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Numerical investigation of a novel vacuum photovoltaic curtain wall and integrated optimization of photovoltaic envelope systems

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Abstract:

This study presents a comprehensive investigation of the thermal and power performance of a novel vacuum photovoltaic insulated glass unit (VPV IGU) as well as an integrated design optimization of photovoltaic envelope systems. A prototype office building model with a curtain wall design is first constructed in EnergyPlus to compare the heat gain, heat loss, thermal load, lighting energy and PV generation for different curtain walls. The comparative analysis proves the excellent thermal insulating performance of VPV IGU, which can reduce up to 81.63% and 75.03% of the heat gain as well as 31.94% and 32.03% of the heat loss in Hong Kong (HK) and Harbin (HB) respectively. With the application of VPV IGU in all available facades of the prototype building, net energy savings of 37.79% and 39.82% can be achieved in diverse climatic conditions. Furthermore, screening and variance based sensitivity analyses are conducted to prioritize building integrated photovoltaic design parameters with respect to specific weather conditions. The selected important design parameters are then optimized with the non-dominated sorting genetic algorithm-II (NSGA-II), by which the optimum building design can achieve a net energy consumption reduction of 48.72% and 60.80% compared to benchmarking designs in Hong Kong and Harbin. Such an integrated design optimization can successfully improve computation efficiency with an acceptable solution accuracy, and assist the incorporation of PV envelop systems with passive architectural designs. The novel VPV IGU is determined to be more suitable for cold areas where the curtain wall design should also be avoided for energy conservation.

Keywords: *Vacuum photovoltaic; Energy saving; Envelope system; Sensitivity analysis; Design optimization*

1. Introduction

The building sector plays a critical role in the total energy consumption of human communities. As reported in the statistical year book of 2015, energy consumption of commercial and residential sectors accounted for 64% of total energy use in Hong Kong, with 43% for the commercial and 21% for the

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residential use [1]. Accompanied by the aggravation of the energy crisis, energy conservation has received more attention from researchers. Although solar energy is recognized as a promising alternative energy source, it merely takes up 1.8% of utilized renewable energy in Hong Kong. As a result, there is still a great potential for developing the building integrated photovoltaic (BIPV), which can help cut down energy bills of the building sector without additional land use [2].

1.1. BIPV applications

BIPV can simultaneously serve as the building component and power generator, and its integration with building facades usually causes no negative impact on their appearance [3]. Semi-transparent photovoltaic (STPV) windows, as one prospective BIPV applications, can generate electricity while allowing partial daylight penetration. Given its increased popularity in building envelope designs, many researchers conducted experimental and simulation studies on this new application. Fung and Yang developed a one-dimensional transient heat transfer model to evaluate the heat gain of semi-transparent photovoltaic modules for the building-integrated application [4]. Lu and Law investigated the overall energy performance of a single-pane semi-transparent PV window for office buildings in Hong Kong [5]. The results showed that the glazing thermal performance was critical for energy saving in the building envelope. The energy saving potential of semi-transparent PV windows was also reported in comparison to the traditional glazing [6, 7]. STPV can contribute to better overall building energy performance compared with single and double-pane clear glazing in Hong Kong' climatic condition [8]. Furthermore, the PV insulating glazing unit (PV IGU) was proved to have better thermal performance than the PV double skin façade (PV DSF) based on numerical simulations and experimental validations conducted in Hong Kong [9, 10].

However, a shortcoming of the current PV curtain wall with common double-glazed PV modules lies in the poor thermal insulation performance due to the high solar heat gain coefficient (SHGC) and U-Value [11]. BIPV modules can still have a thermal conductivity of 1.1 W/m K, even when inert gas filled up the gap within a double-glazing unit [12]. The vacuum glazing technology, which was initially proposed by Zoller in 1913 [13], could minimize conductive and convective heat transfer through the glazing unit by introducing an internal vacuum chamber. Compared with a normal double glazing, the vacuum glazing exhibits superior heat insulation performance, which is identified by its U-values. U-value of the vacuum glazing can be as low as 0.86 W/m^2 K, indicating a much better performance than a double-glazing [14]. Therefore, if the vacuum glazing could be coupled with PV curtain walls in buildings, the heat gain and heat loss could be further reduced. In addition, the vacuum glazing has excellent sound insulation performance owing to its vacuum environment, which is considered an added value for buildings in urban areas.

Based on the above discussion and our previous study of the PV curtain wall application in Hong Kong [10, 15], a novel energy-saving vacuum PV glazing was proposed. The vacuum photovoltaic insulated glass unit mainly consists of an outer PV laminated glass and an inner vacuum glass as shown in Fig. 1. The thermal and power performance has been investigated under both outdoor weather conditions and indoor standard test ambiance, while its application potential on vertical facades of typical high-rise commercial buildings requires further exploration, which will be presented in this research work.

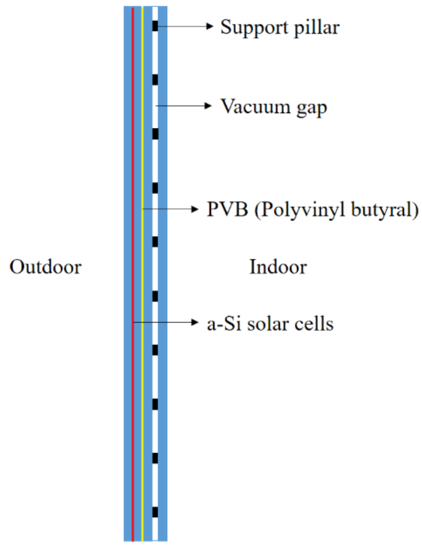


Fig. 1. The structure of VPV IGU

1.2. Building design optimization

High-rise commercial buildings in Hong Kong usually adopts curtain wall as the external building envelope. To maximize the overall energy efficiency of PV curtain wall systems, extensive sensitivity analyses (SA) and optimizations are necessary for facilitating the resource allocation and decision-making to design low-energy buildings. Global sensitivity analysis with screening-based and variance-based methods are proved to be suitable for non-linear and non-additive building models with complicated envelope designs [16]. Morris is a classic screening-based SA approach, where the relative importance of design factors can be qualified with a small sampling dimension [17, 18]. Silva et al. conducted an initial sensitivity analysis with Morris for a multi-criteria decision-making process to improve building energy and thermal performances [19]. The non-linear effect and relative importance of design factors were successfully identified for the factor prioritizing and fixing. The Fourier Amplitude Sensitivity Test (FAST) method, on the other hand, can quantify the influence of each design factor on the model output [20, 21]. Mechri et al. conducted the analysis of variance (ANOVA) for the energy performance of an office building regarding the building compactness, orientation, envelope thermal properties and local shadings [22]. The methodology was proved useful for architects to evaluate the exact impact of each design strategy. ANOVA with FAST was applied to quantify the influence of design parameters over the available solar radiation on building facades. The building location, orientation and shading feature were determined to be the top three factors responsible for the major uncertainty of solar fractions.

The identified key design factors can then be subject to an integrated optimization of the overall building energy performance by simultaneous considering the lighting, cooling, heating and PV energy. Ascione et al. conducted a two-stage cost-optimal analysis of energy retrofit measures with the combination of EnergyPlus and MATLAB [23]. The energy retrofit measures mainly focus on the thermal properties of external building envelope and energy recovery systems. The developed multi-stage optimization approach was also applied in the design of a net-zero energy building in the Mediterranean climate, where the property of building geometry and phase changing materials were also investigated [24]. Multi-objective optimizations involving the lighting, cooling and heating loads were conducted based on both the swarm intelligence and genetic algorithm [25, 26]. These studies also investigated the influence of window thermal and geometric properties under different climatic conditions. Apart from building energy and economic indices, indoor environmental performances including the thermal comfort, visual comfort and air quality were also investigated by a multi-objective optimization with the combination of GenOpt and EnergyPlus [27]. Multi-dimensional Pareto optima were obtained to offer design alternatives for decision-makers to reach the final design solution. Adaptive variation of optimization settings was also conducted to derive the most suitable configuration of genetic algorithms [28]. In addition, surrogate models of traditional simulation tools were incorporated into the optimization process to significantly improve the computation efficiency. Extensive modelling experiments can then be completed within a short time period for a swift decision-making in an early design stage [29].

