using the parametric simulation tool jEPlus for developing L/ZCB scenarios. The carbon emissions of the Base Case building were estimated using the relevant carbon emission conversion factors for the types of energy used. Using the energy saving design strategies identified through desk study and verified through interviews and focus groups, sensitivity analyses were conducted to quantify their impact on the building's energy consumption using jEPlus. By integrating suitable energy saving design strategies, the Quick-Win Scenario was developed.

To further reduce the building's energy consumption and carbon emissions, a desk study was conducted to explore possible social and advanced technical solutions, and this led to the development of the Optimisation Scenario. Moreover, the Decarbonisation Scenario and Emerging Renewable Scenario were explored for the further strategic reduction of building energy use and carbon emissions.

2.3 Methods for Studying Private Office Building

A 26-storey private office building with mixed-use functions located in Kowloon was selected as the reference building for the examination of delivering high-rise private office L/ZCBs. This building adopts an in situ concrete construction method with the GFA of 29,305 m^2 (above ground 24,700 m^2; underground 4,605m^2) and represents the status quo of typical private office building designs in Hong Kong. Out of the total 26 storeys, the podium layers (1-5F) are used for food and beverage purposes and the tower part (6F-26F) is designated for offices. The building was designed to achieve BEAM Plus Gold level.

The office building was designed to be a ‘core tube’ type that has a central core where lift shafts, lobbies and equipment rooms are located, surrounded by open office spaces. A detailed energy model with precise building geometry, space division, façade configuration and system specification was built using the software DesignBuilder. Due to the limited access to actual metered energy use data, a top-down approach was adopted to establish the Base Case energy model by using end-use energy distributions reported by EMSD. As there is a set of standard energy modelling inputs for office buildings in Hong Kong, the use of this top-down approach was considered practical and effective. The geometric model was built using the latest architectural drawings and design specifications. The data inputs of the energy model of the Base Case building were based on the latest mechanical electrical and plumbing (MEP) drawings and relevant information provided by the design team, supplemented by the optimisation design and the overall building performance comparison as set in the Performance-based Building Energy Code (PB-BEC) by the EMSD.

Possible energy saving design measures were first identified through a literature review. Then, using the Base Case energy model, sensitivity analyses were conducted using the jEPlus to quantify the impact of these measures on the building’s energy consumption. By integrating suitable energy saving design strategies, the Quick-Win Scenario was developed. The carbon emissions of the Base Case were estimated using the relevant carbon emission conversion factor.

To further reduce the building’s energy consumption and carbon emissions, a desk study was conducted to explore possible social and advanced technical solutions, which led to the development of the Optimisation Scenario. Moreover, the Decarbonisation Scenario and Emerging Renewable Scenario were explored for further strategic reduction of building energy use and carbon emissions.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 A Definition of L/ZCB for Hong Kong

The developed definition of L/ZCB for Hong Kong regards L/ZCBs as complex socio-technical systems, and recognizes the multidimensional system boundaries of an L/ZCB and the engagement of diverse stakeholder groups (Pan, 2014; Pan and Ning, 2015). The generic form of the definition of a ZCB (or a LCB) is a building within its defined system boundaries with net-zero (or very low) carbon emissions on an annual basis during the operational stage of the building. The system boundaries should be defined in terms of the technical components of the definition within the relevant regulatory, geographic and social contexts (Figure 1).

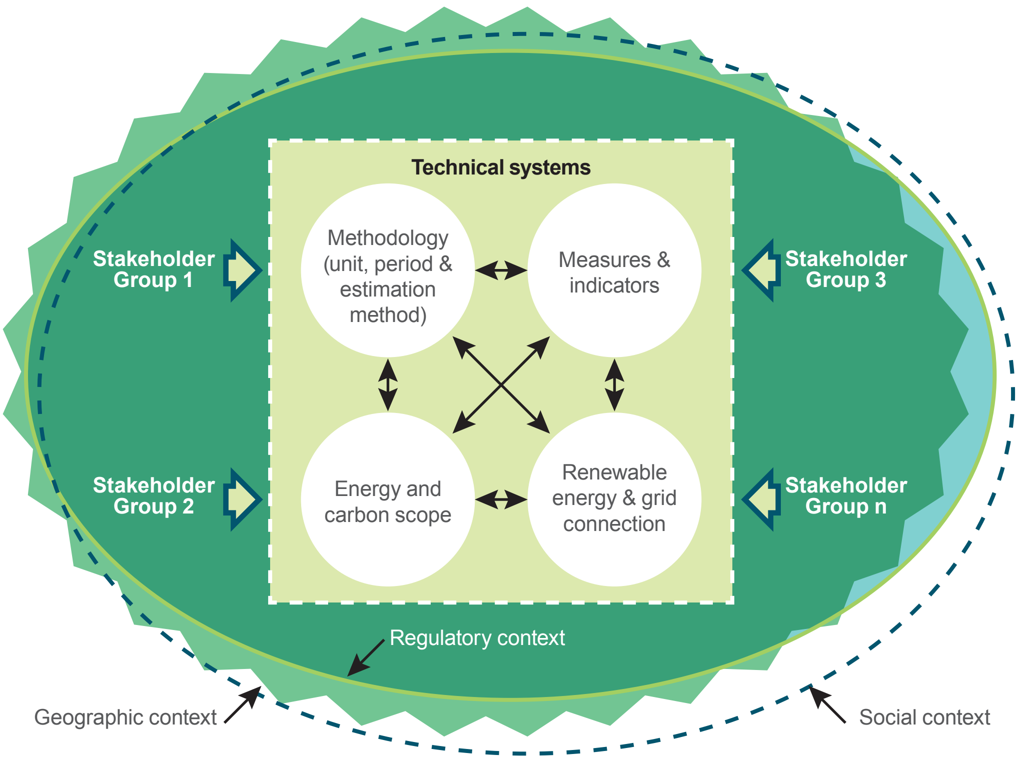

Figure 1 Conceptual model of L/ZCBs as socio-technical systems (Pan and Ning, 2015)

The technical components of the definition are:

- Energy scope. The energy scope covers both regulated and unregulated end-use energy in the building.
  - The regulated energy should be as specified in the Code of Practice for Energy Efficiency of Building Services Installation (referred to as Building Energy Code – BEC) issued under Part 9 of the Buildings Energy Efficiency Ordinance, Chapter 610, and also the Mandatory Energy Efficiency Labelling Scheme (MEELS) through the legislation of Energy Efficiency (Labelling of Products) Ordinance.
  - The regulated energy use under BEC includes energy use for (1) lighting, (2) air conditioning (which covers cooling, heating, dehumidification, humidification, air distribution and air purification), (3) electrical use, and (4) lifts and escalators.
  - The regulated energy use under MEELS includes energy use for (1) room air-conditioners, (2) refrigerating appliances, (3) compact fluorescent lamps, (4) washing machines, and (5) dehumidifiers.
  - The unregulated energy use includes energy use for cooking, hot water, office equipment and others as included in the Hong Kong End-use Energy annually reported by the EMSD.
- Carbon scope. The carbon scope covers the carbon emissions associated with the energy use covered in the energy scope minus any carbon that is offset, captured and/or stored for the building.
- Energy use estimation and/or measurement methods. These should allow measurement at two stages of the building life cycle:
  - As-designed L/ZCB, with simulated end-use energy and estimated renewable energy based on recognised technical and behavioural assumptions.
  - As-occupied L/ZCB, with measured end-use energy and renewable energy generated.
- Carbon estimation methods. Carbon emissions are estimated (1) using the energy use and relevant carbon conversion factors for operation energy related carbon, and (2) following the EMSD EPD's Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings in Hong Kong, and The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (WRI and WBCSD, 2004) and the International Standard on Greenhouse Gases Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals (ISO, 2006).
- Unit of balance. The unit of balance is carbon emissions estimated using the methods above.

- Period of balance. The period of balance is on an annual basis.
- Measures and indicators. The measures include kWh/(m²yr) for energy use and $kgCO_2$/(m²yr) for carbon emissions. The indicators are set in the principles:
    - For LCBs, the indicators of energy use and carbon emissions should be substantially lower than that of standard buildings. Also, there should be several levels of LCBs, enabling progressively approaching zero carbon.
    - For ZCBs, the indicators should be similar to or lower than the lowest level of LCBs, which, coupled with the use of renewable energy, achieve net zero.
- Use of renewable energy. The required renewable energy may be generated on-site, off-site but directly connected with the building, and/or off-site and indirectly connected with the building.
- Grid connection. The building is grid-connected to enable the possible achievement of net zero.

The developed definition is in strategic alignment with the body of knowledge and debate on the definitions of zero carbon buildings (ZCH, 2014) and zero energy buildings (Marszal *et al.,* 2011; Sartori *et al.,* 2012), but moves the debate forward by firmly grounding the definition on system theories, and by explicitly defining the systems boundaries of L/ZCBs. This is therefore a useful contribution to the theory of low energy and low carbon building.

