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Improving Accuracy on Energy Use for High-rise Office Buildings via Considering Microclimate Effect

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ABSTRACT

Increasing attention is paid to the influence of microclimate factors on building energy use. However, there is limited research focusing on high-rise office buildings. This study aims to analyse the accuracy of building energy performance for high-rise office buildings by considering microclimate factors. A real-life high-rise office building located in Hong Kong was selected as the case building. One-year onsite measurement for five microclimate factors was conducted. Three scenarios were considered to evaluate the microclimate effect on building energy use. By using different weather datasets, the deviation of the total building energy use is around 3%, while the deviation of the cooling energy use can be up to 7.9%. The results emphasise the importance of considering the urban microclimate effects on energy consumption.

Keywords: building energy use, high-rise office buildings, microclimate

NONMENCLATURE

Abbreviations	
TMY	Typical Meteorological Year
CHTC	Convective Heat Transfer Coefficients
UHI	Urban Heat Island
GFA	Gross Floor Area
HKO	Hong Kong Observatory
FCU	Fan Coil Unit
VRF	Variable Refrigerator Flow
BMS	Building Management System

1. INTRODUCTION

The influence of microclimate on building energy consumption has shown increasing attention during past years. Previous studies have analysed the influence of different microclimate factors on building energy use from different angles. For example, Hsieh et al [1] concluded that higher outside temperature could increase the building cooling load in the city center. Lee and Jeong [2] found that wind speed and relative humidity are the two most important microclimate factors that influence building energy consumption in Beijing. de La Flor and Domınguez [3] suggested considering air temperature, humidity, wind speed, wind direction and solar radiation in building energy-related research. Ca et al [4] measured air temperature, relative humidity, wind, foliage temperature and surface temperatures and found a 15% cooling demand reduction achieved at noon through modelling of a four-storey building. Allegrini et al [5] emphasised the importance of urban radiation balance, the urban heat island and urban convective heat transfer coefficients (CHTC) on cooling demand. Allegrini et al [6] also found that solar irradiance is the most sensitive microclimatic factor in building energy consumption. Allegrini et al [7] analysed the shortwave solar and longwave radiation in the urban street canyons on cooling and heating demand and found that the strong correlation in energy demand is due to the shading devices strategies. Moonen et al [8] summarized the difference in microclimate factors between an isolated building and a building in an urban area with surroundings.

Urban heat island (UHI) was identified to be another key issue that influences building energy consumption [9], ranging from 15% to 200% [10]. Li et al [11] considered four factors including UHI and found that microclimate factors accounted for about 11% of total summer electricity consumption in Beijing in 2005. Radhi and Sharples [12] assessed wind flow, air temperature and heat distribution fluxes in Bahrain, resulting in a maximum 10% increase in cooling use from April to October in urban regions. Magli et al [13] compared the energy load for a commercial building using hourly air

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temperature data from rural and urban weather stations in Italy and found a 20% reduction in heating load and a 10% increase in cooling load in urban areas. Similarly, in Boston, Street et al [14] analysed data from one urban and two rural weather stations, showing a 14% decrease in heating loads and a 3-9% increase in cooling loads for detached houses. However, some researchers found no correlation between outdoor air temperature and electricity use in the US when investigating four low-rise university buildings [15].

These positive developments in measuring the influence of microclimate factors on energy consumption showed that urban microclimate is one of the important effects influencing building energy consumption. However, high-rise office buildings were seldom analysed in the energy simulation from the perspective of urban microclimate. High-rise office buildings are a major contributor to energy consumption in high-density urban contexts, such as Hong Kong, where high-rises are often the norm [16]. How the microclimate conditions perform on energy consumption in high-rise office buildings in such a high-density area remained vague. Thus, it is important to analyse the effect of microclimate on energy consumption in high-rise office buildings. This paper aims to evaluate the influence of urban microclimate on the energy consumption in high-rise office buildings in Hong Kong. Three scenarios were compared by using three conventional weather datasets. One is from the rooftop real-time monitoring. One is the TMY data obtained from the official website. The last one is obtained from the nearest official observatory.

