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Lifecycle performance of high-rise buildings with maximized Integrated Photovoltaic Façades

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ABSTRACT

Researchers of this paper have shown interest in low carbon high-rise buildings due to limited available studies in Hong Kong. In this study, a potential pathway to carbon reduction through an extensive use of Building Integrated Photovoltaics (BIPV) in low energy high-rise buildings is explored. A typical high-rise building model is developed to conduct a comparative lifecycle energy and carbon assessment based on the Zero Emission Building-Operational and Materials Embodied Energy (ZEB-OM) ambition level of the Norwegian Research Centre on Zero Emission Buildings. The net total impact is expressed in terms of the Cumulative Energy Demand (CED) and Global Warming Potential (GWP).

The results show an increase in GWP for the material production and maintenance phases due to the use of BIPV façades in the alternative design scenario. However, GWP and operational energy reduction from the BIPV generated power far outweigh the increment caused by its production and maintenance. As a result, about 21% reduction in GWP can be achieved compared with the reference model. Also, the BIPV façade is found to be economically viable with a payback period of 4.13 years. Future research will be expanded to all lifecycle phases and other BIPV materials.

Keywords: Building Integrated Photovoltaics (BIPV); Low carbon emission building; Cumulative Energy Demand (CED), Global Warming Potential (GWP)

NONMENCLATURE

Abbreviations	
a-Si	Amorphous silicon
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaic
CED	Cumulative Energy Demand
GWP	Global Warming Potential
GHG	Greenhouse Gas
Mono-Si	Monocrystalline
nZEB	Zero Energy Buildings
ZCB	Zero Carbon Emission Building
ZEB-OM	Zero Emission Building-Operational and Materials Embodied Energy

1. Introduction

High-rise buildings are vital in modern societies as they accommodate the increased demands for residential and commercial spaces within high-density urban areas. Despite their social benefits, buildings generally contribute to about one third of the energy use and anthropogenic greenhouse gases (GHGs) globally [1]. In service-based economies, the ratio is even higher. As shown in Fig. 1, buildings in Hong Kong contribute to about 90% of electricity consumption and 60% of carbon emissions due to the absence of energy intensive industries [2]. Therefore, buildings are critical to reducing energy consumption and related GHGs.

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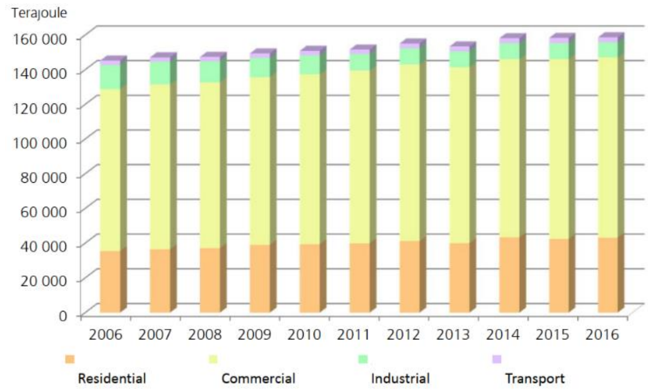

Fig. 1. Hong Kong Electricity consumption by sector [3]

The construction of low energy buildings or nearly Zero Energy Buildings (nZEB) has been promoted as a meaningful step to reduce building energy consumption and GHGs. Although buildings consume energy and produce GHGs throughout their lifecycle, many definitions of low energy buildings or nZEB only address the operational phase energy consumption and neglect the energy embodied in materials production and construction [4]. As operational energy efficiency is a regulatory priority in most regions, the use of energy intensive insulation materials has increased and so has the share of embodied energy and emissions in buildings [5,6].

