Energy Proceedings
Vol 43, 2024
ISSN 2004-2965

Impact of passive design measures on energy performance gap: A case study of high-rise residential buildings in Hong Kong

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ABSTRACT

Passive design measures were regarded as a method to address the energy performance gap (EPG) in buildings. However, there is a lack of quantification of the impact of passive design measures on the EPG. This study aims to quantify the impact of passive design measures on the EPG using a case study of high-rise residential buildings in Hong Kong. First, key passive design variables were identified through a literature review, including window-to-wall ratio and window type. Second, an as-designed energy model and an as-occupied energy model were built using DesignBuilder and EnergyPlus. Third, sensitivity analysis was conducted using passive design variables as inputs in both the as-designed and as-occupied energy models. Results show that the EPG of the case building was about 16%. The window type has a greater impact on the EPG than window-to-wall ratio. This study demonstrates the potential of passive design measures for closing the EPG.

Keywords: passive design measure, energy performance gap, low carbon, high-rise residential buildings, building simulation, sensitivity analysis

NONMENCLATURE

Abbreviations	
EPG	Energy performance gap
SHGC	Solar heat gain coefficient
GFA	Gross floor area

1. INTRODUCTION

In the context of climate change, the building sector plays an important role in achieving carbon neutrality in 2050 [1]. The energy performance gap (EPG), referring to the difference between as-designed and as-occupied energy consumption, was found to be a barrier to energy conservation and emission reduction in buildings [2]. For example, Sunikka-Blank and Galvin [3] investigated the energy performance of 3400 German homes and found that the EPG was -30% on average. In another study by Mitchell and Natarajan [4], the EPGs of 97 dwellings ranged from -15% to +30%. Jain et al., [5] found that the actual energy consumption of a low-energy school was about 5 times higher than the predicted energy consumption. It is necessary to implement strategies to close the EPG in buildings.

Passive design measures have been regarded as an important strategy to address the EPG in buildings. For example, Zou et al., [6] believed that passive design measures can reduce unnecessary energy demand and affect occupant behaviour for closing the EPG. Passive design refers to design technologies that effectively take advantage of the building environmental conditions to meet the indoor comfort requirements for maximizing energy consumption and energy cost [7]. They include building form, building envelope and airtightness [8]. Building form enables the passive design by considering the building shape and orientation. Building envelope involves the geometry and thermophysical properties of the building envelope. Building airtightness is concerned with the control of unfavorable heat gain or loss through cracks in the building envelope. Passive design measures can improve indoor environmental quality, enhance thermal comfort, and reduce energy consumption, without relying on active energy systems heavily [9].

However, whether passive design measures can be used as a method to close the EPG has not been systematically examined and how passive design measures can be used to close the EPG remains largely unknown. A comprehensive understanding of the impact of passive design measures on the EPG is the premise of