In addition, this definition is developed based on the high-density urban setting of Hong Kong with its hot-and-humid subtropical climate, and therefore ably fills a gap in the world's knowledge of L/ZCBs, which has been dominated by low-rise buildings in cold and temperate zones (Pan and Li, 2016).

Furthermore, this definition specifies the energy scope for covering regulated and unregulated end-use energy in the building, as well as the carbon scope to cover the carbon emissions associated with such energy use, minus any carbon that is offset, captured and/or stored for the building, along with a suggested progressive approach towards ZCB. This clear scope contributes a useful approach to address the inconsistent energy/carbon scopes set out in different countries even where governed by the same policy, e.g. EU's nearly ZEB policy target (Thomsen and Wittchen, 2008). If widely adopted, it should allow effective benchmarking internationally. Nevertheless, the suggested progressive approach towards the net zero target should be supported by further research into the feasibilities of emerging technologies.

The developed definition will help to enhance stakeholders' understanding of L/ZCBs as complex socio-technical systems, support the development of a L/ZCB policy for Hong Kong, and influence future reviews of building energy policies, codes and regulations, with the ultimate goal of achieving net zero carbon in the long term.

3.2 Feasibility & Scenario-based Solutions: Public Residential

3.2.1 Scenarios and technical feasibility

Of the established Base Case, the EUI is 106.6 kWh/(m²-yr) (Table 1), and in order of significance covers cooling electricity (23.5%), cooking gas (22.41%), appliances (20.84%), DWH gas (16.22%), lighting for communal areas (4.71%), lighting for residential units (4.55%), lifts (3.24%), water pumps (2.59%), and other communal area use (1.94%) (Table 2). The carbon emissions intensity (CEI) is calculated as 55.51 kg/(m²-yr).

Table 1 Outline of Residential L/ZCB Base Case, Quick-Win and Optimisation Scenarios

Category	Base Case		Quick-Win Scenario		Optimisation Scenario	
	Energy use kWh/m²	Carbon emissions kg/m²	Energy use kWh/m²	Carbon emissions kg/m²	Energy use kWh/m²	Carbon emissions kg/m²
Electricity consumption	65.44	45.81	50.34	35.24	45.07	31.55
Town gas consumption	41.16	9.70	41.16	9.70	31.39	7.40
Total	106.6	55.51	91.5	44.94	76.46	38.95
PV	n/a	n/a	-10.37	-7.26	-21.23	-14.86
Wind turbine	n/a	n/a	-1.39	-0.97	-1.39	-0.97
Net Total	106.6	55.51	79.8 (-25%)	39.71 (-28.5%)	53.88 (-49%)	23.12 (-58.3%)

GFA: 36,286m²; carbon emission factors for electricity & town gas: 0.7 & 0.2356 kg/kWh.

The developed Quick-Win Scenario reduces the Base Case EUI by 25% to 79.8 kWh/(m²-yr) (14% and 11% through efficiency and renewable, respectively) (Table 3), and in order of significance covers cooking gas (26.09%), appliances (24.26%), DWH gas (18.88%), cooling electricity (14.82%), lifts (3.77%), lighting for residential units (3.49%), lighting for communal areas (3.43%), water pumps (3.01%), and other communal area use (2.26%) (Table 4). The CEI is reduced by 28.5% to 39.71 kg/(m²-yr).

Table 2 Residential L/ZCB Base Case, Quick-Win and Optimisation Scenarios

Energy element	Energy use of Base Case kWh/m²	Share (%)	Energy use of Quick-Win Scenario kWh/m²	Share (%)	Further energy use reduction of Optimization Scenario (over Quick-Win)	Share (%)
Cooking gas consumption (inside units)	23.88	22.41%	23.88	26.09%	6% reduction (22.45 kWh/m²)	29.36%
DWH gas consumption (inside units)	17.28	16.22%	17.28	18.88%	48.3% reduction (8.94 kWh/m²)	11.69%
Cooling electricity consumption (inside units)	31.3	23.50%	13.56	14.82%	0% reduction (13.56 kWh/m²)	17.73%
Appliances (inside units)	22.2	20.84%	22.2	24.26%	20% reduction (17.76 kWh/m²)	23.23%
Lighting (inside units)	4.8	4.55%	3.19	3.49%	0% reduction (3.19 kWh/m²)	4.17%
Lighting electricity consumption (communal area)	5	4.71%	3.14	3.43%	0% reduction (3.14 kWh/m²)	4.11%
Lift electricity consumption (communal area)	3.45	3.24%	3.45	3.77%	25% reduction (2.59 kWh/m²)	3.39%
Water pump electricity (communal area)	2.76	2.59%	2.76	3.01%	10% reduction (2.76 kWh/m²)	3.61%
Other (communal area)	2.07	1.94%	2.07	2.26%	0% reduction (2.07 kWh/m²)	2.71%
Total	106.6	100%	91.5	100%	16.4% reduction (76.5 kWh/m²)	100%
Electricity generation by PV	n/a		-10.37	-11.33%	105% increase (-21.23 kWh/m²)	-27.76%
Electricity generation by wind turbine	n/a		-1.39	-1.52%	0% increase (-1.39 kWh/m²)	-1.82%
Net Total	106.6	100%	79.8	87.15%	1955089 kWh (53.88 kWh/m²)	70.43%

The developed Optimisation Scenario reduces the Base Case EUI by 49% to 53.88 kWh/(m²-yr) (28% and 21% through efficiency and renewable, respectively) (Table 1), and in order of significance covers cooking gas (29.36%), appliances (23.23%), cooling electricity (17.73%), DWH gas (11.69%), lighting for residential units (4.17%), lighting for communal areas (4.11%), water pumps (3.61%), lifts (3.39%), and other communal area use (2.71%) (Table 2). The CEI is further reduced by 58.3% to 23.12 kg/(m²-yr).

3.2.2 Quick-Win Scenario based design solutions

The identified design parameters of the Quick-Win Scenario are outlined in Table 3.

Table 3 Design parameters of Quick-Win Scenario (public residential)

Parameter/measure	Value (Base Case)	Value (Quick-Win Scenario)
Orientation	Original	Original
Shading type	n/a	Overhang and side-fin (0.5m projection)
Window to wall ratio	As designed (about 30%)	As designed (about 30%)
Natural ventilation rate when air-conditioner is off	3 ACH	15 ACH
SHGC	0.775	0.2
Visible transmission	0.881	0.6
Solar absorptance of wall	0.58	0.4
Solar absorptance of roof	0.65	0.3
U value of wall	3.85 W/m²k	3.85 W/m²k
U value of roof	0.55 W/m²k	0.55 W/m²k
U value of window	5.78 W/m²k	5.78 W/m²k
Air tightness	0.5 ACH	0.2 ACH
Cooling set point	26°C	28°C
Cooling COP	2.4	5
Lighting	CFL (4W/m²-100lux)	LED (2.5W/m²-100lux)
PV panels	n/a	Conversion rate: 15%; Location: roof, overhang & facades Total electricity generation: 376,459 kWh/yr
Wind turbine	n/a	Small horizontal axis wind turbine Location: roof Total electricity generation: 50,500 kWh/yr

The justifications for adopting the design parameters are provided below.

Morphologically, building orientation is retained in its original orientation, which leads to the best energy performance. Overhangs and side-fins with 0.5m projection are used for shading for their contribution to the lowest energy consumption. Although the 20% window-to-wall ratio (WWR) leads to the lowest building energy consumption, the designed ratio of about 30% is used considering the need for viewing and natural lighting, and that similar building energy performance (to that by a 20% WWR) can be achieved by a 30% WWR coupled with the use of overhangs and side-fins for shading. As the public residential building case only provides single side ventilation for most of the residential space, natural ventilation rate is assumed at 15 ACH for this scenario.

As for building envelope efficiency, although smaller solar absorptance means lower building energy consumption, the practical solar absorptance value of 0.4 for external wall and 0.3 for roof is proposed, as any smaller solar absorptance will result in a smooth surface material with high reflectance, which may cause light pollution for urban areas. The U value for single glass and concrete wall without insulation is used. To ensure a certain level of natural lighting quality for indoor areas, the visible transmission of glazing is assumed to be 0.6. As the SHGC is related to VT, a high performance low-E coated glazing with SHGC at 0.2 is adopted.

With regard to building energy system efficiency, the best available cooling COP of 5 for a room air conditioner and the best lighting technology using LED are adopted. According to the Guidelines on Design and Construction Requirements for Energy Efficiency of Residential Buildings (BD, 2014), if windows are opened for natural ventilation in residential units, occupants are expected to live with the internal temperatures up to 28°C. Therefore, the cooling set point is set to 28°C. Through the above energy saving design measures, the cooling energy usage is reduced from 31.3 to 13.56 kWh/m², and the lighting energy consumption is reduced from 4.8 to 3.2 kWh/m² for residential units, and from 5 to 3.1kWh/m² for communal areas. 376459 kWh PV on the roof top and window canopies, and 50500 kWh wind turbines on the roof top are adopted, which together can offset 12.85% of the building's total energy use. These renewable technologies are assumed with standard efficiency rates for market availability in the Quick-Win Scenario.

