Potentials of Energy Efficiency and Generation Strategies for High-rise Office Buildings in Hong Kong

YU Cong[a], PAN Wei[b]

[a] *The University of Hong Kong, Hong Kong SAR, yucong@connect.hku.hk*
[b] *The University of Hong Kong, Hong Kong SAR, wpan@hku.hk*

ABSTRACT

Office buildings are a major building type responsible for a large proportion of the total electricity consumption in Hong Kong where most office buildings are high-rise due to the scarce developable land resources. There are more limitations to the selection of energy saving strategies for high-rise office buildings compared with low or medium ones, as high-rises are associated with more complex design on the fabric, envelope and service systems. It is therefore vital to explore measures for reducing energy consumption of high-rise office buildings.

This paper aims to examine the potential of energy efficiency and generation strategies for high-rise office buildings in Hong Kong, and to develop scenario-based design strategies. A reference building model was first established using a typical real-life high-rise office building in Hong Kong. Using the reference building, the energy consumption was estimated with the aid of the energy simulation tools DesignBuilder and EnergyPlus. The potential of various energy saving and generation strategies was then investigated using the reference building and the tools. The strategies included chiller system selection, daylighting control, cooling setpoint temperature, PV system, and wind system. The results show that adopting water-cooled HVAC type and daylighting control system can reduce approximately 10% and 11% of the total energy consumption, respectively. The cooling setpoint was found to lead to an energy use saving by 4%. The use of PV systems was found to offset 4% of the total building energy use. The wind turbine however was found to have little effect on energy efficiency. The strategies together can help achieve up to 30% of building energy use reduction, yielding an optimised scenario. The findings inform future high-rise energy use parametric research and are useful to engineers for designing energy-efficient office buildings. Future research should also explore building fabric measures in order to maximise energy reduction potential.

Keywords: *energy use, energy modelling, high-rise office building*

1. INTRODUCTION

Buildings are proved to be the biggest single contributor to total energy consumption in many countries, accounting for as much as half of their primary energy resources (Pan and Garmston 2012). Commercial buildings account for a substantial proportion of energy consumption in Hong Kong. According to the Hong Kong Energy End-use Data published by EMSD (2015), electricity consumption in the commercial sector rose by 19.5% from 84921 Terajoule in 2003 to 101480 Terajoule in 2013. Due to the scarce developable land resources in Hong Kong, the majority of buildings in the city are high-rise; approximately one in five are office buildings, which offer a considerable energy saving potential (Rating & Valuation Department 2000). To realize such potential, it is vital to examine the existing building's energy performance and make comparison with the estimated energy performance of buildings with energy saving strategies. There has been increasing pressure on architects and engineers to design more energy-efficient buildings and building services systems (Yu and Chow 2007, Lam, Wan et al. 2008, Pan 2014). However, there is a limited understanding of the selection of energy-saving measures for high-rise office buildings that require more complex designs for both building fabric and building services compared with low or medium-rise counterparts (Pan, Qin et al. 2016).

It is generally accepted that computer energy analysis techniques are valuable design tools for the design and analysis of buildings and building services installations, particularly for large office buildings. DesignBuilder and EnergyPlus are two typical examples of widely used computer simulation tools for estimating buildings' energy consumption. This paper aims to examine the potential of energy efficiency and generation strategies for high-rise office buildings in Hong Kong, and to develop scenario-based design strategies. For this research, a typical real-life high-rise office building in Hong Kong was selected to be the reference building for investigating measures that affect energy consumption. Five energy strategies, namely, chiller system selection, daylighting control, cooling setpoint temperature, PV system and wind system, were analysed utilizing the tools DesignBuilder and EnergyPlus.

Integrating the results, the paper presents an optimised scenario with maximised energy use reduction from employing these energy efficient measures and draws conclusions.

2. THE REFERENCE BUILDING

Hong Kong Monthly Digest of Statistics (2016) conducted a survey of investigating the existing commercial buildings. It contains the existing buildings basic information in Hong Kong, for instance, building construction, address, number of storeys, building cost, usable floor area and gross floor area. The most prevailing storeys in Hong Kong were found to be between 20 storeys to 40 storeys through the Hong Kong Monthly Digest. Lam (2000) considered that the main type of high-rise office buildings in Hong Kong is with either square or rectangular configurations. Therefore, a 26-storey office building (Figure 1) with square configurations located in Kowloon was selected as the reference building to represent the typical office buildings in Hong Kong for investigating the potentials of energy efficiency and generation strategies. Due to the limited access to the actual metered energy use data, a top-down approach was adopted to establish the reference energy model by using the end-use energy distributions reported by EMSD (2015). 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.