Based on the above brief introduction, it can be clearly seen that the thermal-power performance and energy saving potential of the proposed VPV IGU requires further investigation with a comprehensive whole building simulation. The applicability of such PV envelope systems in diverse meteorological conditions has not been thoroughly discussed and its integration with other architectural design parameters has not been sufficiently addressed. This paper mainly focuses on developing a simulation platform to study the heat transfer performance of VPV IGU and its corresponding energy consumption and production characteristics. An integrated design optimization approach will also be developed and implemented to obtain the most appropriate envelope design for different climate conditions. Findings from this research can serve as low-energy building design guidelines for related stakeholders in an early planning stage. The original contribution of this research can be elaborated as follows: (1) The developed integrated design optimization approach can reduce the optimization problem space by conducting the factor-fixing and prioritizing based on sensitivity analyses, so that the computation efficiency can be greatly improved; (2) This study incorporated PV envelope systems with passive architectural designs, where a consecutive input distribution space covering important independent and dependent design factors was comprehensively investigated; (3) Both qualitative and quantitative sensitivity analyses were conducted and their factor-prioritizing results achieved an ideal consistency; (4) The holistic design approach is closely coupled with local green building design guidelines, so that it can be used to prioritize resource allocation in an early construction stage and update energy assessment benchmarks for commercial buildings; (5) The sensitivity of PV envelope designs to external environmental conditions were verified by applying the design optimization process to diverse climates, where the vacuum PV glazing was found to be more suitable for heating-dominated conditions; (6) The robustness of the simplified design optimization approach was validated with reference to the baseline comprehensive optimization case; (7) The possibility of approaching net-zero energy high-rise buildings was explored by deriving the maximum energy saving potential with coupled passive design and PV envelope systems.

2. Research design and methodology

The methodology framework mainly involves the development of a modelling platform by combining different simulation tools, statistical analysis methods and optimization algorithms. The vacuum PV glazing and other alternative glazing materials are first composed in WINDOW and then incorporated with EnergyPlus to perform dynamic building performance modelling. The PV glazing properties are further coupled with traditional passive architectural parameters to conduct a holistic design optimization approach based on both qualitative and quantitative sensitivity analysis results. The thermal and power generation properties as well as the impact of different design variables on the net building energy demand will be presented and discussed in detail.

2.1. Simulation tools

EnergyPlus 8.8.0 serves as the major simulation tool to evaluate both building energy consumption and photovoltaic power generation. It has been broadly recognized as a robust building performance prediction tool, whose accuracy has been validated by multiple existing studies [25, 30]. Building geometries, thermal zones, operation schedules, internal loads, illumination and HVAC systems as well as power generators are modelled by inter-connected submodules of EnergyPlus [31]. Energy meters are then used as post-processors of on different categories of energy demand and supply.

WINDOW 7.5 holds a vast database of miscellaneous windows composed of single or multiple layers with difference choices of frames. It can generate window properties including U-factor (or U-value), SHGC (Solar Heat Gain Coefficient), and visible light transmittance. Among these three parameters, U-value describes the overall heat transfer, with a lower value indicating a better thermal insulation performance [32]. SHGC represents the percentage of incident irradiance which eventually penetrates the glazing, through either direct transmittance or secondary inward radiation from the part absorbed by the glazing panel [33]. The visible light transmittance (VT) refers to how much visible light passes through a window, having an immediate impact on the daylight and visual comfort performance [34]. For clear glazing, the light-to-solar gain ratio (LSG), presented as VT/SHGC, is generally around 1.0. However, spectrum selective glazing can increase this value up to 3.0, making it an important variable for balancing indoor daylight and thermal performances [35-37]. The active PV module area (PVA) on the window is then determined to vary with VT as a dependent design variable.

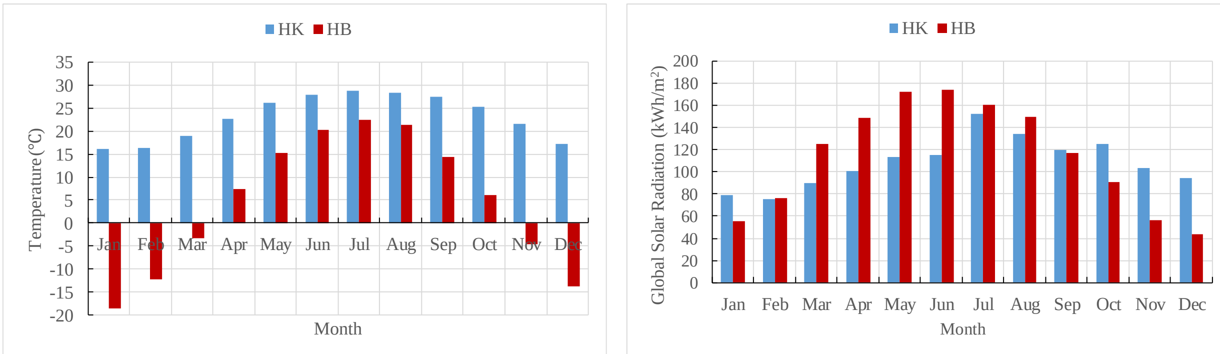
Table 1 shows thermal and optical parameters of curtain wall glasses adopted in four different simulation models. Windows in former three models are derived from the glazing system library in WINDOW, while VPV IGU's property is obtained from previous outdoor and indoor measurements [9, 15]. Model NDP (without PV module and daylight control) and Model NP (without PV module and with daylight control) share the same typical double pane clear glazing. Model VPV (with vacuum PV glazing) is characterized by the lowest SHGC and U-value, while model STPV (with single-glazed semi-transparent PV) presents the worst-case in the overall heat transfer performance (i.e. U-value). An extremely low LSG of 0.325 indicates the poor thermal and daylight performance of STPV.

Table 1 Settings of all windows in different models

Model	U-factor(W/m^2-K)	SHGC	VT
NDP	2.63	0.703	0.786
NP	2.63	0.703	0.786
STPV	5.497	0.471	0.153
VPV	0.557	0.143	0.120

2.2. Weather conditions

Because vacuum glazing is usually not openable especially in a commercial building design, its application in temperate zones is restricted when natural ventilation strategies are usually adopted to modulate indoor thermal comfort [29, 38]. Therefore, the VPV IGU curtain wall system is only examined in a cooling dominated climate in Hong Kong (HK) and a heating dominated climate in Harbin (HB). The two cities are representing the hot summer cold winter and severe cold zones of China with abundant solar radiation resources. The typical weather data of Hong Kong takes the form of IWEC (International Weather for Energy Calculations), while that of Harbin comply with the CSWD (Chinese Standard Weather Data) format. The major difference between the two climates lies in the outdoor dry bulb temperature and solar radiation as shown in Fig. 2. The apparently lower outdoor temperature from October to April leads to the heating-dominated condition in HB, while more solar resources are available in Harbin especially in the summer period due to longer daytime and less cloudy/rainy days.



a. Monthly dry bulb temperature b. Monthly solar radiation

Fig. 2. Weather conditions in Hong Kong and Harbin

2.3. Building modelling

The building model with curtain wall systems was developed from the commercial prototype buildings covering 80% of the total floor area in U.S. Original model settings are referenced to ANSI/ASHRAE/IES Standard 90.1, while they are modified according to the Building Energy Code issued by EMSD of HKSAR and BEAM Plus guidelines from the Hong Kong Green Building Council. As shown in Fig. 3, the typical floor, whose total floor area is 540 m^2 and height is 3 m, is divided to five independent air-conditioning zones, including four perimeter zones facing different orientations and one internal zone (i.e. core zone). The area of this internal zone takes up 40.47% of the total floor area. The window to wall ratio (WWR) of all perimeter zones is evenly set to 83.33%, representing the scenario of curtain walls. In addition to basic building information, the sources of miscellaneous internal gains are presented in Table 2, including the occupancy, lighting, electric equipment and outdoor air flow.