3.2.3 Quick-Win Scenario parameter sensitivity analyses

The input parameters and their ranges and intervals for the Quick-Win Scenario parameter sensitivity analyses are provided in Table 4.

Table 4 Input for sensitivity analyses of Quick-Win Scenario

No	Residential buildings' input design parameters	Range	Interval
1	Orientation	0-360	45
2	Natural ventilation rate (ACH)	0-45	3
3	Window to wall ratio	0.2-0.9	0.1
4	Shading device	No shading, 0.5 m overhang, 1 m overhang, 0.5 m louver, 0.5m overhang and side fin	
5	Airtightness (ACH)	0.25-3	0.25
6	Solar absorptance of roof	0.2-0.8	0.1
7	Solar absorptance of external wall	0.2-0.8	0.1
8	Direct solar transmission of window	0-1	0.1
9	Visible transmission of window	0-1	0.1
10	Insulation thickness of roof	0.02-0.3	0.02
11	U value of external wall	0.5-3.85	0.5
12	U value of window	0.5-5.78	0.5
13	Lighting efficiency (W/(m²-100lux))	4 (CFL), 2.5 (LED)	
14	Cooling set point (°C)	20-29	1
15	Cooling COP	1.5-5	0.5
16	Photovoltaic panel	Roof, overhang, vertical wall	
17	Wind turbine	Roof top	

The highlights of the results are provided below.

Energy saving measures

- Among the energy saving measures, the cooling set point has the most significant influence on the cooling energy consumption of the building. The cooling energy consumed when the cooling set point is at 20°C is nearly 2 times of that when the cooling set point is at 26°C, and 3.5 times of that when the cooling set point is at 29°C.
- The gross rated COP of the air conditioner also has a strong influence on the building's cooling energy use, with an increase of the cooling COP from 2 to 5 leading to a reduction in the cooling energy consumption of nearly 60%. More specifically, raising the cooling COP from 2 to 3 reduces the energy consumption by 15.6kWh/m². A further increase of the cooling COP to 5 can further reduce the energy consumption by 1.55 kWh/m².

Building envelope design variables

- Among the building envelope design variables, building air tightness has the strongest effect on cooling energy consumption. By reducing the infiltration rate from 1.5 ACH to 0.25 ACH, the cooling energy use can be reduced by 8.15 kWh/m², which accounts for nearly 17% of the building's cooling energy use.
- Solar absorptance of the wall has the second strongest influence. Changing external walls' solar absorptance from 0.2 to 0.8 leads to 5 kWh/m² cooling energy reduction.
- With the cooling set point at 26°C, the increase in the U value of the building envelope can actually lead to cooling energy reduction. This suggests that enhanced insulation of the external wall and window may not necessarily be an effective energy saving measure if the occupants adopt a more sustainable living style.
- Changing the roof construction is found to have little influence on the building's total cooling energy consumption, as the top floor area only accounts for less than 3% of the GFA of this 40-storey high-rise.
- Reducing the SHGC from 0.775 to 0.1 leads to a reduction in the building's cooling energy of 5.64 kWh/(m²-yr), which accounts for 14% of the total cooling energy use. However, reducing the VT from 0.881 to 0.3 results in the building's lighting energy increasing from 7.51 to 10.36 kWh/(m²-yr). Therefore, a low-E coating with a large difference between VT and SHGC can provide a better energy saving performance.

Morphological features

- Building orientation has a slight influence on the cooling energy consumption, with the lowest energy consumption in the current orientation and the highest in East or West orientation. However, the influence of building orientation on lighting energy consumption is marginal and so can be ignored.
- A higher natural ventilation rate leads to less cooling energy use. An increase in natural ventilation rate from 12 to 45 ACH leads to a reduction of cooling energy consumption by 4.18 kWh/(m²-yr). Conversely, a reduction in natural ventilation rate from 12 to 3 ACH leads to an increase of cooling energy use by 1.72 kWh/(m²-yr).
- WWR strongly influences the building's cooling energy consumption. When WWR increases, the cooling energy consumption increases but the lighting energy consumption decreases. As the former is much larger than the latter in the overall energy use, a smaller WWR means less overall energy consumption.
- The type of shading device used also has a strong influence on the building's cooling energy consumption. Similar to WWR, shading devices can reduce the solar heat gain of the building, hence reducing the cooling energy demand, but they also block natural light, thus increasing the lighting energy demand. The shading device option of 0.5m projection of overhang plus side-fin is found to provide the strongest shading effect and thus results in the largest energy consumption saving, compared to the other shading device options studied, which include a louver of 0.5m projection, an overhang of 0.5m projection, and an overhang of 1m projection.

3.2.4 Optimisation Scenario based design solutions

The identified design parameters of Optimisation Scenario are provided in Table 5.

Table 5 Design parameters of Optimisation Scenario (public residential)

Measure/parameter	Value or type
Increase cooking stove efficiency	Reduce energy consumption by 6%
Reduce shower time	5 mins per person
Use high efficiency water boiler	Efficiency at 95%
Use exterior wall integrated solar hot water system	Increase the supply water temperature for hot water boiler
Use regenerative lift	Save 25% electricity consumption
Use high efficiency appliance	Reduce 20% energy consumption
Advanced PV	30% conversion rate
Sun tracking PV system	Increase 19% efficiency Total electricity generation: 770,491 kWh/yr

The highlights of the results are provided below.

Cooking

- Cooking is a basic need of humans, and it would be impractical to expect occupants to make behavioural changes in their cooking time (hence saving on cooking energy). However, a reduction in cooking energy consumption may be achieved by using an energy-efficient cooking stove. According to Towngas (2015), a high efficiency cooking stove can reduce energy consumption by 6%.

Domestic water heating (DWH)

- The current DWH gas consumption is calculated based on the daily hot water consumption rate of 30 L/person throughout the year using a water boiler with 85% efficiency, and with the average supply temperature at 21.5°C and the delivery temperature at 40°C. The assumption of daily hot water usage at 30 L/person is based on an average yearly shower rate of 0.5 per occupant per day, with an average duration per shower of 7 minutes. To reduce the energy consumption of DWH, it is crucial to educate the general public to reduce their shower time to 5 minutes or shorter, which would help to reduce DWH gas use by 28.6%.

- In addition, using a gas boiler with a COP of 95% should be adopted for domestic buildings, either through regulation or incentive.
- Although the roof area is occupied by PVs, it is possible to incorporate a solar hot water system within the façade, which may help to preheat the water to a higher degree, such as 25°C.
- If all these measures are successfully adopted, the DWH gas consumption can be reduced by 48.3% to 8.94 kWh/m².

Space cooling

- Cooling energy consumption in the Optimisation Scenario has been achieved mainly by pushing the limits of the glazing SHGC, solar absorptance of the envelope, and the cooling set point. Setting the cooling point at 28°C is already very optimistic. Although in theory both the WWR and natural ventilation rate could be further adjusted to attain maximum energy efficiency, it would not be feasible to set the WWR too low or natural ventilation rate too high due to social needs and morphological constraints.
- It is thus assumed that no further saving can be achieved from cooling energy.

Appliances

- It is complicated to estimate the energy saving potential of appliances, as there is an enormous variety of domestic appliances, such as TVs, vacuum cleaners, washing machines, refrigerators, computers, etc., and the possession rate and power of these domestic appliances vary considerably.
- A further energy saving may be achieved by educating the general public to turn off equipment when not in use. The energy efficiency standard for appliances can be raised, and incentives for adopting more energy-efficient appliances can be provided.
- It is assumed that it may be possible to achieve a 20% saving in appliance energy.

Lighting

- As LED, lighting sensors, motion sensors and lighting controls are already fully adopted in the Quick-Win Scenario, it is assumed that no further saving can be achieved.

Lifts

- Lifts are one of the crucial service installations in high-rise buildings, and account for about one fourth of the energy consumption in communal areas. Traditional lifts, as used in the Base Case, do not make use of the power generated by the traction machine. To reduce the energy requirement, lifts that provide regenerative power can be used. According to the EMSD (EMSD, 2015b), between 17.1% and 27% of electricity can be saved by using regenerative power, and the higher the lift is serving, the greater is the amount of energy that can be saved.
- Therefore, for this 40-storey case building, the amount of electricity saved by the lift's use of regenerative power is assumed to be 25%.

Water pump

- Since the Variable Speed Drive (VSD) system that can reduce energy consumption by 70% is already standard practice in public housing design, there is not much room for improving water pump efficiency. It is assumed, though, that with the ongoing advancement in water pump motor efficiency, a further 10% energy consumption reduction may be achieved.