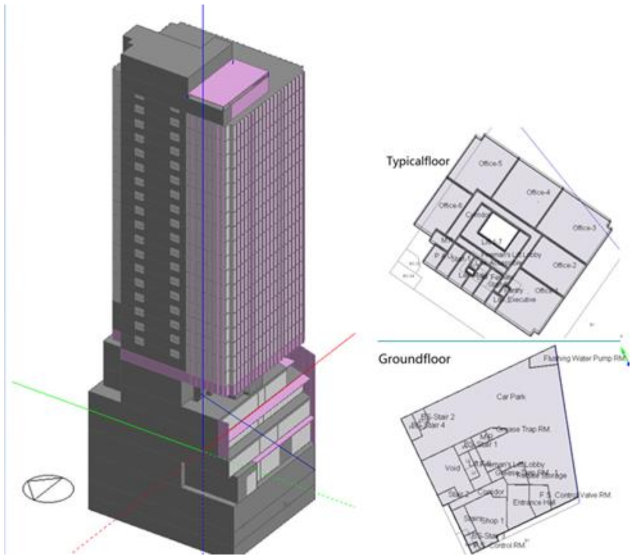

Figure 1: The private office case building and composition of different floors

This building has a total of 26 storeys that the podium layer (1 - 5F) is used for food and beverage and the tower part (6F - 26F) is designated used for offices. The office is designed as core tube type that it has a core area to place lift and lobbies and equipment room surrounded with open office area. This building has the overall area above ground 24698.74m^2; underground 4603.43m^2. The geometric model was built by the architectural drawings and design specifications. The data inputs of the energy model of the prototype were based on the 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 2007). The weather file used in the energy simulation is provided by Energy Plus weather database (CHN_Hong.Kong.SAR.450070_CityUHK.epw). The office is assumed to be opened from 9 am to 6 pm from Mondays to Fridays and from 9 am to 12 am on Saturdays. Occupancy and operation schedules from PB-BEC are used in this study. The lighting of parking is assumed to be on operation all day. The minimum shading coefficient is 0.25. Lighting luminance is 300 Lux for office building according to the Standard for Lighting Design of Buildings (GB50034 2004). The design temperature in summer is assumed as 24°C.

Cooling is provided by a set of centrifugal chillers and no heating is provided. Air Handling Unit (AHU) is adaptable in the spacious space because it provides both fresh air and returned air. All the food areas at 1 - 3F are served by AHU system with variable speed control. However, due to the limited height in the office room, the FCU (Fan Coil Unit) system has smaller size than AHU system. Thus, all the office areas at 6 - 26F are served by FCU system with dedicated outdoor air system. A split-type AC system is provided for the control room since the control room does not have the same schedule compared with other areas. The VRF (Variable Refrigerator Flow) system is used by management office in 1F and lift machine room in 18/ 19F. Table 1 displays the input parameters of the reference building.

Item	Details
Building Type	High-rise office building
Location	Kowloon, Hong Kong, China
Building Height	112.75m (26 above ground, 3 basements)
U value (W/m²K)	Opaque Wall 3.3, Below grade walls 1.99, Window 1.57, Opaque Roof 0.39
Curtain wall type	Low-E Glass with SC=0.25, VLT=42
Fresh air rate	Office, lobby, corridor, retail area 10 l/s/person, parking & mechanical room 6 ACH, restroom 15 ACH, kitchen 50 ACH
Equipment power density	Office 25 W/m², retail-sales area 15 W/m², restaurant 20 W/person
Occupancy density (m²/persons)	Office 8, lobby 10, restaurant 5, corridor 50
Lighting power density (W/m²)	Lobby 14, office 17, parking 2, corridor 5, restroom 10

Table 1: Input parameters of the reference building

3. ENERGY USE IN THE REFERENCE BUILDING

The reference building was established through an iterative process and energy simulation and verification drawing on EMSD released end-use energy data and engagement with professionals. The EUI was estimated to be 282.4 kWh/m², and covered in order of significance, cooling electricity (41.9%), fans (23.6%), appliances (17.5%), interior lighting (16.5%), and then pumps (0.4%) (Figure 2).

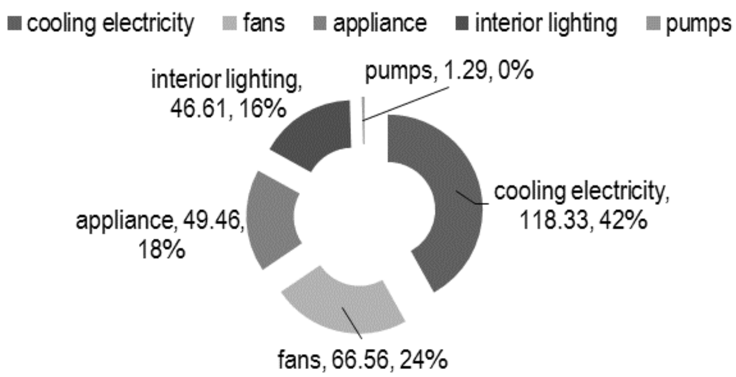

Figure 2: Energy use of the reference building (kWh/m²)