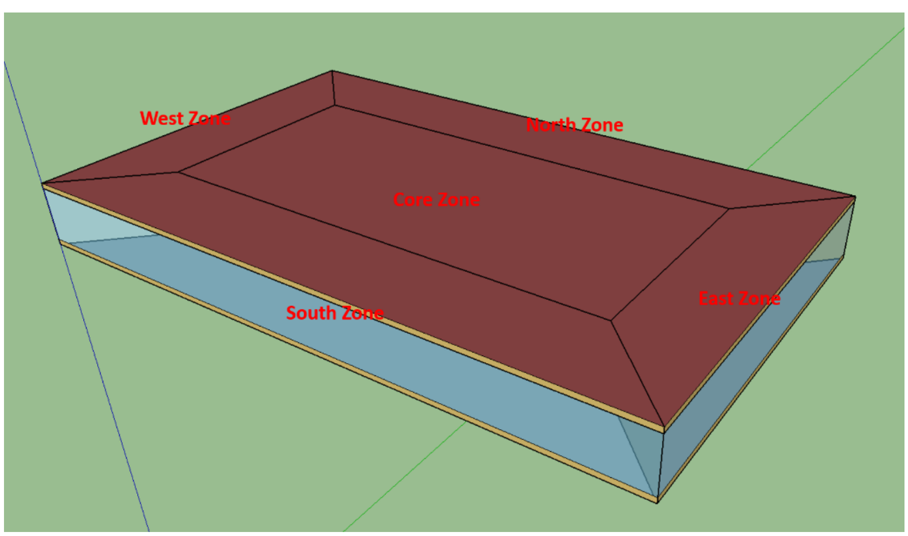


Fig. 3. Typical floor of the building model

Table 2 Basic parameters in all simulation models

Type	Data
Occupancy	8 m^2/person
Lighting	12 W/m^2
Equipment	10 W/m^2
Outdoor air flow	0.008 m^3/s·person

The ideal loads air system (IdeaLoadsAirSystem module in EnergyPlus) is adopted to provide required heating and cooling with 100% energy conversion efficiency as a simplified HVAC system to maintain the research focus on the influence of the building envelope. The cooling and heating demand of the building are obtained with HVAC setpoints kept at 21 ℃ and 24 ℃ respectively. The cooling period is assumed to be from May to September, while the rest time of a typical year is considered as the heating period in the simulation. Infiltration with a constant air change rate and availability schedule is assumed for all four perimeter zones.

The lighting dimming control is used in Model VPV, Model NP and Model STPV, where a reference illuminance level over 300 Lux is considered sufficient for utilizing natural lighting [39]. The position and the quantity of the reference point depend on the different lighting needs of the working situation. In this simulation study, only one reference point is set at the middle of each external zone (i.e. 2 m away from the external facade).

Power generation from PV curtain wall systems are predicted with implanted generator models. Since the Equivalent One-Diode and Sandia model require more detailed experimental data which cannot be confirmed in the early design stage, the Simple model is selected to estimate PV energy supplies based on the assumption of an average efficiency standard test conditions (STC) as specified in Table 3 [8, 10]. The annual electricity and peak power generation can be quickly obtained by this simplified model, which can increase the calculation efficiency in the initial design. Apart from PV panels applied on windows, 90% of opaque facade areas are assumed to be coupled with monocrystalline silicon photovoltaic panels with a conversion efficiency of 15% [40].

Table 3 Photovoltaic parameters

Model	Conversion Efficiency	Reference
STPV	5.9%	[38]
VPV	6.3%	[37]

2.3. Integrated sensitivity analysis and design optimization

To further achieve a holistic design optimization process for daylight, thermal performance and power generation of PV envelope systems, a joint parametric optimization platform is developed with the combination of EnergyPlus and R programming. The probability distribution function is first determined for all related architectural design parameters and a correlation test is conducted to identify the appropriate sensitivity analysis methods. Morris and FAST methods are then conducted to qualify and quantify the significance of design factors in non-linear or non-additive models.

Morris is a popular screening-based SA method to qualify the relative importance between design factors by statistics developed from the Elementary Effect [41]:

$$EE_i(x) = \frac{\left[y(x_1, x_2, \cdots x_{i-1}, x_i + \Delta, \cdots x_k) - y(x) \right]}{\Delta} \tag{1}$$

Morris can explore the input design space efficiently with a randomized "one factor at a time" modelling experiment. The mean μ (stands for the main effect of input variables) and standard deviation σ (stands for the non-linearity and interaction with other variables) of the Elementary Effect are then defined as sensitivity measures:

$$\mu = \sum_{i=1}^{r} EE_i / r \tag{2}$$

$$\sigma = \sqrt{\sum_{i=1}^{r} (EE_i - \mu)^2 / r} \tag{3}$$

The variance-based method is then conducted to quantify the sensitivity indices and validate the ranking of importance obtained from Morris. The total variance of the output is decomposed as Eq. (4):

$$V(Y) = \sum_{i=1}^{k} V_i + \sum_{j>i}^{k} V_{ij} \cdots + V_{12\cdots k} \tag{4}$$

The relationship between different orders of sensitivity indices can be obtained from:

$$1 = \sum_{i=1}^{k} S_i + \sum_{j>i}^{k} S_{ij} + \cdots + S_{12\cdots k} \tag{5}$$

where S_i is called the first-order sensitivity index which is used to prioritize different design inputs. The total sensitivity index summarizing all orders of sensitivity indices are expressed by Eq. (6).

$$S_{Ti} = S_i + \sum_{j \neq i}^{k} S_{ij} + \cdots + S_{i \cdots j \cdots k} \tag{6}$$

Based on selected important design parameters from SA, a multi-objective optimization with NSGA-II is applied to explore the optimum design for specific outdoor weather conditions. The crossover and mutation probability are set to be 0.9 and 0.355 according to a previous modelling experiment conducted by the authors [28]. The population size is determined as 18, twice the dimension of input variables. To obtain a single final solution, the weighted sum method is adopted by allocating equal weightings to all energy aspects (i.e. the lighting, cooling, heating demand and PV generation supply) with the net building energy consumption as the univariate optimization target.

3. Preliminary analysis of VPV curtain wall

This section mainly demonstrates the thermal and power generation properties of the vacuum PV glazing in comparison with other available glazing materials in the building industry. The heat transfer through windows, lighting energy, HVAC demand and power generation in different modelling scenarios are analysed and discussed.