PV

- The PV panels adopted for the Quick-Win Scenario are assumed to have a conversion rate of 15%. According to NREL (2014), the highest conversion efficiency for solar cells achieved in the laboratory reaches 45.7%. Therefore, it is foreseeable that in the near future commercial PV panels with a conversion efficiency of 30% will be available.
- In addition, by using a sun tracking PV system for the roof, the electricity generation from the roof PV can be increased from 5% to 32%, with an average increase of 19% (EMSD, 2013).
- Overall, the electricity generation from the case building PV panels can be increased to 770,491 kWh (21.23 kWh/m^2).

3.3 Feasibility & Scenario-based Solutions: Private Office

3.3.1 Scenarios and technical feasibility

Of the established Base Case the EUI is 282.4 kWh/(m²-yr) (Table 6), and in order of significance covers cooling electricity (41.9%), fans (23.6%), appliances (17.5%), interior lighting (16.5%), and pumps (0.4%) (Table 7). The CEI is estimated to be 197.7 kg/(m²-yr).

Table 6 Outline of Office L/ZCB Base Case, Quick-Win and Optimisation Scenarios

Category	Base Case		Quick-Win Scenario		Optimisation Scenario	
	Energy use kWh/m²	Carbon emissions kg/m²	Energy use kWh/m²	Carbon emissions kg/m²	Energy use kWh/m²	Carbon emissions kg/m²
Electricity consumption	282.40	197.70	188.86	132.20	149.52	104.66
PV	n/a	n/a	-11.64	-8.15	-27.6	-19.32
Wind turbine	n/a	n/a	-1.72	-1.20	-1.72	-1.20
Net Total	282.40	197.70	175.5 (-38%)	122.85 (-38%)	120.2 (-57%)	84.14 (-57%)

GRA: 29,305.9m²; carbon emission factor for electricity: 0.7 kg/kWh.

The developed Quick-win Scenario reduces the Base Case EUI by 38% to 175.5 kWh/(m²-yr) (28.5% and 7.1% reductions through efficiency and renewable, respectively) (Table 6), and in order of significance covers cooling electricity (30.51%), appliances (25.15%), fans (23.39%), interior lighting (12.61%), pumps (4.58%), and then heat rejection (3.76%) (Table 7). The CEI is reduced by 38% to 124.96 kg/(m²-yr).

The developed Optimisation Scenario reduces the Base Case EUI by 57% to 120.2 kWh/(m²-yr) (47% and 19.65% reductions through efficiency and renewable, respective) (Table 6), and in order of significance covers cooling electricity (28.28%), fans (24.92%), appliances (21.17%), interior lighting (16.58%), pumps (5.04%), and then heat rejection (4%) (Table 7). The CEI is reduced by 57% to 84.14 kg/(m²-yr).

Table 7 Office L/ZCB Base Case, Quick-Win and Optimization Scenarios

Energy element	Energy use of Base Case kWh/m²	Share (%)	Energy use of Quick-Win Scenario kWh/m²	Share (%)	Energy use reduction of Optimization Scenario (over Quick-Win)	Share (%)
Cooling electricity use (inside units)	118.33	41.9%	52.2	30.51%	19% reduction (42.28 kWh/m²)	28.28%
Interior Lighting	46.61	16.5%	24.8	12.61%	0% reduction (24.8 kWh/m²)	16.58%
Interior Appliances	49.46	17.5%	49.46	25.15%	36% reduction (31.65 kWh/m²)	21.17%
Fans	66.56	23.6%	46	23.39%	19% reduction (37.26 kWh/m²)	24.92%
Pumps	1.29	0.4%	9.3	4.58%	19% reduction (7.53 kWh/m²)	5.04%
Heat rejection	0	0	7.4	3.76%	20% reduction (6 kWh/m²)	4.0%
Total	282.4	100%	188.86	100%	20.83% reduction (149.52 kWh/m²)	100%
Electricity generation by PV	n/a		-11.64	-6.16%	-808843 kWh (-27.6 kWh/m²)	-18.5%
Electricity generation by wind turbine	n/a		-1.72	-0.87%	-50500 kWh (-1.72 kWh/m²)	-1.15%
Net Total	282.4	100%	175.5	92.93%	3522569.18 kWh (120.2 kWh/m²)	80.35%

Base Case is based on air-cooled system; Quick-Win Scenario is based on water-cooled system.

3.3.2 Quick-Win Scenario based design solutions

The input parameters and their ranges and intervals for the Quick-Win Scenario sensitivity analyses are summarised in Table 8.

Table 8 Input for sensitivity analyses of Quick-Win Scenario

Input design parameters	Range	Interval
1. Building envelope/load		
Orientation	0-360	45
Solar heat gain coefficient (SHGC)	0.2-1.0	0.2
U value of external wall	0.5-3.3	0.5
Lighting load (W/m²)	10-30	5
Infiltration	0.5-4	0.5
2. HVAC system		
HVAC system type	Air-cooled chiller with COP 3, water-cooled chiller with COP 5	-
Cooling set point (℃)	21-26	1
Fan efficiency (%)	30-90	20
3. Day lighting control	Daylighting control sensor, 300 Lux	-
4. Underfloor air supply and chilled ceiling system	Applicable in office areas	-
5. Exhaust air heat recovery	Applicable in office areas	-
6. Facade integrated PV system	Facade	-
7. Rooftop PV system	Roof top	-
8. Wind turbine	Roof top	-

The design parameters of the Quick-Win Scenario are identified in Table 9.

Table 9 Design parameters of Quick-Win Scenario

Measure/parameter	Value (base case)	Value (quick-win scenario)
Orientation	Original	Original
Chiller type	Air-cooled	Water-cooled
SHGC	0.2	0.2
Solar absorptance of wall	0.4	0.4
Solar absorptance of roof	0.3	0.3
U value of wall	3.3	3.3
U value of roof	0.39	0.39
U value of window	1.57	1.57
Visible transmission	0.6	0.6
Airtightness (ACH)	0.5	0.5
Cooling set point (°C)	24	26
Cooling COP	5	5
Lighting	17 kWh/m^2	LED (2.5 W/m^2-100lux)
PV panels & BIPV	n/a	PV panels on roof (15% efficiency); BIPV on façades (4.6% efficiency)
Daylighting control	n/a	Yes
Underfloor air supply	n/a	Yes
Exhaust air heat recovery	n/a	Yes
Wind turbine	n/a	Small horizontal axis wind turbine on roof

Energy efficient services systems are the most important factor that affect the building's energy performance, and these include: HVAC (pumps, fans, heat rejection), lighting, and equipment. The parameters, including SHGC, U value, external walls, HVAC system selection, cooling set point, fan efficiency, and lighting load were analysed for their sensitivity to energy use. Among these parameters, the HVAC system is found to be the most sensitive to energy use, followed by fan efficiency and lighting load. Most old commercial buildings in Hong Kong adopt air-cooled chiller systems with a typical COP of 3, which is adopted for the Base Case. For the Quick-Win Scenario, water-cooled chiller systems were adopted, and these were analysed in comparison with air-cooled systems. The results show that, by using water-cooled chillers, the building's cooling energy consumption can be reduced by 65.61%, yielding an overall building energy use reduction of 11.47% (Table 10).

Table 10 Comparison of two types of HVAC systems

Element	Water-cooled	Air-cooled	Proportion
HVAC	157.43	186.18	18.26%
- Cooling	71.45	118.33	65.61%
- Fans	66.56	66.56	0.00%
- Pumps	11.46	1.29	-88.74%
- Heat Rejection	7.96	0	-100.00%
Interior Lighting	46.43	46.61	0.39%
Interior Equipment	49.34	49.46	0.24%
Total energy use	253.34	282.4	11.47%

Philip and Chow (2007) modelled daylighting for offices using Trance 600, and found that applying daylighting strategies would save as much as 41% of the lighting energy use and 16% of the overall building energy use. In this present study, the use of a daylighting control system as a proven technology is assumed to reduce the building's total energy consumption by 11%. Alajmi and El-Amer (2010) argued that higher ceilings enabled more energy saving in using underfloor-air-distribution (UFAD) than do lower ceiling heights; if the building height is 4.8m with supplied air at 16°C, the total energy saving is 12.8%. In this present study, after simulation, the use of an UFAD system as another effective measure is estimated to reduce the building's total energy use by 13%. Through the adoption of the energy saving design measures above, the cooling energy usage is reduced from 118.33 to 52.2 kWh/(m²-yr) and the total energy consumption is reduced from 282.4 to 178.5 kWh/(m²-yr). The PV system adopted in this Quick-Win Scenario can generate 253 MWh/yr, equivalent to an energy saving of 11.64 kWh/(m²-yr), offsetting 6.16% of the building's total energy consumption. The wind turbine adopted can generate electricity of about 1.72 kWh/(m²-yr), offsetting 0.87% of the total energy use.

3.3.3 Optimisation Scenario based design solutions

The identified design parameters of Optimisation Scenario are outlined in Table 11.