In response to developing a more comprehensive measure of building energy use and carbon emissions, a new concept of low or zero carbon emission buildings (ZCB) has emerged to comprehensively addresses all phases of a building's lifecycle. In UK, a zero carbon policy was proposed for residential buildings and non-residentials in 2016 and 2019 respectively. In Australia, a definition and road map are proposed towards ZCB by the Australian Sustainable Built Environment Council [7]. The Norwegian Research Centre on Zero Emission Buildings also proposed various ambition levels for ZCB in conformity with the European Standard EN 15978:2011 [4]. ZCB policies in Asian countries are relatively immature although some studies have been conducted in this region lately. Zhang et al. [8] proposed some critical factors for low carbon development. Kedia [9] identified some obstacles to low carbon developments for China and India. Hong Kong researchers [7] proposed a dialectical framework for ZCB and identified strategies including the building envelope energy efficiency and passive design.

Evidently, the potential of sustainable energy technologies such as BIPV [4,7,10] and passive design strategies [7] has been explored to achieve ZCB. BIPV has the advantage of lowering emissions from fossil-based plants [11] and displacing emissions embedded in conventional materials [12]. Chen et al. [13] proposed an optimized passive design coupled with photovoltaics, leading to a reduction of the operational energy use by 71.36%. Such significant energy use reduction has repercussions for GHG reduction. Mochetti et al. [4] explored the use of wood and photovoltaics and recommended a focus on materials with low embodied energy for ZCB.

An important observation of existing BIPV studies for low-carbon or ZCB is that photovoltaic materials are usually attached to conventional materials rather than integrated into the building envelope. This is a research gap in current low-carbon building research. Therefore, this study analyzes the possibility of achieving low carbon high-rise buildings from the maximized use of BIPV in high-rise commercial buildings. This approach explores the interaction between: (a) variation in embodied carbon emissions by integrating photovoltaic applications with traditional envelop materials and (b) reduction of operational carbon emissions due to BIPV generated electricity. In addition, the Life Cycle Cost (LCC) of the BIPV system is investigated. The results of this study will provide valuable contributions to low carbon high-rise building research.

2. Research methodology

2.1 Reference high-rise building

The developed reference model is a typical high-rise office building with a reinforced concrete structural frame and double-pane clear glazing curtain wall as shown in Fig. 2. It has 30 floors and each floor has a dimension of 48m (length), 48m (width) and 3m (height). The main passive design parameters for energy reduction are listed in Table 1 [14,15]. Materials are selected based on reference values of these parameters in existing studies [15]. Rooftop monocrystalline (mono-Si) BIPV modules are the only source of renewable energy in the reference model, while the alternative design replaces all curtain walls with BIPV modules. The entire façade is replaced with semi-transparent amorphous silicon modules and opaque mono-Si modules. Operable windows still account for about 10% of the façade area. The u-values are determined with reference to research studies and commercially available products [15–17]. The material inventory is generated from the BIM model and the missing data is approximated based on [15].

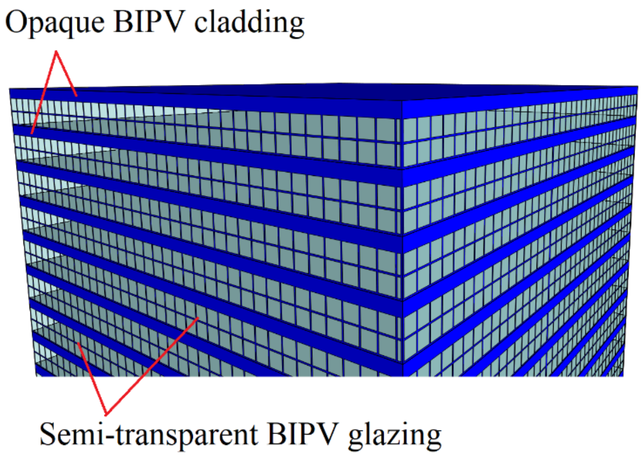

Fig. 2 Developed reference model with alternative BIPV façade

2.2 *Cumulative energy demand*

The cumulative energy demand is calculated using the approach of [4] as shown in Eq. (1)