3.1. Heat gain and loss through windows

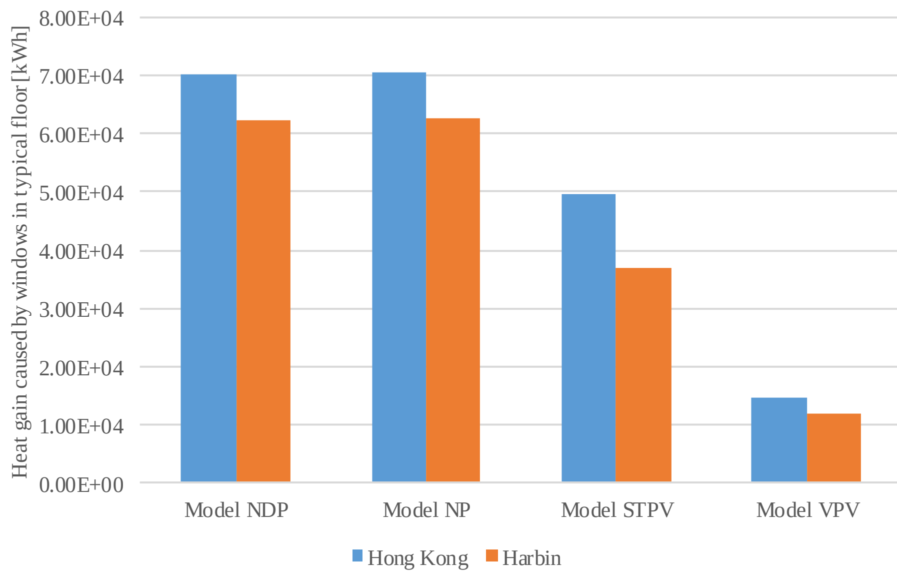


Fig. 4. Heat gain through windows in typical floor

The heat gain and loss through windows in the two climatic conditions are first predicted by EnergyPlus. As shown in Fig. 4, the prototype office building gains more heat through windows in Hong Kong than in Harbin. With the same settings of window properties, Model NDP and Model NP exhibit similar heat gain levels in both climates. A remarkable reduction in the heat gain can be observed when PV glazing is adopted in Model VPV and STPV. Model VPV gets the lowest heat gain among the four models, leading to a reduction of 81.63% in Hong Kong and 75.03% in Harbin compared with Model NDP. This result validated the excellent thermal performance of VPV IGU in isolating solar radiation. As for the heat loss through windows, Fig. 5 clearly indicated that the office building in Harbin is subject to more heat losses due to lower outdoor temperatures through most time of a typical year. The difference of heat losses between two climates is much more conspicuous than that of heat gains. Similar to heat gain conditions, heat losses of Model NDP and Model NP are very close, indicating a minor influence of the daylight control strategy on the indoor thermal environment. Compared with Model NDP, Model VPV achieved a 31.94% and 32.03% reduction of the heat loss in Hong Kong and Harbin respectively, where the excellent thermal performance of VPV IGU is highlighted again. However, it is noteworthy that Model STPV lost more heat than Model NDP and Model NP, possibly caused by its relatively higher U-value.

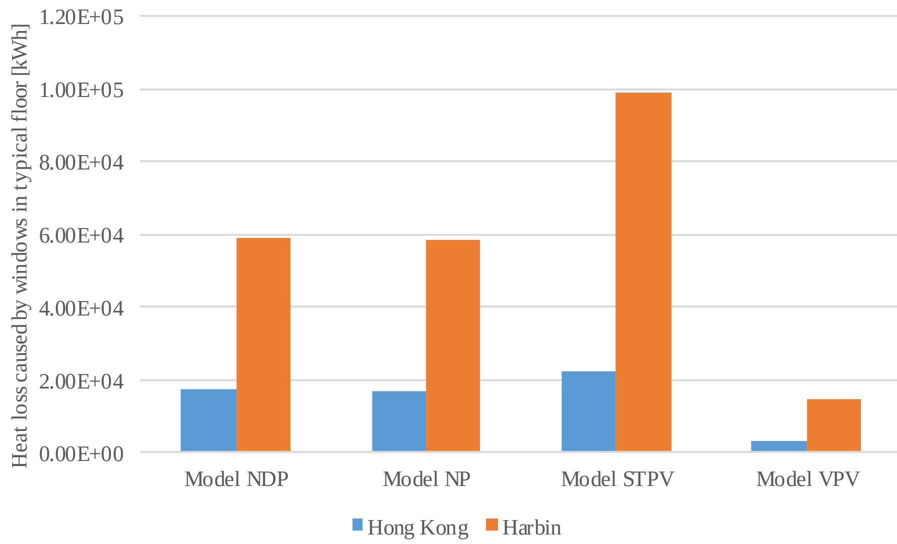


Fig. 5. Heat loss through windows in typical floor

3.2 Lighting and equipment electricity use

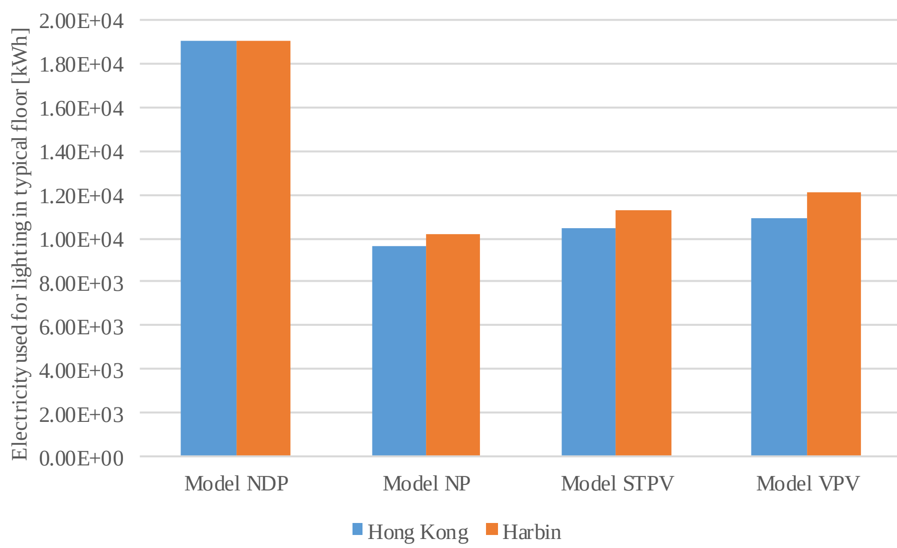


Fig. 6. Electricity used for lighting in typical floor

Lighting energy consumption of the four models in Hong Kong and Harbin is presented in Fig. 6. It can be found that Model NDP consumes the highest lighting energy in the two climates, because no daylight control is adopted for energy saving. According to the graph, Model NP, Model STPV and Model VPV consume more energy in Harbin, because of less available daylight access at higher latitudes. Among these three models, a slightly growing tendency can be observed in lighting energy use because PV windows impaired the visible light transmittance. Comparing all models, it can be found that the setting of daylight controls can contribute to an energy saving up to 9.32% (maximum difference between Model NP and NDP). When it comes to the demand of miscellaneous equipment, all four models share the same schedule and peak power setting, leading to an equal annual consumption. Specific data will be given in the following analysis and tabular summary.

3.3 Heating electricity use

Heating energy consumption in Hong Kong and Harbin is presented in Fig. 7, where the building in Hong Kong has almost zero heating demand due to its warm and short winter. Although it might be hard to tell from the figure, the heating energy use in two cities has identical trend in which Model STPV consumes the most energy and Model VPV consumes the least. The best heat insulation performance of Model VPV, represented by its lowest U-value, is identified as the main contributor to the heating energy reduction. In addition, the heating energy in Model NP slightly exceeded that in Model NDP, because the daylight control also decreased the internal gain from lighting facilities.

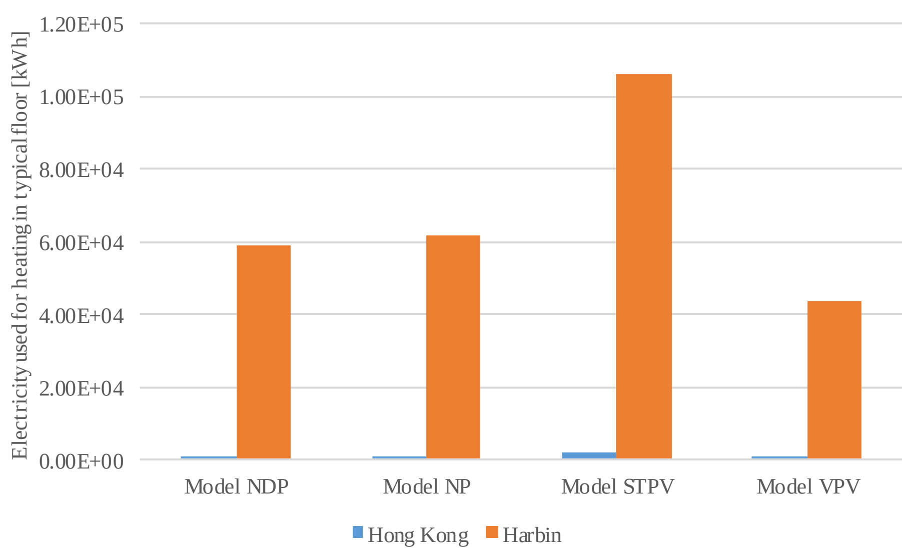


Fig. 7. Electricity used for heating in typical floor

3.4 Cooling electricity use

On the contrary, building models in Hong Kong consume more cooling energy than Harbin, with a smaller gap between the two cities compared to Fig. 7. The cooling consumption of each model in Hong Kong almost tripled that in Harbin. Fig. 8 shows a gradual reduction of the cooling energy among the four models, leading to a decrease more than 50% in Harbin. The reduction can be mainly attributed to the daylight dimmable control and low SHGC. The daylight control lowered the cooling demand by removing the lighting heat gain, which can be clearly observed by comparing Model NDP and Model NP. Low SHGC of PV glazing contributes to the cooling load reduction by restricting the penetration of solar radiation. Similar to the scenario of heating energy, Model VPV is predicted with the lowest cooling energy consumption.