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

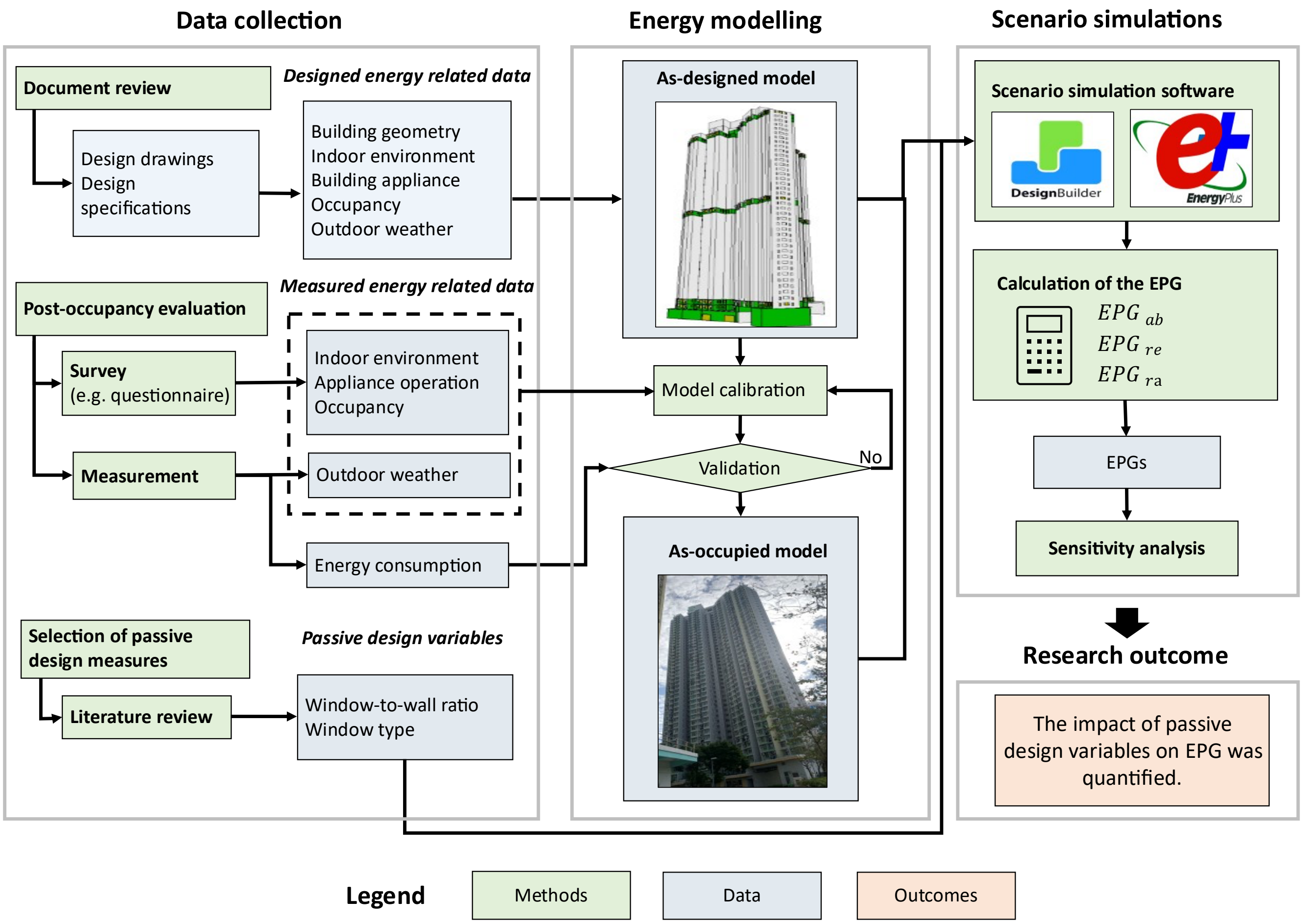

Fig. 1. Methodological framework of this study

providing strategies to close the EPG. Therefore, It is important to explore the impact of passive design measures on the EPG in buildings.

To fill this gap, this study aims to quantify the impact of passive design measures on the EPG using a case study of high-rise residential buildings in Hong Kong. High-rise residential buildings are common in Hong Kong and account for a large proportion of energy consumption. By analyzing the as-designed and as-occupied energy consumption of the high-rise residential building, this study reveals how passive design measures affect the EPG and further contribute to closing the EPG. This study contributes to the knowledge of the impact of passive design measures on the EPG and provides insights into the utilization of passive design measures to close EPG.

2. METHODOLOGY

2.1 Methodological framework

Fig. 1 shows a methodological framework for quantifying the impact of passive design measures on the EPG, which integrates the methods of document review, measurement, questionnaire survey, energy modelling, scenario simulations and sensitivity analysis. This framework establishes both the as-designed and as-occupied energy models, selects passive design variables, conducts scenario simulations and performs sensitivity analysis to identify how passive design variables impact the EPG.

2.1.1 Development of as-designed and as-occupied energy models

Document review is used as a method to review the building project documents (e.g. design drawings and design specifications) to collect energy-related data in the design stage, including building geometry, indoor environment, typical outdoor weather, cooling system, lighting, equipment and occupancy. Based on the collected data, an as-designed energy model can be established using energy simulation software, such as EnergyPlus and DesignBuilder. An as-occupied energy model can be established by calibrating the as-designed energy model using the actual energy-related data in the operational stage, such as energy consumption, actual indoor environment, actual outdoor weather, building appliance operation, and real occupancy. These actual energy-related data can be collected using a post-occupancy evaluation method, including measurement and questionnaire.

The calibrated energy model is validated using Normalized mean bias error (MBE) and Coefficient of Variation of Root Mean Square Error (CV RMSE). The MBE and CV RMSE are demonstrated to be effective metrics for the accuracy of the simulated and measured energy simulations [10]. According to the ASHREA Guideline 14, monthly MBE and CV RMSE should be within 5% and 15% respectively.

$$MBE(\%) = \frac{\sum_{i=1}^{N}(EU_{measured} - EU_{simulated})}{\sum_{i=1}^{N}(EU_{measured})} \quad \text{Eq. (1)}$$

$$CV\ RMSE(\%) = \frac{\sqrt{\left(\sum_{i=1}^{N}(EU_{measured} - EU_{simulated})^2/N\right.}}{\overline{EU_{measured}}} \quad \text{Eq. (2)}$$

Note: $EU_{measured}$ and $EU_{simulated}$ are measured and simulated energy consumption. i and N are instance and the number of energy use data (i.e N=12 month) $\overline{EU_{measured}}$ is the average of the measured energy consumption.