$$\mathrm{CED} = \sum_{\mathrm{k}} \mathrm{EE_k m_k} + \sum_{\mathrm{c}} \mathrm{OE_c e_c} \tag{1}$$

where CED is the cumulative energy demand over the lifecycle of buildings (kWh); $\mathrm{EE_k}$ is the embodied energy of construction materials k for the initial construction or lifecycle maintenance (kWh/kg); $\mathrm{m_k}$ is the mass of construction material k; $\mathrm{OE_c}$ is the primary energy factor of the energy carrier; and $\mathrm{e_c}$ is the operational delivered energy of energy carrier c (kWh).
The embodied energy is modelled with GaBi Lifecycle Assessment Software in conjunction with the Ecoinvent database. The "unit processes" data is confined to mainland china as most construction materials are imported from this region. The study does not include the impacts of construction, transportation and end-of-life use phases. Monthly energy demands for the space cooling, domestic hot water, lighting and electrical appliances alongside monthly BIPV electricity generation are simulated in Integrated Environmental Solutions Virtual Environment (IES-VE). Primary energy for the operation stage ($\mathrm{OE_{use}}$) is estimated using the approach of [4] as shown in Eq. (2).

$$OE_{use} = \sum_{y=1}^{50} \sum_{m=1}^{12} \{EL_{PV,m}(y) \times CED_{PV} + [EL_m(j) - EL_{PV,m}(j)] \times CED_{grid}\} \times I_m + EL_m \times CED_{PV} \times (1 - J_m) \tag{2}$$

where $EL_{PV,m}$ is the monthly electricity generated by the BIPV (kWh); *m* is a month in the year; *y* is a year in the building's lifespan; CED_{PV} and CED_{grid} are the CED values of BIPV and grid generated electricity; *Elm* is the monthly delivered electricity need; and J_m is a binary variable with $J_m = 0$ when $El_m < EL_{PV,m}$ and $J_m = 1$ otherwise.
As BIPV generated electricity may be exported to grid in months when $EL_{PV,m}$ is greater than El_m, energy export during the operation stage is calculated using Eq. (3).

$$CED_{ex} = \sum_{y=1}^{50} \sum_{m=1}^{12} [EL_{PV,m}(y) - EL_m(j)] \times [CED_{PV} - CED_{grid}] \times (1 - I_m) \tag{3}$$

Table 1 Specification of design parameters

Window to Wall Ratio	Reference model (0.80) Alt. design model (0.1)	**Cooling setpoint (˚C)**	23
Opaque wall U-value (W/m²·k)	Reference model (1.9) Alt. design model (1.1)	**Outdoor airflow (m/s)**	1.2
Curtain wall U-value (W/m²·k)	Reference model (2.6) Alt. design model (1.5)	**Occupancy gain (W/m²)**	15
Roof U-value (W/m²·k)	0.39	**Lighting gain (W/m²)**	12
Floor U-value (W/m²·k)	1.2	**Equipment gain (W/m²)**	10
Schedule	Weekdays (8:30 - 19:30), Weekends (8:30 - 14:00)		

2.3 *Global warming potential*

Total GWP connected with the embodied energy, grid electricity and PV generated electricity are estimated based on Eq. (4) [4].

$$\mathrm{GWP} = \sum_{\mathrm{k}} \mathrm{GWP_k m_k} + \sum_{\mathrm{c}} \mathrm{GWP_c e_c} \tag{4}$$

where GWP is the total GWP during the lifecycle of the building; $\mathrm{GWP_k}$ is the GWP of construction material k used for the initial construction or lifecycle maintenance