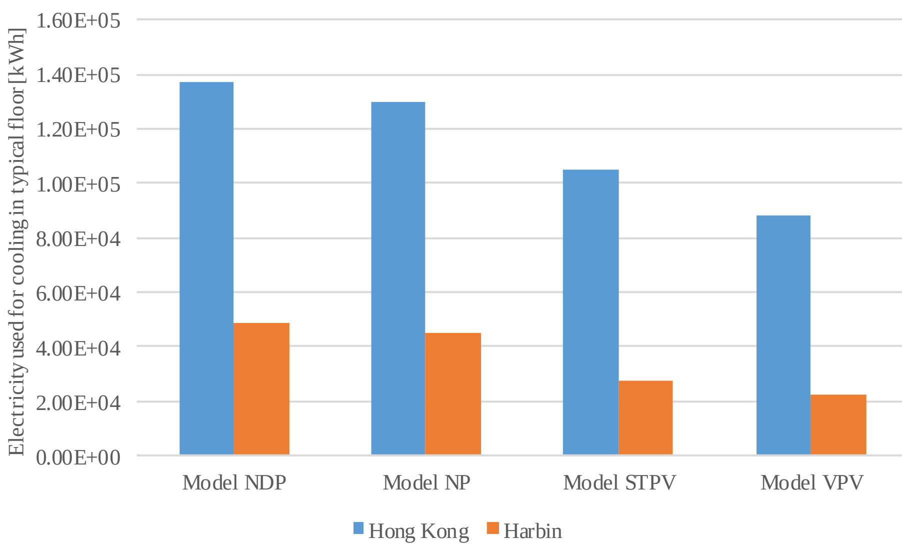


Fig. 8. Electricity used for cooling in typical floor

3.5 PV power generation

Fig. 9 compares the power generation of all vertical façades in models with PV glazing in Hong Kong. Model VPV produces slightly more electricity than Model STPV, which can be seen in each façade as per the bar chart. This trend is also shown in Fig. 10 for building models in Harbin. Model STPV generates slightly less electricity due to its lower power conversion efficiency. South-facing PV glazing always yields the most electricity among four building facades across the two climates. Especially in Harbin, the output of south façade almost takes up half of the total power generation. The difference between Hong Kong and Harbin appears among north, west and east facades. In Hong Kong, the disparity of the electricity yield between these three facades is quite small, whereas it is more apparent in Harbin. Besides the south façade, the west façade ranks second in power generation which is followed by the east and north façade in sequence.

This is mainly caused by the variety in both the global solar radiation and solar altitude between the two climates.

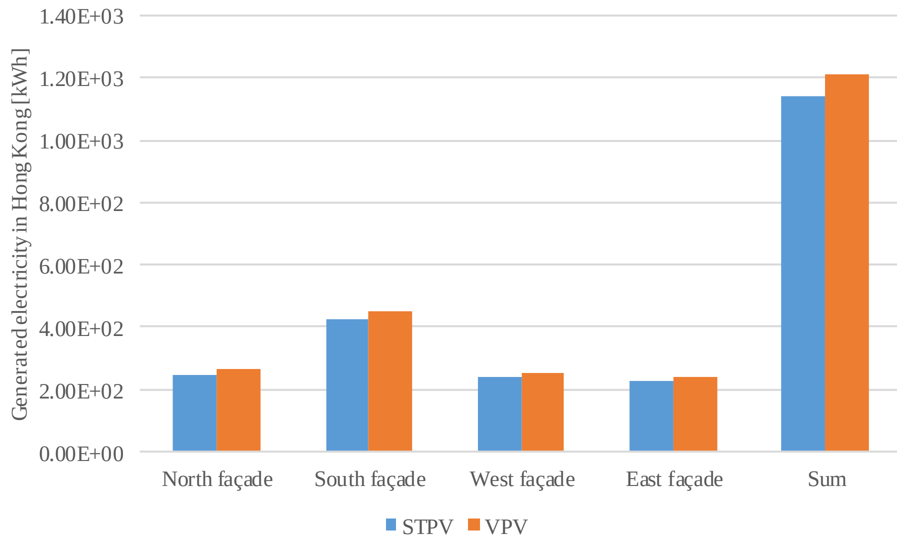


Fig. 9. Generated electricity in Hong Kong

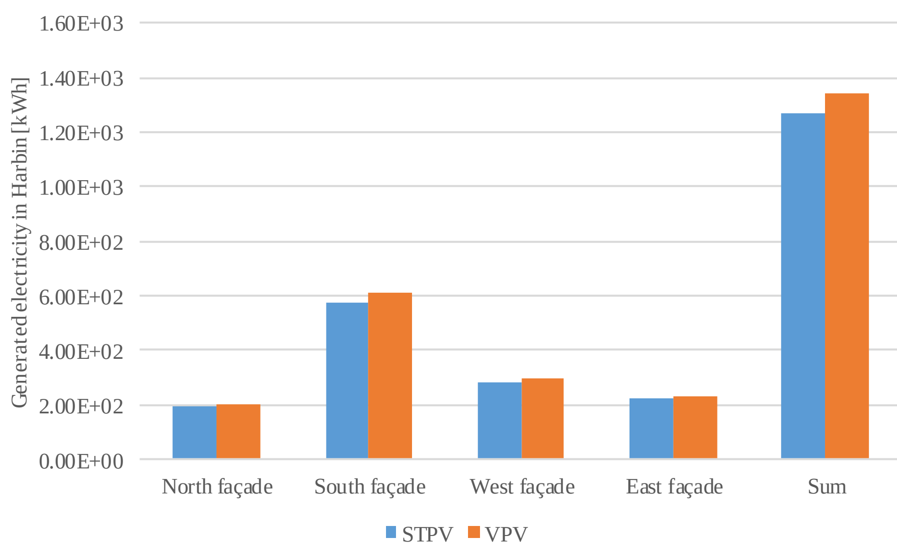


Fig. 10. Generated electricity in Harbin

3.6 Overall building energy performance

The total building energy demand is calculated by summing up lighting, equipment, heating and cooling loads, which are illustrated in Table 4 and Table 5. The daylight control brings about nearly 9.32% and 6.58% lighting energy saving in Hong Kong and Harbin. Although Model STPV achieved energy saving (i.e. 21.82% compared with Model NDP) in Hong Kong, it increased the total demand by 12.11% in Harbin. Model VPV, however, achieved the most saving of 31.94% and 32.03% compared to Model NDP in both climates. The application of VPV IGU curtain wall is preferable for reducing energy demands even when the electricity production is not included.

If power generation is considered when calculating the net purchased energy as per Table 6, the energy saving of Model STPV and Model VPV can be further increased. On top of the demand reduction, the net purchased electricity can be reduced by up to 37.79% and 39.82% in Hong Kong and Harbin. VPV IGU is therefore proved to be slightly more suitable for replacing the traditional double-pane clear glazing in cold areas like Harbin. On the contrary, the STPV curtain wall still consumes more net purchased energy in Harbin because its power generation cannot neutralize the additional building demand.