2. METHODOLOGY

2.1 Overall process

A 26-story private office building with mixed-use functions located in the city center of Hong Kong was selected as the base case. This building adopted concrete construction with a gross floor area (GFA) of 29,305 m2 (above ground 24,700 m2; underground 4,605 m2) and represents the status quo of typical private office building designs in Hong Kong. Out of the total 26 stories, the podium layers (1-5F) are used for food and beverage purposes and the tower part (6F-26F) is designated for offices.

EnergyPlus is a widely used building energy simulation tool developed by the Lawrence Berkeley National Laboratory in the US [17], and was used in this study to model the selected building. DesignBuilder, developed based on EnergyPlus, was used to establish the building model [18].

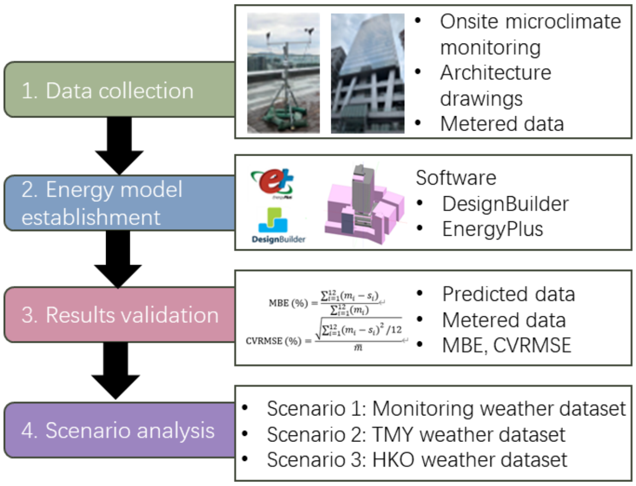

Fig. 1. Flowchart of the overall process

This study mainly engaged four research steps: (1) collect data on energy-related parameters, (2) establish the base case energy model, (3) validate results, and (4) conduct scenario analysis (Fig. 1).

2.2 Data collection

2.2.1 Weather datasets collection

This study utilises the three conventional weather datasets to estimate building energy use and compares the difference in building energy use. The first weather dataset is the TMY (Typical Meteorological Year) data which was obtained from the official website. The second weather dataset is the monitoring data obtained from the rooftop microclimate weather station. The third weather dataset was obtained from the nearest Hong Kong Observatory (HKO weather dataset).

One weather station was established on the rooftop of this 26-storey office building, as displayed in Fig 1. The station comprised a battery-powered self-standing data logger and five sensors. The measured items include air temperature, air humidity, wind velocity, wind direction, and global solar irradiance. It measures these elements every 15 minutes and restores data in the data logger. The measured duration time is from June 2018 to May 2019.

2.2.2 Building physical data collection

The building physical data, such as the construction materials, the layout, the internal loads, were obtained based on the architecture drawings and onsite survey, as listed in Table 1. The base case was designed as a core tube type that has a core area to place lifts and lobbies and an equipment room surrounded by an open office area. Lighting luminance was 300 lux for office buildings according to the GB50034 [19]. A set of centrifugal water-cooled chillers were applied. All the office areas at 6-26F were served by a fan coil unit (FCU) system with a dedicated outdoor air system. A split-type AC system was provided for the control room. The variable refrigerator flow (VRF) system was used in the management office and lift machine room. The public space of the office building was served with the FCU system. Equipment rooms and corridors adopted mechanical ventilation without air-conditioning.