The whole energy use is in agreement with that reported in previous studies, e.g. 259.2 kWh/m² by (Yu and Chow 2007). The total HVAC system consumes 66% of the overall energy use, which reveals substantial energy saving potential. Energy use of appliances is mainly caused by the use of office equipment, such as computers, printers and so on, and also depends on human behaviours with uncertainties to a great extent. The appliances are therefore not considered in the analysis in this paper. Although the proportion of interior lighting is not high (16%), it still has the conservation space by adopting the energy efficiency measures.

4. ANALYSES OF ENERGY EFFICIENT STRATEGIES

Previous studies indicated that the following strategies showed remarkable energy saving potential. Those are chiller system selection, daylighting control, cooling setpoint temperature, PV system and wind system. Ellis and Mathews (2002) estimated that energy savings could be maximum around 70% through the use of better design technologies to coordinate the building demand with its HVAC system capacity. The Hong Kong government, with the support of EMSD, encourages the owners of non-domestic premises to use water-cooled chiller system (EMSD 2015). Yu and Chow (2007) modelled daylighting for offices using Trance 600 and found that applying daylighting strategy will save as much as 41% of the lighting energy use and 16% of the overall building energy use. In the year 2006, the Hong Kong Environmental Protecting Department (EPD 2006) suggested a recommended temperature (25.5°C) of the indoor cooling setpoint temperature to reduce the energy use. There is a belief that operating at the high end of this range or above it will reduce the total energy use in the office buildings by making the cooling system more efficient. Fong and Lee (2015) indicated that the high-rise office buildings in Hong Kong had the energy saving potentials by adopting PV system. However, based on site survey, the existing office buildings in Hong Kong are normally air-cooled with low temperature and do not utilize daylighting control or energy generation strategies. It is significant to analyze whether these strategies are still applicable in Hong Kong. Therefore, the energy efficiency and generation strategies investigated in this paper are: (1) Chiller plant system optimisation, (2) Indoor air setpoint temperature, (3) Daylighting control, (4) Photovoltaic system, and (5) Wind power generation. The design parameters of these five strategies are listed in Table 2. Table 3 displays the energy saving comparison of five energy saving measures. By adopting these energy efficient strategies, the performance of energy use for the high-rise office building ranged to different extents as detail explained below.

Energy saving strategies	Original	Optimisation
Chiller type optimisation	Air-cooled with COP 3	Water cooled with COP 5
Indoor air setpoint temperature	24℃	26℃
Daylighting control system	No	Yes
PV panels & BIPV	No	Roof (15% efficiency) and facades (4.5% efficiency)
Wind turbine	No	Roof

Table 2: Design parameters of five strategies

	Water-cooled chiller	Indoor air setpoint temperature	Daylighting control	Original	PV system	Wind turbine
HVAC system (kWh/m^2)	157.43 (-15.44%)	171.20 (-8.04%)	177.57 (-4.62%)	186.18 (0%)		
- Cooling	71.45	105.35	110.37	118.33		
- Fans	66.56	64.63	65.91	66.56		
- Pumps	11.46	1.23	1.29	1.29		
- Heat Rejection	7.96	0.00	0.00	0.00		
Interior Lighting (kWh/m^2)	46.43 (0%)	46.61 (0%)	25.03 (-46.30%)	46.61 (0%)		
Interior Equipment (kWh/m^2)	49.34	49.46	49.46	49.46		
Electricity generation (kWh/m^2)	0	0	0	0	-11.64	-1.72
Total End Uses (kWh/m^2)	253.34 (-10.29%)	270.41 (-4.25%)	252.06 (-10.74%)	282.40 (0%)	270.76 (-4.1%)	280.68 (-0.35%)

Table 3: Comparison of energy saving measures

Ciller plant system optimisation (Compared with water-cooled chiller)

Most existing commercial buildings in Hong Kong adopt air-cooled chiller system with a typical COP of 3, which is adopted for the reference building. The government, with the support of EMSD, encourage the owners of non-domestic premises to use water-cooled chiller system by joining Scheme for Wider Use of Fresh Water in Cooling Towers in Air Conditioning Systems for their fresh water cooling towers installations (EMSD 2015). Water-cooled chiller systems are therefore adopted with the COP of 5, which are analysed in comparison with the air-cooled system.

The scenario adopting water-cooled chiller system consumes much lower energy (282.4 kWh/m^2) than the reference building adopting air-cooled chiller system (253 kWh/m^2). This is mainly because of the significantly reduced (by 65.6%) cooling energy of the water-cooled chiller (71.45 kWh/m^2) from that of the air-cooled chiller (118.33 kWh/m^2).