Table 11 Design parameters of Optimisation Scenario (private office)

Measure/parameter	Value or type
Adopt new HVAC system	District cooling scheme (DCS), direct seawater cooled chillers, variable speed distribution loop pumps, saving 18% of overall energy
Turn off equipment when not in use	Saving 20% of interior appliance energy use
Improve equipment efficiency	Saving 16% of interior appliance energy use
Reduce heat gain with better building orientation	Saving 4% of the total energy use
Advanced PV	BIPV façade, up to 15% efficiency rate PV panel, roof, up to 30% efficiency rate
Fans	No further decrease
Interior lighting	No further decrease

The highlights of the results are provided below.

District cooling scheme (DCS)

- DCS with direct seawater cooled chillers and variable speed distribution loop pumps are adopted, to achieve optimised energy savings. According to the EMSD (2016), the use of DCS can reduce relevant energy use by 20% compared with the water-cooled system. Therefore, compared with using a water-cooled chiller in the Quick-Win Scenario, 20% energy savings are expected.

Cooling

- The design features/parameters, including HVAC systems, daylighting control, SHGC of glazing, cooling set point and human behaviour have already been fully considered in the Quick-Win Scenario. For example, it would not be feasible to further reduce the lighting load, due to the minimum luminance requirement. Also, the cooling set point at 26°C is already high for office buildings in Hong Kong. Building orientation can affect cooling energy consumption. According to Li, Jones and Lannon (2014), by adopting the best orientation, energy use can be slightly reduced to 95%.

Fans

- The fan efficiency of 0.9 in the Quick-Win Scenario is already very optimistic. It is therefore assumed that no further reduction can be attained in the use of fans.

Interior lighting

- Measures including LED, lighting sensors, motion sensors and lighting controls are already adopted in Quick-Win Scenario. No further improvement is assumed.

Interior appliances

- Further energy saving may be achieved by educating the general public to turn off equipment when not in use. Energy efficiency standards for appliances may be raised, and incentives for adopting energy-efficient appliances may be provided. Zhang (2014) reported that energy consumption caused by personal unreasonable use consumes almost 30% of the total energy consumption. Therefore, a 36% appliance energy saving over the Quick-Win Scenario is assumed for the Optimisation Scenario.

PV

- The BIPV used on the façade in the Quick-Win Scenario are assumed to have an efficiency rate of 4.5%. According to Fong and Lee (2012), the highest efficiency achieved for solar cells reaches more than 40%. Therefore, it is foreseeable to have commercial BIPV with a conversion efficiency of 15% in the near future. The electricity generation from BIPV in this building can thus be increased to 632,500 kWh (21.58 kWh/m²). The PV panels used on the roof in the Quick-Win Scenario are assumed to have an efficiency rate of 15%. According to NREL (2014), the highest conversion efficiency for solar cells achieved in the laboratory reaches 45.7%. Therefore, it is foreseeable to have commercial PV panels with a conversion efficiency of 30% in the near future. The electricity generation from PV panels in this building can thus be increased to 176,438 kWh (6.02 kWh/m²).

3.4 Strategic Scenarios

Although significant EUI and CEI reductions are attainable, it is still not feasible to achieve net-zero carbon or net-zero energy for high-rise L/ZCBs in Hong Kong given the current carbon-intensive energy supply and the renewable energy and carbon reduction technologies available in the market. To achieve high-rise net zero carbon, more efficient or emerging renewable energy technologies and/or decarbonisation measures must be explored and adopted. Two strategic scenarios are developed.

3.4.1 Emerging Renewable Scenario

This scenario is based on the Optimisation Scenario but also takes into account emerging renewable energy technologies such as CCHP, DCS and FC, that together may further reduce the net energy use (hence net carbon emissions) of the building towards zero or negative (Figure 2 & 3). For example, CCHP systems refer to the simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector. Previous research (Fong and Lee, 2015) suggested that when using internal combustion engine primed trigeneration (ICEPT) systems, the annual overall energy consumption of an office building could be reduced by up to 10.4% compared to one using a natural gas fuelled system. Ho *et al.* (2004) studied a cogeneration system that includes a single effect commercial micro-turbine, and indicated that the electrical energy use could be reduced by 21%.

However, most of such technologies are still in their earlier stage of development, with only one or a small number of trial applications in Hong Kong, and therefore suffer from a lack of available performance data. Also, there is a scarce supply of developable land in Hong Kong, and limited roof space on high-rise buildings, so it can be difficult to allocate building floor areas for such technologies. Nevertheless, the use of these technologies should be considered strategically in conjunction with Hong Kong's land, planning and infrastructure policies.

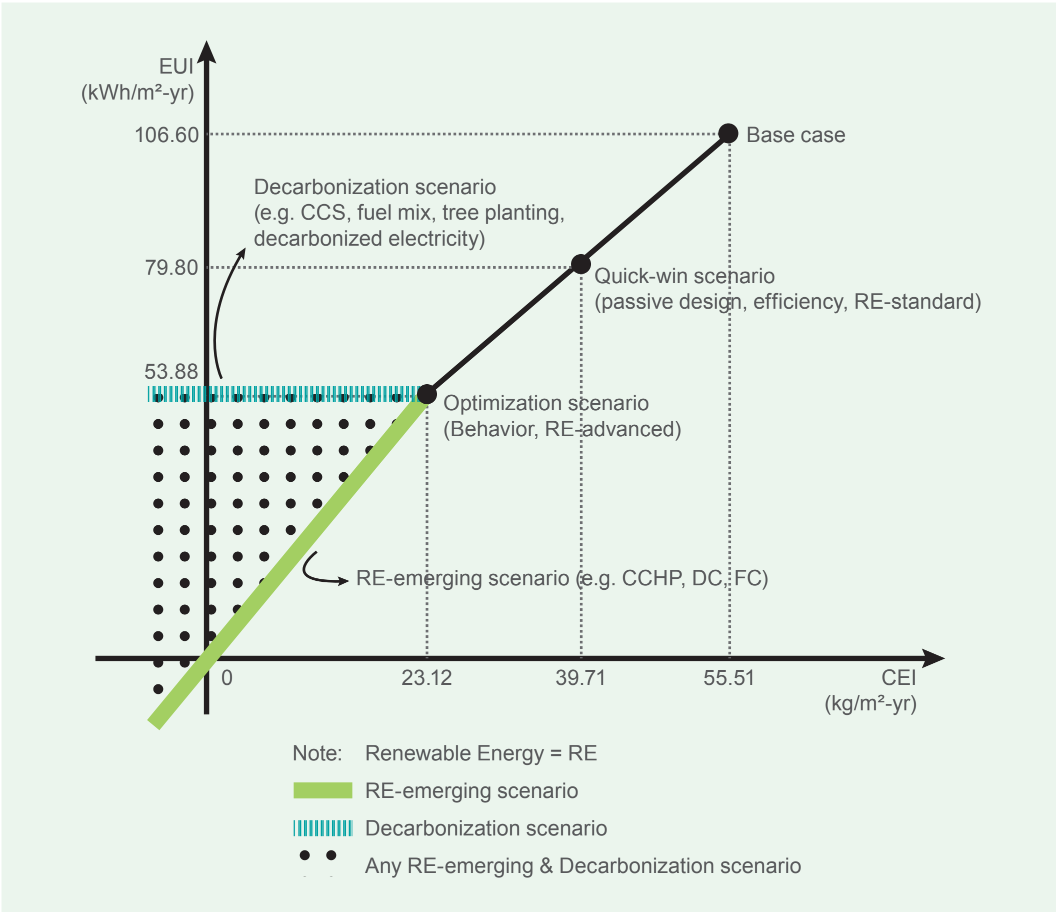

Figure 2 L/ZCB Case and Scenarios model (public residential)

Notes:
According to Hong Kong End-use Energy Data (EMSD, 2015a), the overall annual energy consumption of public rental housing within the units was 17,045 Terajoule (4,734,722,222 kWh) in 2012. Since the overall public rental housing population accounts for 29.1% (HKHA, 2012) of the total population of 7,154,600 (HKCSD, 2013), the average annual energy consumption of public rental housing per person was estimated at 2,274 kWh. Based on the average living space of public rental housing at 12.9 m² (HKHA, 2012), the benchmark for public housing energy consumption within the units is calculated as being 176.3 kWh/(m²-yr).