Table 4 Building Energy Consumption of each model in Hong Kong

Energy Uses [kWh]	Lighting	Equipment	Heating	Cooling	Sum	Consumption Saving
Model NDP	19046.02	24229.80	324.74	137353.27	180953.83	-
Model NP	9657.97	24229.80	466.72	129729.55	164084.04	9.32%
Model STPV	10491.29	24229.80	1681.78	105072.47	141475.34	21.82%
Model VPV	10945.33	24229.80	169.20	87813.58	123157.91	31.94%

Table 5 Building Energy Consumption of each model in Harbin

Energy Uses [kWh]	Lighting	Equipment	Heating	Cooling	Sum	Consumption Saving
Model NDP	19046.02	24229.80	59047.98	48865.83	151189.63	-
Model NP	10179.87	24229.80	61951.93	44876.99	141238.59	6.58%
Model STPV	11274.69	24229.80	106366.17	27628.59	169499.25	-12.11%
Model VPV	12098.90	24229.80	43815.53	22625.94	102770.17	32.03%

Table 6 Overall energy use in Hong Kong and Harbin

City	Subcategory	Model NDP	Model NP	Model STPV	Model VPV
HK	Total electricity use	180953.83	164084.04	141475.34	123157.91
	Electricity production	-	-	9985.82	10592.80
	Purchased electricity	180953.83	164084.04	131489.52	112565.11
	Saving percentage	-	9.32%	27.34%	37.79%
HB	Total electricity use	151189.63	141238.58	169499.25	102770.17
	Electricity production	-	-	11106.12	11781.20
	Purchased electricity	151189.63	141238.58	158393.13	90988.97
	Saving percentage	-	6.58%	-4.76%	39.82%

The purchased electricity of each model in the two cities is presented in Fig. 11. The total electricity shows a monotonous descending tendency in Hong Kong, but such trend is interrupted by Model STPV in Harbin for above mentioned reasons.

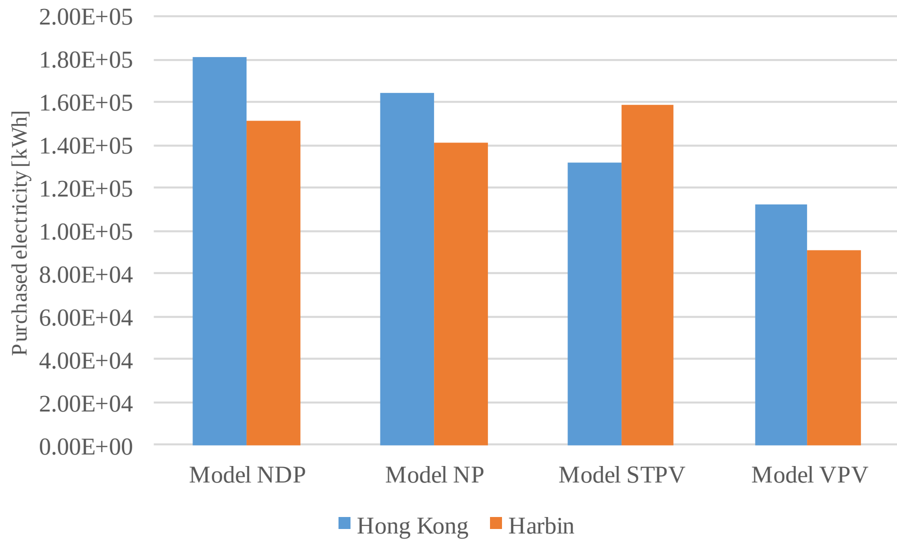


Fig. 11. Purchased electricity of building models in the two climates

4. Further optimization of PV envelope systems

To further validate the applicability of VPV IGU and maximize overall building energy performance, an integrated sensitivity analysis and design optimization is conducted by addressing major architectural design factors in the prototype high-rise commercial building.

Table 7 Value ranges of design parameters

Design parameter	Value range	Baseline value
BO (°)	0~180°	0
WSH (J/kg·K)	800~2000	840
VT	0.24~0.9	0.786
WTR (m^2·K/W)	0.09~6.25	0.136
LSG	1.0~2.4	1.118
WWR	0.1~0.8	0.833
WU (W/m^2·K)	0.2~6	2.630
OPF	0.0~0.6	0.000
IACH	0.05~1.5	0.600

4.1 Design input intercorrelations

Before conducting the sensitivity analysis, the distribution of building envelope design parameters is first determined as Table 7. The building orientation (BO), wall specific heat (WSH), visible light transmittance (VT), wall thermal resistance (WTR), light to solar gain ratio (LSG), window to wall ratio (WWR), window U-value (WU), overhang projection fraction (OPF), and infiltration air changes per hour (IACH) are chosen as model inputs distributed uniformly in specified ranges based on existing literatures and sustainable building guidelines [38]. The benchmarking value of each design parameter (i.e. in Model NDP) is presented for comparative analyses.

The correlation between 9 design parameters is first analysed with colour-painted ellipse and rectangular areas in the upper and lower parts of the matrix shown in Fig. 12. The blue proportion filling the ellipse in clockwise directions means positive reciprocity between two corresponding factors, while the red one filling anti-clockwise directions indicates negative correlation. Darker colours and higher saturation signify stronger correlations. Rectangles at lower left half of the figure indicate the same relationship as those ellipses. As a result, WWR and ICAH have the strongest positive reciprocity while BO and WTR have the strongest negative correlation. These inter-correlations and covariate characteristics indicated that linear regression analysis is not suitable for this sensitivity analysis, so that Morris and FAST methods are used instead.