(kg CO_2eq./kg); and GWP_c is the GWP of energy carrier c (kg CO_2eq./kWh).
The operation stage impact is calculated using Eq. (5) [4]

$$GWP_{use} = \sum_{y=1}^{50} \sum_{m=1}^{12} \{EL_{PV,m}(y) \times GWP_{PV} + [EL_m(j) - EL_{PV,m}(j)] \times GWP_{grid}\} \times I_m + EL_m \times GWP_{PV} \times (1 - J_m) \quad (5)$$

where GWP_{PV} is the GWP of BIPV; and GWP_{grid} is the GWP of the grid electricity.
The exported GWP (GWP_{ex}) resulting from the exported BIPV generated electricity is calculated using Eq. (6).

$$GWP_{ex} = \sum_{y=1}^{50} \sum_{m=1}^{12} [EL_{PV,m}(y) - EL_m(j)] \times [GWP_{PV} - GWP_{grid}] \times (1 - I_m) \quad (6)$$

2.4 Economic performance assessment

An economic assessment is conducted to investigate the viability of the proposed alternative design. The economic performance is estimated by LCC of BIPV and the total income from BIPV generated electricity (I_{BIPV}) as per Eqs. (7) and (8) respectively [18].

$$\mathrm{LCC} = \mathrm{C_i} + \mathrm{C_m} + \mathrm{C_r} + \mathrm{C_s} \quad (7)$$

where C_i is the initial cost of BIPV installation, C_m is the maintenance cost, Cr is the replacement cost and C_s is the salvage value.

$$\mathrm{I_{BIPV}} = \mathrm{A_i} \times \mathrm{L_{BIPV}} \quad (8)$$

where L_{BIPV} is the lifespan of the BIPV system and A_i is the annual income from BIPV generated electricity.

Table 2 Main assumptions for economic assessment

Parameter	Detailed description
Analysis period	50 years
Discount rate	5%
PV module (HK$/ W_p)	7.81
Inverter (HK$/$W_p$)	3.91
Other hardware (HK$/$W_p$)	12.50
Soft cost and profits (HKD/W_p)	19.53
C_m (% of C_i)	2
C_s (HK$/$W_p$)	0.78
Electricity rate (HK$/kWh)	1.125

The main assumptions for the economic assessment are summarized in Table 2 [19,20]. Discounted payback period (PP) and net profit margin (PM) are estimated using the discounted LLC and A_i by Eqs. (9) and (10) respectively.

$$\mathrm{PP} = \frac{\mathrm{LCC}}{\mathrm{A_i}} \quad (9)$$

$$\mathrm{PM} = \frac{\mathrm{I_{BIPV}} - \mathrm{A_i}}{\mathrm{A_i}} \quad (10)$$

3.0 Results and discussion

The main findings of this study are presented in this section. The results are summarized in Table 3 as per net total CED and GWP. It must be noted that monthly energy demands far exceed BIPV power generation so that no power is exported to the grid. The energy and GHG savings are estimated based on reduced grid electricity consumption and reduced materials compared with the reference model.

Table 3 Comparison of CED and GWP for the two designs

	CED ($kWh/m^2/y$)		**GWP ($kgCO_2/m^2$)**	
	Ref. model	Alt. design	Ref. model	Alt. design
Materials Production	46.91	47.93	7.88	8.05
Materials Replacement	17.57	19.62	2.95	3.3
Operational Energy	251.32	217.25	198.29	171.63
BIPV	-1.73	-24.09	-1.37	-19.03
Total	314.06	260.72	207.75	163.95
Savings (%)	-	16.98	-	21.08

3.1 Cumulative energy demands

A comparison of lifecycle CED in terms of $kWh/m^2/y$ are illustrated in Fig. 3. It can be observed that the BIPV façade results in a lower operational energy use on top of energy generation. The results indicate that CED can be reduced by about 17%. Also, the BIPV generated electricity accounts for about 12% of the operational energy use.