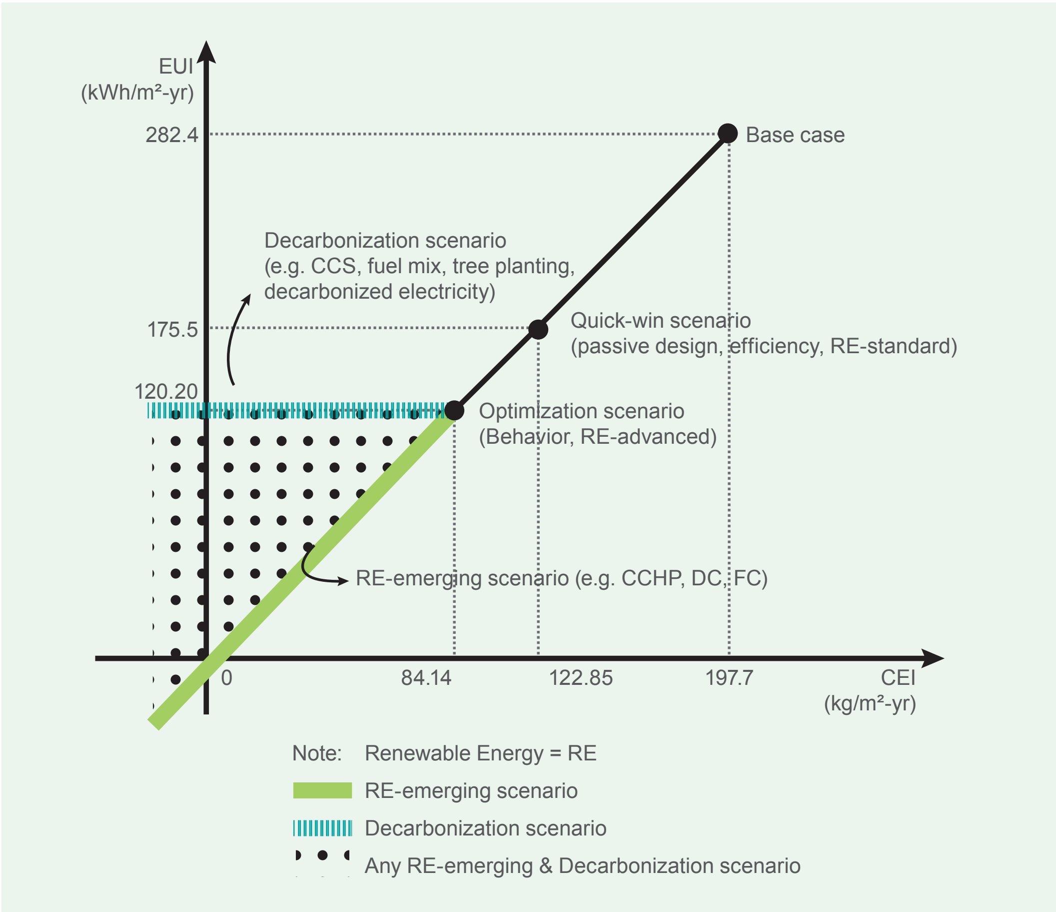

Figure 3 L/ZCB Case and Scenarios model (private office)

Notes:

According to Hong Kong End-use Energy Data (EMSD, 2015a) and Hong Kong Annual Digest of Statistics (HKCSD, 2013), the annual energy consumption of office buildings and the stock of office buildings in use in Hong Kong are 12,663 Terajoule (3,517,500,000 kWh) and 10,239,000 m² respectively. Therefore, the benchmark energy consumption for office buildings in Hong Kong is estimated as 343.5 kWh/(m²-yr).

3.4.2 Decarbonisation Scenario

This scenario is also based on the Optimisation Scenario, but takes into account additional measures such as decarbonised electricity generation, changing the fuel mix, CCS, and planting trees, that together may further reduce the net carbon emissions of the building towards zero or negative (Figure 2 & 3).

The government (ENVB, 2014) proposed two fuel mix options for electricity generation for Hong Kong. Thanks to the proposed significant reduction in coal use for both options (from 55% in 2012 to 10% or 20%), the carbon conversion factors for electricity in Hong Kong would be significantly reduced. This proposal, if implemented, would form a fundamental element to the solution for achieving L/ZCBs in Hong Kong. The measure of planting trees is specified in the Guidelines to Account for and Report on GHG Emissions and Removals for Buildings (EPD and EMSD, 2010). According to the guidelines, each tree that is able to reach at least 5 meters in height may remove 23kg of carbon emissions per annum. This measure has been tested by the HKHA and has been found to be able to offset 0.2-0.5% of the lifecycle carbon emissions of new public housing developments in Hong Kong (Ng and Kwok, 2013). Given the scarce land supply (hence limited land or space for planting trees) and the high-rise feature of buildings (hence high density) in Hong Kong, carbon offset by tree planting can only be marginal.

The examined L/ZCB technical feasibility and developed scenario-based solutions will provide the stakeholders with a better understanding of the energy and carbon 'hotspots' (i.e. energy and carbon intensive areas or functions) of high-rise buildings in Hong Kong, and the technical solutions for addressing such 'hotspots'. Finding out the maximum possible energy use and carbon emission reductions in the Quick-Win and Optimization Scenarios provides building clients and their professional advisors with useful guidance in designing L/ZCBs. The quantified feasibility of L/ZCBs could be integrated into the revisions of green building assessment schemes (e.g. BEAM Plus New Building) to review the energy use and carbon emissions related criteria and credits. These findings will also support the development of a L/ZCB policy for Hong Kong, as well as future reviews of building energy policies, codes and regulations, with the ultimate goal of achieving net zero.

3.5 High-rise L/ZCB Design Strategies

A wide range of L/ZCB design strategies have been developed for both the public residential and private office building cases. These strategies are grouped under the ten elements of energy use and carbon emission reductions (Table 12).

Table 12 High-rise L/ZCB design strategies

Elements of energy use & carbon emissions	Strategies for public residential building	Strategies for private office building
A1: energy demand by user behaviour changes	• Increase the cooling set point to 28°C • Use natural ventilation • Use fan rather than air-conditioner • Reduce shower time to 5 minutes • Turn off the light when leaving room • Turn off the TV/computer/monitor after using them	• Increase the cooling set point • Turn off the task light when leaving workstation • Turn off the computer/monitor when not in use
A2: energy loss through building fabric	• Reduce heat gain with better building orientation • Improve unit natural ventilation performance (to more than 15 ACH) through better building orientation, unit configuration, window design • Use light colour surface for exterior wall with solar absorptance as low as 0.4; • Use light colour roof surface with solar absorptance as low as 0.3 • Use advanced glazing with SHGC as low as 0.2 and VT larger than 0.6 • Use overhangs and side-fins with 0.5m projection • Use insulation when cooling set point is lower than 26°C	• Reduce heat gain with better building orientation • Improve unit natural ventilation performance through better building orientation, unit configuration, window design • Use light colour surface • Use advanced glazing • Use overhangs and side-fins • Use roof insulation • Use green roof • Provide opening window for room with natural ventilation potential

Table 12 High-rise L/ZCB design strategies

Elements of energy use & carbon emissions	Strategies for public residential building	Strategies for private office building
A3: energy for M&E systems	• Use high efficiency air-conditioner with cooling COP reaching 5 • Use high efficiency water boiler with efficiency reaching 95% • Use LED lighting with lighting efficiency reaching 2.5 W/m^2-100lux • Use lighting control such as timer, lighting level sensor, motion sensor and manual control for communal areas • Use lifts with regenerative power • Use high efficiency water pumps	• HVAC system combining chilled-ceiling with desiccant cooling • A combination of cooled ceiling, microencapsulated phase change material slurry storage and evaporative cooling technologies in air-conditioning • Combining cooled ceiling and a microencapsulated phase change material (MPCM) slurry storage tank • Liquid desiccant cooling system (LDCS) • Multi-zone demand-controlled ventilation (DCV) strategy with two schemes using several sensors for multi-zone offices. • Variable speed pumps • Underfloor air supply and chilled ceiling system • Exhaust air heat recovery
A4: energy for white goods (appliances)	• Use high efficiency appliances • Include more appliance types in the MEELS • Use town gas driven appliances	• Use high efficiency office equipment and appliances (MEELS) • Use town gas driven appliances
A5: energy loss in transmission	• Reduce electricity loss in transmission • Use town gas	• Reduce electricity loss in transmission • Use town gas (e.g. for DWH)
A6: energy production and supply	• Decarbonise electricity supply • Change fuel mix for electricity generation • Purchase and use bio-fuel	• Decarbonise electricity supply • Change fuel mix for electricity generation • Purchase and use bio-fuel

Table 12 High-rise L/ZCB design strategies

Elements of energy use & carbon emissions	Strategies for public residential building	Strategies for private office building
B1: On-site renewable energy generation	• Use solar power with PV efficiency reaching 30% or more • Use wind power with small wind turbine • Explore existing technologies with higher efficiency • Explore emerging renewable energy technologies (e.g. CCHP, fuel cells)	• Use solar power with PV efficiency reaching 30% or more • Use wind power with small wind turbine • Explore existing technologies with higher efficiency • Explore emerging renewable energy technologies (e.g. CCHP, fuel cells)
B2: Off-site renewable energy generation direct	• Explore wind farm • Use tidal power • Explore solar farm • Explore existing technologies with higher efficiency • Explore emerging renewable energy technologies (e.g. DCS)	• Explore wind farm • Use tidal power • Explore solar farm • Explore existing technologies with higher efficiency • Explore emerging renewable energy technologies (e.g. DCS)
B3: Accredited renewable energy	• Explore wind farm • Use tidal power • Explore solar farm • Use of nuclear power • Carbon trading	• Explore wind farm • Use tidal power • Explore solar farm • Use of nuclear power • Carbon trading
C: Carbon offset, capture & storage	• Plant trees • Carbon offset, capture & storage	• Plant trees • Carbon offset, capture & storage

Notes:
The literature review expands and verifies the strategies developed from the case studies and analyses. However, care should be taken when generalising the strategies.