Table 1. Basic information of the base case building

Item	Details
Building Type	High-rise office building
Building footprint	1486.4 m^2
Building height	112.75m
Floors	26 above grade, 3 basements
Weighted U-value ($W/m^2{\cdot}K$)	Opaque wall 1.7, window 1.6, below grade walls 1.99, opaque roof 0.5
Window (Curtain wall)	Low-E glass with double glazing, SC=0.4, VLT=42
Occupancy density (m^2/persons)	Lobby 10, office 8, retail-sales area 10, restaurant 5, corridor 50, parking 50, mechanical room 20, restroom 20
Lighting power density (W/m^2)	Lobby 14, office 11, retail-sales area 18, restaurant 21, corridor 5, parking 2, mechanical room 16, restroom 10
Design indoor temperature	23℃ with 55% humidity
Fresh air rate	Office 10 l/s/person, parking and mechanical room 6 ach, restroom 15 ach

2.2.3 Metered data collection

Metered data were obtained through the building management system (BMS), which reported every 15-minute electricity energy consumption for HVAC, lighting, and equipment during the observation period (Fig. 2). The raw metered data could not be used directly because of some wrong or missing data. This study thus processed the raw data by excluding the incorrect data and adopting the interpolation method to fill in the missing data. The HVAC was found to account for the majority of total energy consumption throughout the year. Because of the characteristics of the newly built building such as the changeable occupancy rate and the decoration circumstance, the fluctuation of the total energy consumption of this building was unlike other previous variations of buildings in Hong Kong. The majority of the total energy consumption was found to fluctuate from above 9000 kWh to around 30,000 kWh.

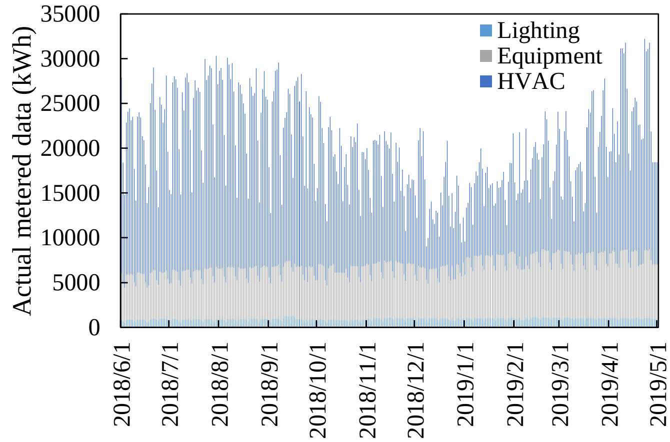

Fig. 2. Daily energy consumption of metered data for lighting/equipment/HVAC during the observation period

2.3 Building energy model establishment

A detailed energy model with precise building geometry, space division, façade configuration and system specification was built using the energy simulation software DesignBuilder (Fig. 3). Notably, the nearby buildings were considered and modelled in this paper. Internal window blind control and daylighting control systems were also considered to reflect the real environment. The geometric model was developed using architectural drawings and design specifications. To reduce the problematic time and analyse data conveniently, this research simplified the model by defining a typical floor to represent the twenty-one floors since these floors (6F-26F) for the tower part only have subtle distinctions.

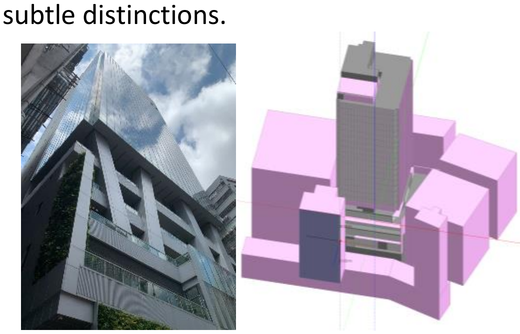

Fig. 3. Appearance and model of base case building with surroundings built by DesignBuilder

2.4 Results validation method

Building energy model by using the weather datasets obtained from the rooftop monitoring was selected as the base case model to be further validated. Hourly metered data were used to calibrate the energy model.

Previous research showed that a 10% difference between the energy predictions of the model and sub-metered data was considered acceptable each month, and a 5% difference was acceptable when comparing the data on an annual scale [20]. Standard ASHRAE Guideline 14 also displays that the monthly criteria of the Mean Bias Error (MBE) should be within 5% and the Coefficient of Variation of Root Mean Square Error (CVRMSE) should be within 15% (Eq. (1), Eq. (2)). The MBE is a suitable indicator of measuring the overall bias in the model, and the CVRMSE is also a widely used indicator since it allows one to determine how well a model fits the data by capturing offsetting errors between measured and simulated data [21].