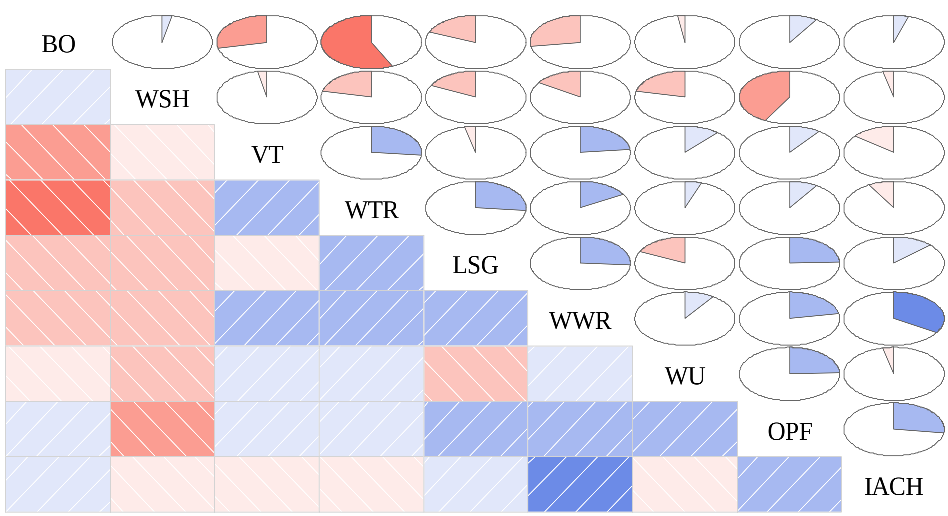


Fig. 12. Correlogram of design input intercorrelations

4.2 Qualitative analysis of design input

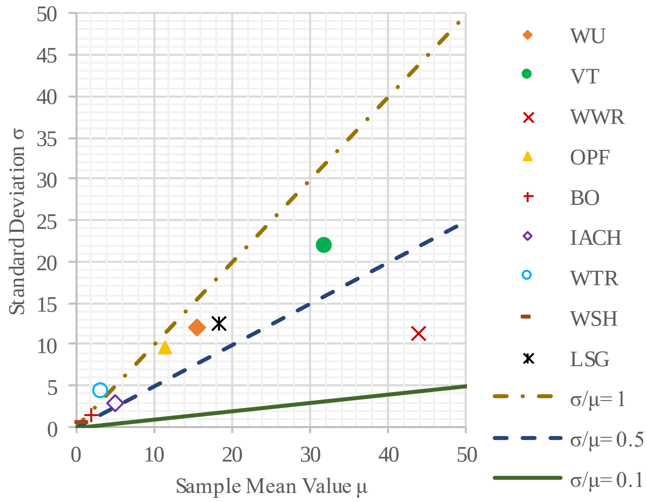


Fig. 13. Morris indices in Hong Kong

Sensitivity analysis with 100 modeling experiments was first conducted with the Morris method. A scatter plot with three reference lines is illustrated as Fig. 13, which describes the relationship between the model input and output. Based on the absolute value of μ, WWR (window to wall ratio) and VT (visible light transmittance) can be identified as the two most influential design factors in Hong Kong. WWR lies between the line σ/μ=0.5 and σ/μ=0.1, indicating a monotonic relationship with the total building energy consumption. VT lies between the line σ/μ=0.5 and σ/μ=1.0, is thus considered almost monotonic with the model response [17, 42]. Following these two factors, LSG (light to solar gain ratio) and WU (window U-value) are also identified as significant parameters by their relatively high μ values. OPF (overhang projection fraction) also seems to have an important role in the building design but its exact impact on the energy usage needs further quantitative analysis. Remaining factors gathering around the corner of the chart (i.e. WTR, IACH, BO and WSH) are therefore of minor importance to the model response judging by their low μ and σ values. Except WTR, which lies above the line σ/μ=1.0 and holds a non-linear and non-monotonic relationship with the model response, most factors are almost monotonically correlated with the building energy consumption. Furthermore, given the fact that no design parameter lies under the line σ/μ=0.1, the model output is clearly not linearly correlated with any design input, so that the most commonly used linear regression analysis is again proved to be not suitable for this SA. The above qualitative SA can be easily obtained with merely 100 simulation runs but cannot decide the exact contribution of each design factor to the variation of building energy consumption, leading to the necessity of further quantitative analyses.

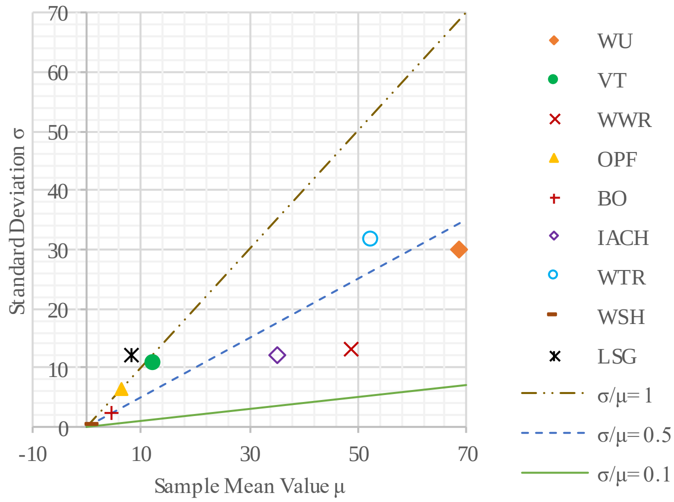


Fig. 14. Morris indices in Harbin

Unlike Hong Kong, Morris indices in Harbin, as shown in Fig. 14, identified WU, WTR, WWR and IACH as the top four influential design parameters in sequence. Among these four factors, WTR (wall thermal resistance) has an almost monotonic relationship while the others have monotonic relationship with the model response. Besides the window geometry (WWR) and its thermal property (WU), wall insulation (WTR) and air-tightness (IACH) are also considered to have significant impact on the building energy consumption in cold areas.

4.3 Quantitative analysis of design input

To quantify the exact impact from each design input, first-order sensitivity indices based on FAST are presented in Fig. 15 and Fig. 16 below with more than 5000 simulation runs in each climate [22]. It can be seen from Fig. 15 that WWR ranks first among all design factors with a contribution of 47.43% to the variation of building energy consumption. The second important factor is VT, which is followed by LSG and WU, accounting for 20.72%, 7.68% and 3.87% of the variation in the model response respectively. The above ranking consolidated the previous qualitative results shown in Fig. 13. It is also illustrated that OPF only contribute to 1.14% of the explainable variation of the model response. Other factors including IACH, WTR, WSH and BO, however, have a total contribution less than 1%. In addition, interactive impacts of all design factors add up to a total contribution of 18.74%.

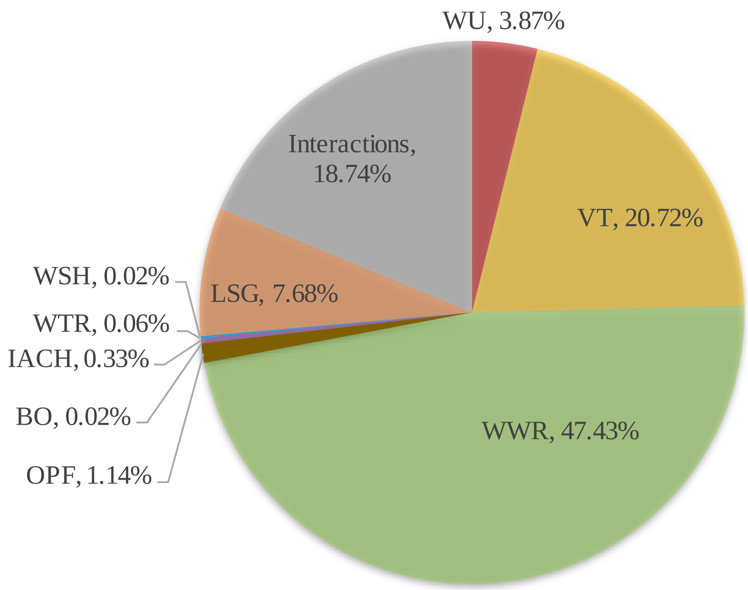


Fig. 15. First-order sensitivity indices in Hong Kong

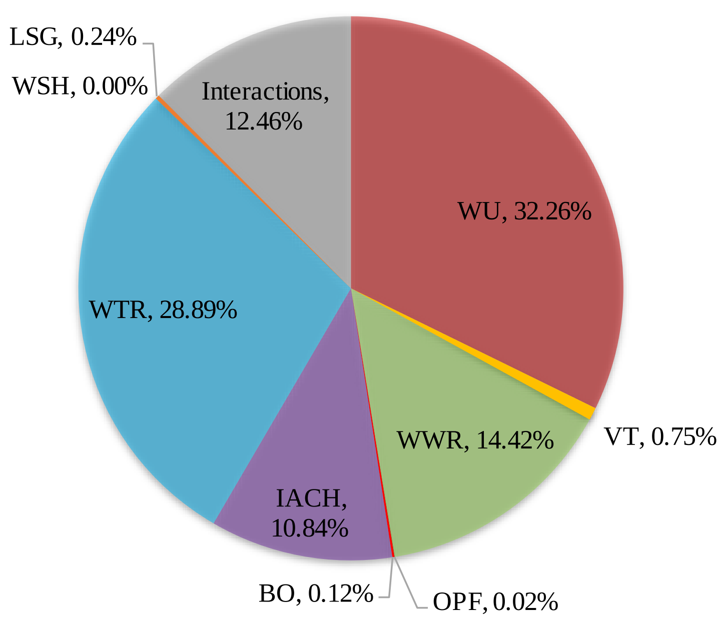


Fig. 16. First-order sensitivity indices in Harbin

Fig. 16 also validated that the four crucial factors (i.e. WU, WTR, WWR and IACH) identified from Fig. 14 also account for the major variation of building energy consumption in Harbin. The total contribution of the other design factors and their interactions is reduced to 13.59%. It is noteworthy that WU makes an independent contribution of 32.26% to the building energy performance in Harbin, which is much larger than the 3.87% contribution in Hong Kong. It can be concluded that thermal insulation using vacuum glasses is a more effective strategy in cold areas.

From above Morris and FAST indices, we can find that five design factors in each climate make minor independent contribution to building energy consumption. However, to completely exclude them form key design factors, total-order indices have to be calculated to take their interactive effects into account. Based on 1000 bootstrap replications, FAST total-order indices are estimated with standard errors and 95% confidence intervals. OPF, BO, IACH, WTR and WSH were validated as insignificant desgin factors with possible zero total-order indices in Hong Kong, while VT, LSG, OPF, BO and WSH were screened out in Harbin based on the same standard. These eliminated factors have ingorable influence over building energy consumption, so that they can be excluded from the optimization problem space in the primary building design. This practice is considered appropriate for architects and engineers when a high-efficiency design optimization is preferred for early decisions. Hence, four key design factors in each climate are selected for a simplified optimization approach (SOPT) in both Hong Kong and Harbin, while a comprehensive optimization approach (COPT) involving all 9 factors is used as the reference case for comparison.