Indoor air setpoint temperature (24°C to 26°C)

Theoretically, the higher indoor air setpoint temperature will lead to the lower cooling demand, and thus it will save energy. However, the consideration of the conflict between human comfort degree and energy saving is significant as well. By comprehensive consideration, the recommended cooling setpoint is set as 26°C. The cooling setpoint was found to lead to an energy use saving by 4%.

Daylighting control in office area

Daylight control is an energy management technique that reduces overhead lighting use by utilizing the ambient (natural & artificial) light present in a space and dimming or switching off lighting when sufficient ambient light is present or when space is unoccupied. It is quite useful in the open office area with plenty of windows. Daylighting control is proved to be a good strategy to decrease the overall building's energy consumption by around 11%.

Photovoltaic system

The electricity generation of PV system would be closely related to the availability of solar irradiation of a place. In this paper, the building-integrated photovoltaics (BIPV) on facades and PV panels on the roof are investigated. BIPV and PV panels for the reference building are assumed with the efficiency rate of 4.5% and 15% respectively. Seventy-two solar cells in each m-si PV module. The size of the solar cells is 125 mm × 125 mm. Table 4 displays the detail input parameters for PV system at standard testing conditions. The annual cumulative global solar radiations on the vertical walls facing different directions are investigated. The result indicates that the PV system can generate 11.64 kWh/m^2 electricity annually, which can afford approximately 4% of the overall energy use.

System	BIPV system (facade)	PV system (roof)
Solar cell type	a-si	m-si
Rated power at the maximum power point (P_{mp})	105 W	180 W
Rated voltage at the maximum power point (V_{mp})	30.2 V	35 V
Rated current at the maximum power point (I_{mp})	3.48 A	5.14 A
Open-circuit voltage (V_{oc})	38.8 V	43.5 V
Short-circuit current (I_{sc})	4.3 A	5.53 A
Size of module	1.4 m ×1.1 m×7 mm	1.580 m × 0.808 m× 50 mm
Temperature coefficients of I_{sc}	0.00559 A/K	0.002765 A/K
Temperature coefficients of V_{oc}	-0.13968 V/K	-0.1479 V/K
Photovoltaic efficiency	6.8 %	14 %

Table 4: The operational data of a-si and m-si PV modules at standard testing conditions (STC) (AM1.5, 1000 W/m^2, 298 K)

Wind power generation

Wind velocity at the height of wind turbine rotor center can be calculated by V = VTMY(Z/ZTMY)1/7. Where, VTMY is the wind velocity at the data collection site, here wind velocity in the TMY weather data used, m/s; Z and ZTMY are the wind turbine rotor center height and data collection site height, respectively. The annual average wind speed: 7.3 m/s (113 m) 7.4 m/s (124 m). Detail information is showed in Table 5. The result shows that the wind turbine has little effect on the energy use.

Manufacturer	Windspot
Model	Windspot 3.5kW
Rated power	3.5 kW
Reference annual energy output	18 MWh
Cut-in wind speed	3 m/s
Rated wind speed	12 m/s
Cut-out wind speed	20 m/s
Rotor diameter	4.05 m
Hub height	12 m

Table 5: Details of the small horizontal axis wind turbine (HAWT)

5. CONCLUSION

The reference high-rise office building was established through an iterative process and energy simulation and verification drawing on EMSD released end-use energy data and engagement with professionals. The EUI of the building was estimated to be 282.4kWh/m^2, and covered in order of significance, cooling electricity (41.9%), fans (23.6%), appliances (17.5%), interior lighting (16.5%), and pumps (0.4%).

Five energy strategies, namely, change of chiller type, daylighting control, increase of cooling setpoint temperature, PV systems and wind turbine, were then investigated. By adopting these strategies individually, the EUI was found to range from 252 to 282.4kWh/m^2/year. More specifically, the adoption of water-cooled HVAC type and daylighting control system can reduce approximately 10% and 11% of the total energy consumption, respectively. The cooling setpoint was found to lead to an energy use saving by 4%. The use of PV systems was found to offset 4% of the total building energy use. The wind turbine, however, was found to have little effect on energy efficiency. Thus, should the four measures (i.e. excluding wind turbine) be adopted, the building's energy use reduction could sum up to 30%, yielding an optimized scenario. Nevertheless, further energy use reduction can be enabled through addressing passive energy saving factors such as building design and fabric (e.g. envelope, infiltration), which should be explored in future research.

The findings contribute to a better understanding of the energy saving measures influencing energy use in high-rise office buildings and should inform energy-efficient building design in urban contexts. These findings have significant implications for future high-rise energy use parametric research and practices of engineers and architects in both building initial design and retrofit stages.

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