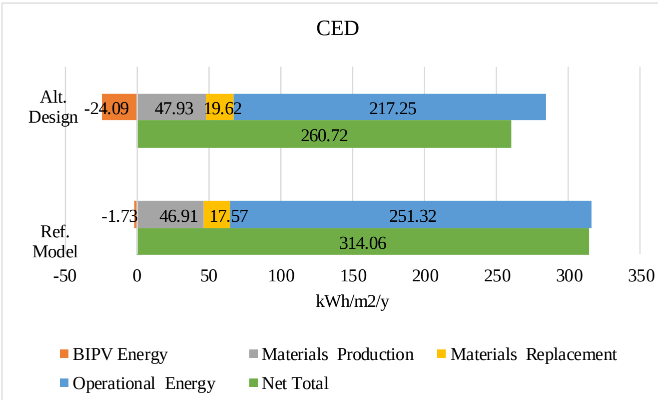

Fig. 3 Cumulative energy demand for the two designs per unit CFA and across the building lifespan

3.2 Global warming potential

Fig. 4 illustrates lifecycle GHG in terms of GWP. This is a measure of GHG by the equivalent carbon dioxide. The net total GWP for the reference model and the alternative design is 207.75 $kgCO_2eq./m^2/y$ and 163.95 $kgCO_2eq./m^2/y$ respectively, leading to a saving of 21%. It can be observed that the main contributor to GWP is the operational energy. This study assumed the main supplier to be HK Electric where 0.79 $kgCO_2eq.$ is emitted for every kWh of electricity generation. The embodied emission is found to be higher in the alternative design as the emissions from BIPV façade is much higher than that of the reference model.

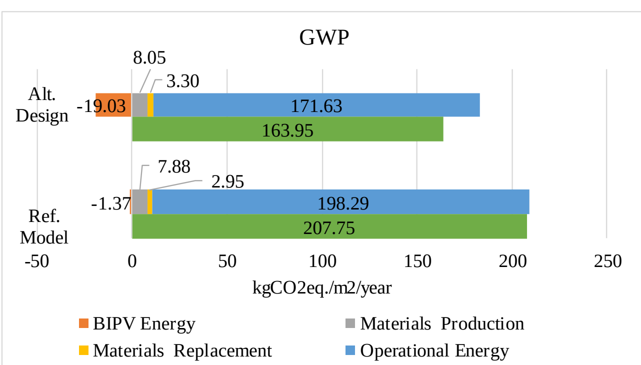

Fig. 4 Global warming potential for the two designs per unit CFA and across the building lifespan

3.3 Economic performance assessment

The economic performance of the BIPV system over a lifespan of 50 years is provided in Table 4. All values are expressed in terms of the net present value. The discounted payback period is estimated as 4.3 years while the net profit margin is estimated as 14.12.

Table 4 Economic performance assessment

Item	**Value**
Initial cost of BIPV system (HK$)	838,821.14
Cost of maintenance (HK$)	306,270.37
Cost of replacement (HK$)	957,127.80
Salvage value (HK$)	5,722.11
Total LCC of BIPV (HK$)	2,096,497.19
Annual revenue from BIPV (HK$)	1,699,050.94
Total revenue from BIPV (HK$)	31,017,704.01
Cost of BIPV generated electricity (HKD/kWh)	0.027
Discounted payback period (years)	4.3
Profit margin	14.12

4.0 Conclusion

This study mainly presents the impact of extensive BIPV applications in high-rise buildings towards a low carbon emission. Two models are developed for comparing the lifecycle GHG emission alongside CED and LCC of BIPV. It is found that GWP embodied in materials of the alternative design is increased due to the extensive use of BIPV on all available façade areas. However, about 21% reduction in GWP can be achieved because of the BIPV generated electricity and the decrease in operational energy demands as an integrated passive design. Nonetheless, inefficient utilization of BIPV may result in higher costs as solar radiation is not available on all façades simultaneously. It is expected that a further reduction in GWP and cost can be achieved by optimizing the alternative design. Future studies should explore the impact of optimizing BIPV design in conjunction with other BIPV materials for a complete lifecycle assessment.

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