2.1.2 Selection of passive design variables

The application of passive design measures is significantly influenced by the climate conditions [11]. Therefore, the selection of passive design variables takes into consideration the specific climatic conditions of the location. According to the Uniform Standard for Design of Civil Buildings (GB 50352-2019) in China, buildings need to meet different design requirements in different climatic zones. Passive design variables were popularly identified through a literature review in previous studies and the method is also adopted in this study.

2.1.3 Scenario simulations and sensitivity analysis

Scenario simulations are conducted using selected passive design variables as inputs for as-designed and as-occupied energy models. The energy consumption obtained from the as-designed and as-occupied energy models is used to quantify the EPG of the case building. The calculation method is important to determine the magnitude of EPG. Previous calculations for quantifying EPG mainly are absolute difference (EPG_{ab}) [12], relative difference (EPG_{re}) [13] and ratio (EPG_{ra}) [14]. They are used as three important indicators for calculating the EPG in buildings.

$$\text{EPG}_{\text{ab}} = EP_{as-occupied} - EP_{as-designed} \quad \text{Eq. (3)}$$

$$\text{EPG}_{\text{re}} = \frac{EP_{as-occupied} - EP_{as-designed}}{EP_{as-designed}} \quad \text{Eq. (4)}$$

$$\text{EPG}_{\text{ra}} = \frac{EP_{as-occupied}}{EP_{as-designed}} \quad \text{Eq. (5)}$$

Sensitivity analysis is an effective method to identify the impact of passive design variables on building energy consumption [15]. Similarly, sensitivity analysis is adopted to quantify the impact of passive design variables on EPG and rank the importance of different passive design variables on EPG in buildings.

2.2 Case study

The case building is a typical Y-shaped public high-rise residential building in Hong Kong. The case building was completed in 2013 and its basic information is listed in Table 1. The building information was obtained by reviewing the project documents in the design stage to establish an as-designed energy model.

Table 1 building information of the case building

Item	Details
Building type	High-rise residential building
Location	Kowloon, Hong Kong, China
Climate	Hot and humid climate
GFA	36227 m^2
Building height	113m
Floor	42 stories
Household unit	988
Window to wall ratio	30%
U value of window	5.78 W/m^2K
SHGC	0.775
U value of wall	3.19 $W/\ m^2K$
U value of roof	0.55 $W/\ m^2K$

A questionnaire survey was conducted in 2018 to collect actual energy-related data in the operational stage and 135 effective questionnaires were obtained. The collected actual energy-related data includes the indoor temperature, energy-consumed appliances and occupant schedules. The actual outdoor weather data is collected from Hong Kong Observation. The measured electricity and gas consumption was also collected to validate the calibration and then an as-occupied energy model was completed.

The case building is located in a hot and humid climate, thus preventing heat gain and decreasing cooling demand in summer is critical. Windows account for 20%-60% of energy loss and excessive solar gain in buildings [16]. The window is an important building envelope component for preventing heat gain. Two passive parameters related to windows were selected to conduct a case study to preliminarily explore their impact on the EPG, as summarised in Table 2.

Table 2 Passive design variables for the case building

Variables	Range
Window-to-wall ratio	Range 20%-80 %
	Interval 20
Window type	Single glazed (5.78 W/m^2K)
	Double glazed (3.09 W/m^2K)
	Triple glazed (2.15 W/m^2K)

3. RESULTS AND DISCUSSION

3.1 Energy performance gap of the case building

As shown in Fig. 2, the annual energy consumption of the as-designed model, as-occupied energy models and the measurement were 145 $kWh/m^2/year$, 173 $kWh/m^2/year$ and 175 $kWh/m^2/year$. The MEB and CV RMSE were 1% and 13% respectively, which satisfies the requirements of the ASHREA Guideline 14. The EPG_{ab}, EPG_{re} and EPG_{ra} of the case building were 871 MWh, +16.13% and 1.16 respectively.