$$\text{MBE}\ (\%) = \frac{\sum_{i=1}^{12}(m_i - s_i)}{\sum_{i=1}^{12}(m_i)} \quad \text{Eq. (1)}$$

$$\text{CVRMSE}\ (\%) = \frac{\sqrt{\sum_{i=1}^{12}(m_i - s_i)^2/12}}{\bar{m}} \quad \text{Eq. (2)}$$

Where:

m_i respective measured data for each month

s_i respective simulated data for each month

$\bar{m}$ average of the measured data

2.5 Scenario analysis method

Three scenarios were proposed in this paper which showcase the three conventional ways to embed weather datasets into the building energy model. Scenario 1 adopted the monitored one-year microclimate data from the rooftop of the building, which is regarded as the actual data compared with the other two scenarios. Scenario 2 adopted the HKO weather datasets. Scenario 3 adopted the TMY data.

Deviation of building energy use in the result section refers to the deviation between Scenario 2/3 and Scenario 1 (Eq. 3), which shows the accuracy by using different weather datasets compared to the actual monitored data.

$$Deviation\ (\%) = \frac{E_{HKO/TMY} - E_{Actual}}{E_{HKO/TMY}} \quad \text{Eq. (3)}$$

3. RESULTS AND DISCUSSION

3.1 Model validation

The original generated energy data should be calibrated with the processed metered data to keep accuracy and reflect the real situation. To reflect the real occupancy rate, the occupancy density was calculated by multiplying the original occupancy density by the real occupancy rate (Fig. 4).

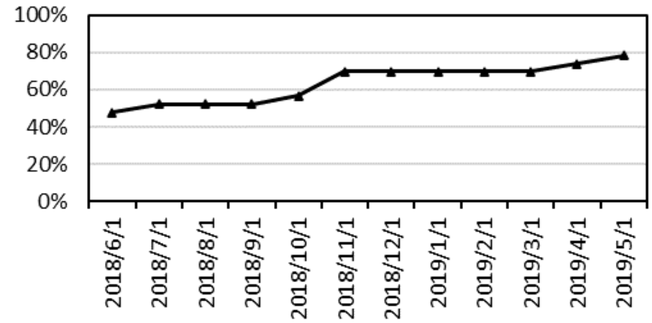

Fig. 4. Occupancy rate for the case building

The monthly simulated energy data were calibrated with the actual processed data. The error of monthly measured data is below 5% in all the calibrated months. Table 2 shows the MBE and CV RMSE results. It can be seen that MBE is within 5% and CVRMSE is within 15%, which shows the results subsequently satisfied the criteria of ASHRAE 14.

Table 2. MBE and CV RMSE results

	MBE (%)	CV RMSE (%)
HVAC	0.73	6.50
Lighting	1.09	4.22
Equipment	1.30	3.49
Total	0.91	4.93

3.2 Comparison of building energy use among the three scenarios

3.3.1 Comparison of annual building energy use

The annual building energy use of three scenarios is compared in Table 3 and Fig. 5. As shown in Table 1, the annual total building energy use by using three weather datasets is not obvious, varying from 2-3%.

Table 3. Comparison of annual total building energy use by using three weather datasets

	Scenario 1 with actual data	Scenario 2 with HKO data	Scenario 3 with TMY data
Total energy use (kWh)	7117804	6964879	6903225
Deviation (%)	/	-2.15	-3.01

Fig 5 shows that cooling energy use takes the majority percentage of the total energy use, followed by equipment and fans. Lighting, pumps, and heat rejection have a modest effect on building energy use.