These design strategies together advocate the adoption of systems theory for delivering buildings towards net zero carbon. The design strategies are in strategic alignment with the widely recognised four tiers, i.e. change user behaviour, improve energy efficiency, adopt on-site and off-site renewable energy technologies, and explore carbon offset, capturing and storage systems (Pan and Li, 2016).

The developed L/ZCB design strategies will help to address the difficulty with delivering L/ZCBs by providing systems strategies for substantial and significant energy use and carbon emission reductions. The findings will also provide guidance and references to building designers in their decisions on low energy and carbon buildings. Furthermore, the strategies will support the development of a L/ZCB policy and future reviews of building energy policy in Hong Kong.

3.6 Non-technical Feasibility of High-rise L/ZCB

A number of findings arise from the examination of the four non-technical feasibility aspects of high-rise L/ZCB in Hong Kong. First, the non-technical feasibility aspects, namely, socio-cultural preference, commercial viability, supply chain competency and statutory and regulatory acceptance, are found to be interactive with each other and as a whole interact with the technical feasibility as well. Socio-cultural preference is largely shaped and guided by political and regulatory acceptance. Supply chain competency has an important implication for commercial viability. Technical feasibility will determine the commercial viability. The relevant technical scenarios and design solutions will be governed by the political agenda and regulatory framework and, if adopted, will be influenced by the other aspects.

Second, the degree of feasibility of the non-technical aspects depends on the technical scenarios and design solutions developed, thus possessing a dynamic aspect. Although the Quick-Win Scenarios are developed using more established efficiency and renewable technologies, the Optimisation Scenarios are based more on predicted behavioural changes and adopt more advanced renewable energy technologies, thus being open to more uncertainties. The two strategic scenarios, Decarbonisation Scenario and Emerging Renewable Scenario, find themselves more exposed to political, economic, socio-cultural and technological risks.

Third, the non-technical feasibility aspects are also value-laden, so different stakeholders may have different perspectives and interests relative to the multi-dimensional aspects of the complex system boundaries of L/ZCBs (Pan, 2014).

Fourth, statutory and regulatory acceptance was considered to be fundamental and the most important of all the non-technical feasibility aspects involved in delivering high-rise L/ZCB in Hong Kong, as it will largely shape and guide the socio-cultural preferences. A clear and ambitious carbon reduction target can motivate both the industry and the market for L/ZCB. This will then enhance the supply chain competency. Also, the government itself is a major client for buildings in Hong Kong, so the government can take the lead in adopting the developed technical scenarios and design solutions and nurture a sharing culture within the industry. Also, for the developed strategic scenarios, the statutory and regulatory acceptance of high-rise L/ZCB in Hong Kong can enable long-term energy planning and fuel mix re-structuring for decarbonised electricity generation.

Finally, because of the interactive, dynamic and value-laden features of the non-technical feasibility aspects, the use of indices may not be an appropriate measurement of the feasibility, due to such possible issues as double-counting owing to interdependency, and to the non-linearity of measurements. The non-technical feasibility profiles of the two types of building are found to be very different from each other, but the findings provide useful points of reference for other types of building in Hong Kong, such as private residential and public office buildings.

The study suggests a need for further research into the non-technical feasibility aspects of the L/ZCB strategies, scenarios and solutions. Post-Occupancy Evaluation (POE) should help to substantiate the recommendations for behavioural changes, which would require access to end-users. Cost comparison between the scenarios could also help to better understand the commercial viability, but this would require access to the cost databases of developers. Supply chain value analysis could enable a more thorough appreciation of the supply chain competency and cost-benefit distribution, which would require access to relevant supply chains.

4 RECOMMENDATIONS

4.1 The L/ZCB Definition for Hong Kong

The developed L/ZCB definition for Hong Kong regards L/ZCBs as complex socio-technical systems, and recognizes their multidimensional system boundaries and wide-ranging stakeholder engagement. The system boundaries should be defined in terms of the technical components of the definition within the relevant regulatory, geographic and social contexts. The technical components of the definition should be explicitly specified, these being: Energy scope, carbon scope, energy use estimation and/or measurement methods, carbon estimation methods, unit of balance, period of balance, use of renewable energy, and grid connection.

The definition provides a consistent energy and carbon scope. If adopted, it should allow effective benchmarking, and enable an effective, progressive approach toward the net zero target, as well as support the development of a L/ZCB policy for Hong Kong and future reviews of building energy policies, codes and regulations.

4.2 Technical Feasibility & Scenario-based Solutions

4.2.1 Public residential building

The first finding is that the Base Case, albeit representing the greenest public housing, is still energy use and carbon emission intensive. The EUI is 106.6 kWh/(m^2-yr) and the CEI is 55.51 kg/(m^2-yr). At first glance, this EUI greatly challenges the feasibility of achieving net zero energy or carbon. Due to the hot-and-humid (hence the need for cooling) and high-rise (hence the need for communal area use, lifts and water pumps) features of buildings in Hong Kong, the EUI is unavoidably much higher than that of low to medium-rise buildings in temperate climates. Also, cooking gas and appliances (which together account for 43.25% of building energy use) are included in the EUI calculations, which is different from many other countries, where such items are excluded in the definition of L/ZCB (e.g. UK). These findings explain the perceived infeasibility of and apparent great challenge to delivering net zero carbon.

The second finding is that the Quick-Win Scenario is substantially less energy use and carbon emission intensive. The EUI is reduced to 91.5 kWh/(m^2-yr) (with 14% reduction over the Base Case), and the CEI is reduced to 39.71 kg/(m^2-yr). The combination of cooking gas and appliances (which are not included in some definitions elsewhere) account for over half of the building energy use (50.35%). This technically optimised case considers the use of PV and wind turbine, which together help to further reduce the net EUI by 11% to 79.8 kWh/(m^2-yr), yielding a total EUI and CEI reduction of 25% and 28.5% over the Base Case, respectively.

The third finding is that the Optimisation Scenario is significantly less energy use and carbon emissions intensive. The EUI is further reduced to 76.5 kWh/(m^2-yr) (with 28% reduction over the Base Case), and the CEI is further reduced to 23.12kg/(m^2-yr). The combination of cooking gas and appliances (which are not included in some definitions elsewhere) account for over half of the building energy use (52.59%). This ideal case considers the use of more advanced PV and wind turbines, which together help to further reduce the net EUI by 30% to 53.88kWh/(m^2-yr), yielding a total EUI and CEI reduction of 49% and 58.3% over the Base Case, respectively.

According to the above-summarised findings it is concluded that the maximum potential of achieving technically feasible reductions is 49% EUI (52.72 kWh/(m^2-yr)) and 58.3% CEI (32.39 kg/(m^2-yr)), through the integration of passive design, efficiency, behavioural changes and renewable energy. This represents very low energy and low carbon high-rise residential buildings, particularly for a hot-and-humid climate. However, it is also concluded that it is technically not feasible to achieve net-zero carbon or net-zero energy for high-rise public residential buildings in Hong Kong given the current carbon-intensive energy supply and the renewable energy and carbon reduction technologies presently available in the market.

4.2.2 Private office building

The first finding is that the Base Case, albeit representing very green office buildings, is still energy use and carbon emission intensive. The EUI is 282.4kWh/(m^2-yr) covering, and the CEI is 197.7 kg/(m^2-yr). At first glance, this EUI greatly challenges the feasibility of achieving net zero energy or net zero carbon. Due to the hot-and-humid (hence the need for significant cooling) and high-rise (hence the need for lifts) features of office buildings in Hong Kong, the EUI is unavoidably much higher than that of low to medium-rise office buildings in temperate climates. These findings explain the perceived infeasibility of and apparent great challenge to delivering net zero carbon office buildings in Hong Kong.

The second finding is that the Quick-Win Scenario is substantially less energy use and carbon emission intensive than the Base Case. The EUI is reduced to 188.86 kWh/(m^2-yr) (with 33% reduction over the Base Case), and the CEI is reduced to 124.96 kg/(m^2-yr). This technically optimised case considers the use of PV and wind turbines, which together help to further reduce the net EUI by 7.1% to 175.5 kWh/(m^2-yr), yielding a total EUI and CEI reduction of 38% and 38%, respectively, over the Base Case.

The third finding is that the Optimization Scenario is significantly less energy use and carbon emissions intensive. The EUI is further reduced to 149.52 kWh/(m^2-yr) (with 47% reduction over the Base Case), and the CEI is further reduced to 84.14 kg/(m^2-yr). This ideal case also considers the use of PV and wind turbines, which together help to further reduce the net EUI by 19.65% to 120.2 kWh/(m^2-yr), yielding a total EUI and CEI reduction of 57% and 57%, respectively, over the Base Case.