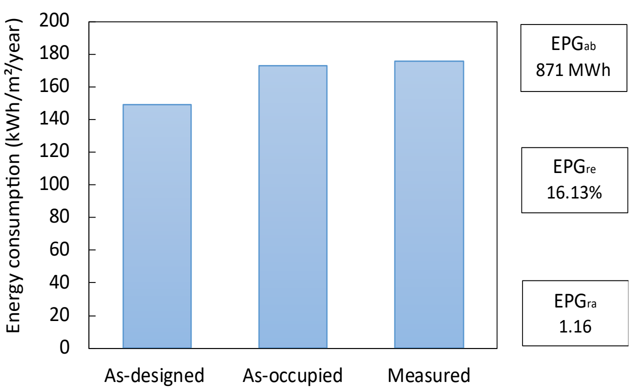

Fig. 2. Energy consumption and energy performance gap

3.2 Impact of window-to-wall ratio on EPG

Impact of window-to-wall ratio on EPG_{ab}, EPG_{re} and EPG_{ra} is listed in Table 3. The window-to-wall ratio had a relatively significant effect on EPG_{ab} than EPG_{re} and EPG_{ra}. EPG_{ab} varied from 870417 kWh to 872005 kWh. EPG_{re} had a minor variation from 16.12% to 16.14%. EPG_{ra} had no change, which indicated that it is difficult to observe small changes in gaps in buildings through the indicator of EPG_{ra}. As shown in Fig. 3, EPG_{ab} decreased by 364 kWh when window-to-wall ratio increased from 20% to 40%, but EPG_{ab} increased by 1588 kWh when window-to-wall ratio rose from 40% to 80%.

Table 3 EPGs under different window-to-wall ratio

Window-to-wall ratio	EPG_{ab} (kWh)	EPG_{re} (%)	EPG_{ra}
20%	870781	16.13	1.16
40%	870417	16.12	1.16
60%	871476	16.13	1.16
80%	872005	16.14	1.16

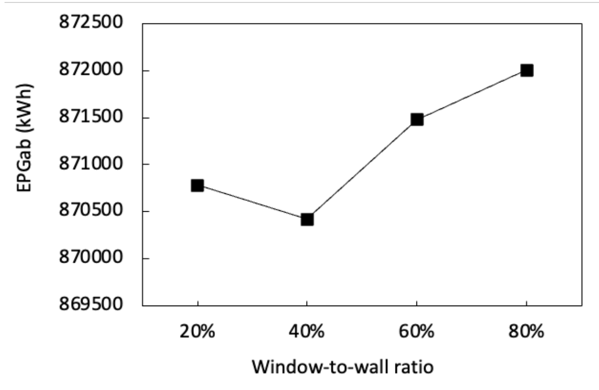

Fig. 3. Impact of window-to-wall ratio on EPG_{ab}

Energy consumption of the case building was analysed, as shown in Fig. 4. Energy consumption in both as-designed and as-occupied models increased as the window-to-wall ratio increased from 20% to 80%. The main reason for the increase is that buildings with higher window-to-wall ratio gain more heat and require more cooling energy consumption. When window-to-wall was from 20% to 40%, the as-designed energy consumption increased faster than the as-occupied energy consumption, so the EPG became smaller. On the contrary, when window-to-wall grew from 40% to 80%, the as-designed energy consumption increased slower than as-occupied energy consumption, therefore the EPG became larger.

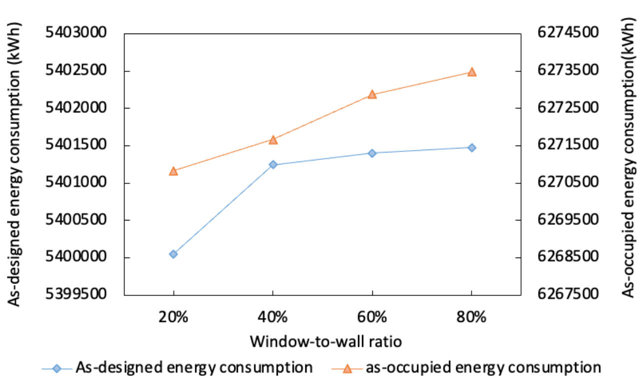

Fig. 4. Energy consumption of as-designed and as-occupied models under different window-to-wall ratio

3.3 Impact of window type on EPG

Table 4 and Fig. 5 illustrate the relationship between the window types and EPGs in the case building. The U-value of single, double and triple glazed windows were 5.78 W/m^{2}K, 3.09 W/m^{2}K, 2.15 W/m^{2}K respectively. It was discovered that the EPG increased as the U-value descreased. EPG_{ab} was influenced more significantly than the EPG_{re} and EPG_{ra}, which ranged from 871077 kWh to 874228 kWh. The EPG_{re} increased from 16.13% to 16.62%, with a slight increase of 0.49%. The EPG_{ra} had a small change of 0.01 across all window types.