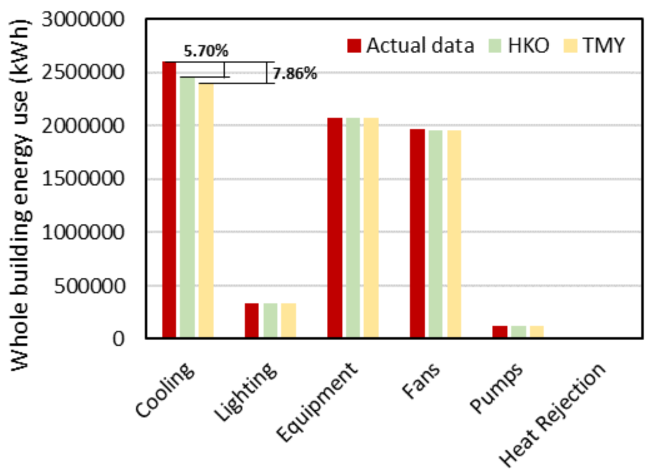

Fig. 5. Comparison of annual total building energy use by using three weather datasets

Regarding the effect of the different weather datasets, the deviation of the cooling energy use between the actual data and TMY data is 7.86%, larger than that between the actual data and HKO data (5.70%). That means that the energy results with the weather obtained from the nearest Hong Kong Observatory (HKO data) are close to the actual results. Thus, if the actual data is limited, it is more convenient to use the HKO data instead of the TMY data. Although using HKO data has a relatively small deviation, the energy discrepancy is more than 5% and cannot be ignored. This office building has several surrounding buildings which are close to this building. The inter-building effect by the surrounding buildings may be large based on our previous study [16] and thus may weaken the impact of meteorological parameters on energy consumption.

3.3.2 Comparison of monthly building energy use

Since cooling accounted for the majority of the building energy use, this study compares the monthly cooling energy use of three scenarios, listed in Fig. 6. The three scenarios share a similar total trend that the cooling energy use is large in summer and small in winter due to the use of air-conditioners. It is noted that the difference between the three results in the cooling energy use is larger in cold seasons. The monthly building energy use using HKO data is closer to the actual data. The reason may be due to that the Hong Kong Observatory is located in the city center, while the weather data from TMY was already twenty years ago [22].

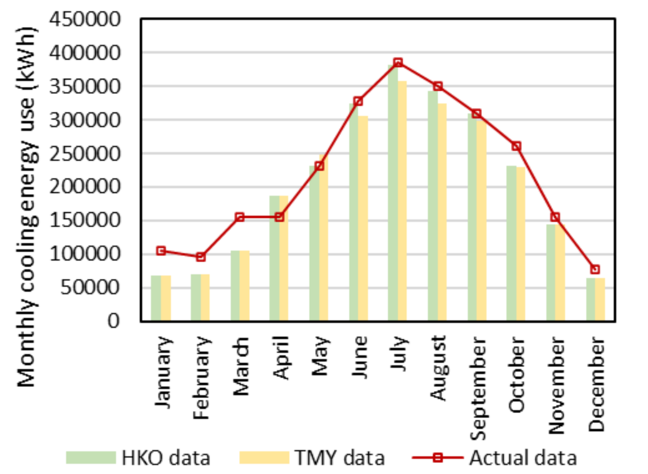

Fig. 6. Comparison of monthly cooling energy use by using three weather datasets

4. CONCLUSIONS

This study analysed the urban microclimate effects on building energy use through three scenarios. A real-life 26-storey high-rise office building is selected as the case building. One-year onsite measurement for microclimate factors was conducted, covering air temperature, relative humidity, wind speed, wind direction, and solar radiation.

Results showed that by using the three weather datasets, the deviation of the total building energy use was not obvious (around 3%). Based on this result, if the actual data is limited, it is acceptable to use the other conventional weather datasets such as the HKO data or TMY data to represent the building energy use in urban areas for modelling high-rise office buildings. However, the deviation of the cooling energy use can be up to 7.9% which shows that the microclimate factors shall be carefully considered in the building energy modelling, especially in subtropical or tropical regions with hot weather. Also, by comparing the monthly building energy use, the results showed that the deviation of the cooling energy use was large in summer and small in winter.

These findings contribute to a better understanding of the urban microclimate effects on energy consumption in Hong Kong. It appeals to the energy modelling technicians for modelling energy consumption of buildings fully considering the microclimate effects. Although the work has been conducted in Hong Kong, the technology and the procedures can be applied to other locations.

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DECLARATION OF INTEREST STATEMENT

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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