According to the above-summarised findings it is concluded that the maximum potential of achieving technically feasible reductions is 57% EUI (162.2 kWh/(m^2-yr)) and 57% CEI (113.56 kg/(m^2-yr)), through the integration of passive design, efficiency, behavioural changes and renewable energy. This represents very low energy and low carbon high-rise office buildings, particularly for a hot-and-humid climate. However, it is also concluded that it is technically not feasible to achieve net-zero carbon or net-zero energy for high-rise private office buildings in Hong Kong given the current carbon-intensive energy supply and the renewable energy and carbon reduction technologies presently available in the market.

4.2.3 High-rise L/ZCB strategic scenarios

To achieve high-rise net zero carbon in the long term, more efficient or emerging renewable energy technologies and/or decarbonisation technologies must be explored and adopted, of which two strategic scenarios are developed:

- Emerging Renewable Scenario, which is based on the Optimisation Scenario but further takes into account emerging renewable energy technologies such as CCHP and FC, that together may further reduce the net energy use (hence net carbon emissions) of the building towards zero or negative;
- Decarbonisation Scenario, which is also based on the Optimisation Scenario but in addition takes into account measures such as decarbonised electricity generation, changing the fuel mix, CCS, and planting trees, that together may further reduce the net carbon emissions of the building towards zero or negative.

It is more realistic to integrate some of the technologies and measures proposed for the two strategic scenarios in order to more effectively achieve energy use and carbon emissions reductions, while addressing the non-technical feasibility aspects.

4.3 High-rise L/ZCB Non-technical Feasibility

The non-technical feasibility aspects, namely socio-cultural preference, commercial viability, supply chain competency, and statutory and regulatory acceptance, are found to be interactive, dynamic and value-laden.

They interact with each other, and as a whole interact with the technical feasibility. Socio-cultural preference is largely shaped and guided by political and regulatory acceptance. Supply chain competency has an important implication for commercial viability. The technical feasibility will determine the commercial viability. The relevant technical scenarios and design solutions will be governed by the political agenda and regulatory framework, and if adopted will be influenced by the other aspects.

Being dynamic, the degree of feasibility of the non-technical aspects depends on the technical scenarios and design solutions developed. Although the Quick-Win Scenarios are developed using more established efficiency and renewable technologies, the Optimisation Scenarios are based more on predicted behavioural changes and adopt more advanced renewable energy technologies, thus being open to more uncertainties. The two strategic scenarios find themselves more exposed to political, economic, socio-cultural and technological risks.

Being value-laden, how the non-technical feasibility aspects are perceived by different stakeholders depends on their respective interests in the multi-dimensional aspects of the complex systems boundaries of L/ZCBs.

Nevertheless, statutory and regulatory acceptance was considered to be fundamental and the most important of all the non-technical feasibility aspects involved in delivering high-rise L/ZCB in Hong Kong, as it will largely shape and guide the socio-cultural preferences. A clear and ambitious carbon reduction target can motivate both the industry and the market for L/ZCB. This will then enhance the supply chain competency. Also, the government itself is a major client for buildings in Hong Kong, so the government can take the lead in adopting the developed technical scenarios and design solutions and nurture a sharing culture within the industry.

4.4 High-rise L/ZCB Design Strategies

A wide range of high-rise L/ZCB design strategies have been developed, and these are grouped under the themes of ten elements below.

1. Reduce and minimize energy demand by user behaviour changes, e.g. reasonably increase the cooling set point
2. Reduce energy loss through the building envelope in a dynamic trade-off with natural lighting, e.g. reduce heat gain and adopt overhangs and side-fins
3. Reduce and minimize energy use for M&E systems, e.g. adopt LED and lighting controls, and increase the COP of air conditioners
4. Reduce and minimize energy use for appliances, e.g. adopt higher efficiency appliances, or adopt town gas driven appliances
5. Reduce and minimize energy loss in transmission or explore town gas driven counterparts
6. Decarbonise energy production and supply, e.g. decarbonise electricity generation by using CCS, change the fuel mix, and use bio-fuel
7. Adopt and maximise on-site renewable energy generation in a dynamic trade-off with land, space and view availability, e.g. adopt BIPV, explore CCHP
8. Adopt and maximise off-site renewable energy generation in a dynamic trade-off with land and space availability and energy loss in transmission, e.g. adopt DCS, solar farm
9. Adopt accredited renewable energy and/or carbon reductions, e.g. use nuclear power, promote carbon trading
10. Adopt carbon offset, capture and storage measures, e.g. plant trees and adopt CCS in a dynamic trade-off with land and space availability

Underlying these strategies is the systems theory of dynamic integration, which is required for the possible achievement of net zero carbon in the long term. Systems optimisation is required for achieving different levels of low carbon while simultaneously addressing socio-technical trade-offs.

4.5 Recommendations for Further Research

In relation to the L/ZCB definition, further research should develop detailed descriptions to elaborate on the scope of energy use and carbon emissions by addressing their systems boundaries, which will allow effective benchmarking and learning. Further research along this line should also firm up the Hong Kong L/ZCB definition as a model for other high-density and/or hot-and-humid urban environments, contributing to a worldwide consistent understanding of net zero.

With regard to the technical feasibility of high-rise L/ZCB in Hong Kong, further research should explore the following areas:

- A comprehensive user behaviour survey should be conducted to fully understand how occupants use their building, especially about their schedule at home, tolerance of high temperature and humidity, use of fan and air-conditioner, and preferences with regard to lower SHGC and WWR in a trade-off with viewing and natural lighting. The survey could also examine the possibility of making the release of energy use data a legal requirement. Incorporating smart metering technology into the building design should be useful.
- A study should investigate the construction and installation of prefabricated wall panels that incorporate horizontal PV panels, larger air-conditioner platforms, and solar hot water preheat systems. The potential for improving the morphological design of corridors and corresponding unit arrangements can also be explored, as the current corridor design in public housing has few open exterior walls, resulting in relatively higher lighting energy use in the communal areas.
- More efficient and emerging renewable energy technologies should be explored to reveal how they could be effectively applied to buildings in Hong Kong, and to what extent they will contribute to energy use and carbon reduction in the future.
- Decarbonisation technologies and measures should also be explored to reveal how they could be effectively applied to buildings in Hong Kong and the extent to which they will contribute to carbon emission reduction in the future.
- To address accuracy issues with data conversion, and to develop a user-friendly interface for possible industry take-up for productivity, the process of integrating BIM with energy simulation should be investigated.

With regard to the non-technical feasibility of high-rise L/ZCB in Hong Kong, further research should explore the following areas:

- A cost Base Case should be developed using the technical Base Case of the buildings studied, based on which any cost increase or decrease should be quantified for both the Quick-Win and Optimisation Scenarios and the Emerging Renewable and Decarbonisation strategic scenarios.
- L/ZCB policy for Hong Kong should be examined, both to mitigate the risks and to maximise the opportunities for the formulation of such a possible policy, in order to create a more encouraging policy context for the achievement of the L/ZCB scenarios developed in this study.

4.6 Way Forward

Although it is still technically infeasible to achieve net-zero carbon or net-zero energy, the developed Quick-Win and Optimisation Scenarios for both high-rise public residential and private office buildings in Hong Kong nevertheless achieve significant reductions through the integration of passive design, efficiency, behavioural changes and renewable energy. For high-rise public residential buildings, the maximum potentials of reductions are 49% EUI (52.72 kWh/(m^2-yr)) and 58.3% CEI (32.39 kg/(m^2-yr)), and for high-rise private office buildings the maximum potentials of reductions are 57% EUI (162.2 kWh/(m^2-yr)) and 57% CEI (113.56 kg/(m^2-yr)), which are significant. Both of these represent very low energy and low carbon high-rise buildings, particularly in such a hot-and-humid climate.

- The industry, via CIC, should raise awareness of these scenarios and design solutions in new building planning and design. The industry, via HKGBC and BEAM Society, may take as a reference point these scenarios and design solutions in future revisions of the BEAM Plus scheme.
- The industry should also establish a performance database or portal, and nurture a sharing culture, as sharing performance data and good practices, as well as lessons learned, are critical to understanding and exploring emerging renewable energy technologies.
- Universities should continue exploring systems theory within the context of high-rise L/ZCB. Universities and institutions should integrate L/ZCB into their curricula and programmes, as education is fundamental to shaping user behaviours, changing the design practices of professionals, raising awareness and ensuring that client investment decisions are properly founded.
- The government should implement its proposed fuel mix and consider adopting a L/ZCB policy, as decarbonising electricity generation and changing the fuel mix for energy supply are crucial to achieving net zero carbon in the long term.
- Government, industry and university stakeholder groups should work together to further explore the two strategic scenarios, namely, the Emerging Renewable and the Decarbonisation Scenarios, together with their underlying technologies and solutions for addressing the socio-technical aspects of their feasibility.

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