Table 4 EPGs under different window types

Window-type	EPG_{ab} (kWh)	EPG_{re} (%)	EPG_{ra}
Single glazed	871077	16.13	1.16
Double glazed	872736	16.42	1.16
Triple glazed	874228	16.62	1.17

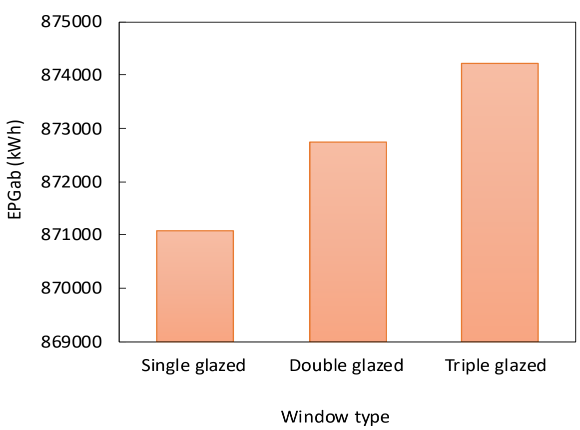

Fig. 5. Impact of window type on EPG_{ab}

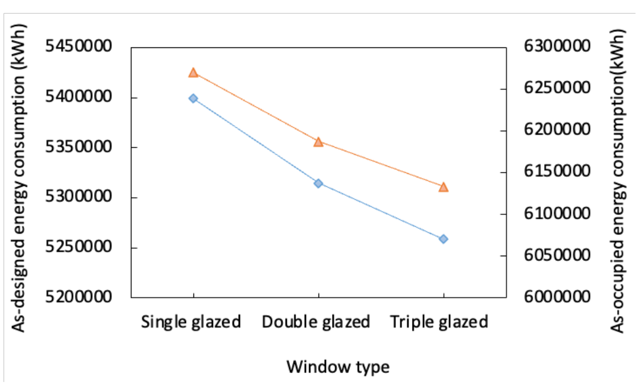

Fig. 6. Energy consumption of as-designed and as-occupied models under different window types

Energy consumption in both as-designed and as-occupied models was compared in Fig. 6. The energy consumption reduced as the U-value decreased (see Fig. 6), but the EPGs increased (see Fig. 5). This means that while passive design measures reduced energy consumption in buildings, there was no guarantee that the EPG was smaller.

3.4 Significant level of passive design variables

Table 5 summarises the significant level of window-to-wall ratio and window type. The impact of window type on EPG was more significant than the impact of window-to-wall ratio on EPG in this case building.

Table 5 Significance level of passive design variables

Variables	ΔEPG_{ab} (kWh)	ΔEPG_{re} (%)	ΔEPG_{ra}	Rank of significance
Window-to-wall ratio	1588	0.02	0	2
Window type	3151	0.49	0.01	1

4. CONCLUSIONS

This study proposed a methodological framework to quantify the impact of passive design measures on the EPG in buildings. A real-life high-rise residential building in Hong Kong was used to conduct a case study. Window-to-wall ratio and window type were identified as two key passive design variables for the case building. EPG_{ab}, EPG_{re} and EPG_{ra} were used as three calculation indicators to quantify the EPG. The results revealed that window type is more sensitive to the EPG than the window-to-wall ratio. EPG_{ab} varied by 1588 kWh when the window-to-wall wall was between 20% and 80%. Regarding window type, the EPG_{ab} of single, double, and triple glazed windows were 871077 kWh, 872736 kWh, and 874228 kWh respectively, which varied by 3151 kWh. It was also found that a lower U-value reduced energy consumption but increased the EPG of the case building. In other words, the design of a building with lower energy consumption does not guarantee a lower EPG in the operational stage.

The innovation of this study is to quantify the impact of passive design measures on the EPG using three indicators of EPGab, EPG_{re} and EPG_{ra}. This study developed a methodological framework integrating methods of document review, post-occupancy evaluation energy modelling and sensitivity analysis. The findings expanded knowledge of the impact of passive design measures on the EPG in buildings. It should provide insight into how to use passive design measures to achieve low-energy design, while ensuring that the actual operation is as good as the design.

A limitation of this study is that only two representative passive design variables were used for the case study. Future research should examine more key passive design variables to comprehensively understand their impact on the EPG in buildings.

ACKNOWLEDGEMENT

We would like to acknowledge the Collaborative Research Fund of the Hong Kong Research Grants Council (Project No.: C7047-20G).

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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