4.4 Design optimization and decision-making

This section presents detailed comparisons between all design optimization approaches including SOPT and COPT. As mentioned above, SOPT optimizes only four significant design inputs while model COPT optimizes all factors. The difference is that WWR, VT, LSG and WU are involved in SOPT of Hong Kong, but these factors are changed to WU, WTR, WWR and IACH in SOPT of Harbin. Through NSGA-II and the weighted sum method, final optimum designs are summarized in Table 8. In the case of Hong Kong, both optimum solutions are characterized by high WU of 5.194 and 5.747 and low SHGC of 0.109 and 0.112, which fit in with typical thermal properties of STPV. In contrast, optimum solutions in Harbin require low U-value between 0.211 and 0.345 and relatively higher SHGC between 0.263 and 0.703, which make vacuum glasses more applicable. In addition, a small window to wall ratio between 0.107 and 0.132 are preferred in both models so that curtain walls are not recommended for energy-saving envelope designs.

Table 8 Values of factors after optimization

Area	Model	BO	WSH	VT	WTR	LSG	WWR	WU	OPF	IACH
HK	Model SOPT	0.000	840.000	0.257	0.136	2.297	0.132	5.747	0.000	0.600
	Model COPT	71.000	1465.000	0.251	1.147	2.297	0.131	5.194	0.004	1.396
HB	Model SOPT	0.000	840.000	0.786	2.036	1.118	0.110	0.211	0.000	0.059
	Model COPT	359.000	1188.000	0.572	2.417	2.172	0.107	0.345	0.332	0.072

Table 9 Energy uses of all models in Hong Kong

Energy Uses [kWh]	Model NDP	Model NP	Model STPV	Model VPV	Model SOPT	Model COPT
Lighting	35.27	17.89	19.43	20.27	19.48	19.52
Equipment	44.87	44.87	44.87	44.87	44.87	44.87
Heating	0.60	0.86	3.11	0.31	4.15	1.30
Cooling	254.36	240.24	194.58	162.62	144.14	137.12
Total use	335.10	303.86	261.99	228.07	212.64	202.82
Generated power	-	-	18.49	19.62	40.79	42.33
Purchased electricity	335.10	303.86	243.50	208.45	171.85	160.48
Total saving	-	9.32%	27.34%	37.79%	48.72%	52.11%

Table 9 and Table 10 show energy consumption data per floor area of all building models. As per Table 10, Model VPV in Hong Kong can save up to 37.79% total energy compared with Model NDP, which is the ideal scenario without the integrated design optimization. 10.93% and 14.32% more electricity can be reduced after the simplified and comprehensive optimization on top of Model VPV. Approximately 50% reduction of purchased electricity can be achieved by lowering building demands and increasing power supplies in both SOPT and COPT. The difference between total energy consumption of Model SOPT and Model COPT is within 5%, which means the simplified design optimization approach is capable of delivering an acceptable solution in the early design stage [43].

In Harbin's case, all models in Harbin use the same amount of equipment energy and Model NP is the one with least lighting energy consumption. In the SOPT approach, the optimum solution saves additional 20.98% total building consumption compared with Model VPV, despite a minor increase in lighting and heating energy. The difference between SOPT and COPT is further reduced to 1.18%, leading to a total energy saving up to 61.98% compared with Model NDP. This minor disparity between SOPT and COPT verified again the robustness of the simplified optimization approach in the initial building design. The increased total energy saving in Harbin also confirmed the conclusion by Ghosh et al. that vacuum glazing performs better in cold climate region where a low U-value is highly recommended [44].

Table 10 Energy uses of all models in Harbin

Energy Uses [kWh]	Model NDP	Model NP	Model STPV	Model VPV	Model SOPT	Model COPT
Lighting	35.27	18.85	20.88	22.41	19.87	20.57
Equipment	44.87	44.87	44.87	44.87	44.87	44.87
Heating	109.35	114.73	196.97	81.14	42.02	45.76
Cooling	90.49	83.11	51.16	41.90	47.84	40.42
Total use	279.98	261.55	313.89	190.32	154.59	151.61
Generated power	-	-	20.57	21.82	44.84	45.16
Purchased electricity	279.98	261.55	293.32	168.50	109.75	106.44
Total saving	-	6.58%	-4.76%	39.82%	60.80%	61.98%

5. Conclusion

This research investigated the energy-saving potential and applicability of a novel vacuum photovoltaic insulated glass unit (VPV IGU) in high-rise commercial buildings under diverse climatic conditions. Hong Kong and Harbin are selected as representative cities in hot summer warm winter and severe cold areas for modelling experiments. Comparisons of building thermal and energy performances were conducted with different curtain walls and control strategies. Furthermore, design optimizations were performed to achieve optimal PV envelope designs based on factor-prioritizing and factor-fixing results. Main conclusions are drawn as below:

(1) The vacuum photovoltaic insulated glass unit (VPV IGU) can reduce up to 81.63% and 75.03% of heat gain in Hong Kong and in Harbin compared to the baseline window system. Meanwhile, heat loss can be decreased by 31.94% and 32.03% in the two climatic areas. Although the conventional semi-transparent PV (STPV) also performed well in reducing heat gain, it caused extra heat loss especially in cold areas. Above differences highlighted the excellent thermal insulation performance of the vacuum glazing in minimizing convective and radiative heat transfers.

(2) When comparing buildings with VPV IGU (i.e. Model VPV) to buildings without the PV glazing and daylight control (i.e. Model NDP), approximately 32% reduction of the energy demand can be observed in both Hong Kong and Harbin. Furthermore, PV power supplies can further increase the saving of net purchased energy to 37.79% and 39.82% in the two areas. It can be also found that daylight controls can contribute to an energy conservation up to 9.32% for indoor lighting. All simulation models share the same energy consumption in equipment because of the uniform setting. On the contrary, the conventional STPV

curtain consumed more net purchased energy in cold areas because its power generation cannot neutralize its addition to building demands.

(3) Sensitivity analyses with Morris and FAST were conducted to qualify and quantify the influence of design parameters on the net building energy consumption. Window dimensions and physical properties are proved to be significant factors for the PV envelope design in Hong Kong. However, the wall thermal insulation (i.e. WTR) and air-tightness (i.e. IACH) substitute for the visible lighting transmittance (VT) and light-to-solar gain ratio (LSG) as key design factors in Harbin. The ranking of key design factors by the qualitative approach was completely consistent with that obtained by the quantitative approach. The insignificant design factors were also excluded from optimization problem space by bootstrapped FAST total-order indices.

(4) Both the simplified optimization (SOPT) based on key design factors and comprehensive optimization (COPT) based on all factors were conducted to derive the optimum solution for PV envelope designs in the two climatic conditions. The difference of net energy saving with both optimization approaches was within 5%, indicating that high-efficiency SOPT is suitable and reliable for initial design pursuing a swift decision-making process. Up to 52.11% and 62.98% energy conservation can be achieved with reference to the benchmarking building design.

(5) The integrated design optimization validated that VPV IGU is more suitable for application in cold areas, where a low U-value between 0.211 and 0.345 is recommended. In addition, a small window to wall ratio between 0.107 and 0.132 is preferred in both climates so that large-area curtain walls are not recommended for optimal envelope designs, when energy saving is the priority of a green building project. The systematic approach in this study can also be utilized to provide detailed user guidelines for building integrated PV applications.

(6) This work not only discussed the applicability of the novel vacuum PV glazing in different climates but also proposed an integrated design optimization framework for its application in high-rise buildings. This approach can be used to identify potential energy efficient measures in a new construction or renovation project of the green building industry. The main findings can be used to develop energy assessment benchmarks for commercial buildings, where the net-zero energy target can be further approached by jointly considering the synergy of passive architectural design and PV envelope systems.

Acknowledgements

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