Energy Efficiency Evaluation for Buildings with Solar Window Technology using BEC Codes of Thailand: Case Study of Skyscrapers in Nanning, China

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Abstract. *Energy efficiency and management for buildings plays a more and more important role for modern and smart city development worldwide, especially for glass buildings. The new technology of solar windows allows possibility of increasing renewable energy (RENEW) utilization while decreasing the overall total thermal transfer value (OTTV) based on most global Building Energy Codes. This research proposed an empirical study that explicitly confirmed the successive profile when utilizing solar windows for glass buildings compared to conventional glass windows. Three skyscrapers in Nanning, China (China Resources Center, Nanning Long Guang Century, and Guangxi Financial Plaza) when implementing with the hot summer and warm winter zone BEC such one of Thailand were investigated due to similarity of their annual weathers. The test results showed that the OTTV of the buildings was greatly reduced from 134.90 – 167.30 W/m^2 to 29.30-40.49 W/m^2, which was 3.89-4.96 times reduction. The additional renewable energy of 3,525-4,526 MWh/year was generated for solar windows compared with 0 MWh/year the standard glasses, which covering 87-92.2% of the total energy consumption for the buildings (4,058-4911 MWh/year). However, when considering in terms of investment cost, the implementation of solar windows was extremely expensive, reflected by all negative net present value (NPV) of -42 to -64 MRMB. These results revealed that replacing solar windows significantly provided high energy efficiency with additional green energy production, as well as the feasibility of using BEC of Thailand for Naning-Guangxi of China, but extremely high investment cost would still be the main challenge for further research.*

Keywords:

Building energy codes, energy efficiency evaluation, solar window technology, solar energy.

1. Introduction

Urbanization and technology have evolved buildings from mere shelters to sustainable, interconnected entities known as smart buildings. These utilize advanced technologies to optimize energy, enhance comfort, and reduce environmental impact [1]. However, many challenges persist for smart buildings, e.g. a blend of architecture and technology, use sensors and microchips to autonomously manage systems like lighting and heating, ventilation, and air conditioning (HVAC) based on occupancy, as well as, the most focused challenges related to energy savings, comfort, cost reduction, and a smaller carbon footprint for large or skyscraper buildings as listed below [2]-[3]:

- Energy inefficiency due to design flaws, like expansive glass facades causing insulation issues.
- Design-usage disconnect, where actual building usage deviates from design assumptions, leading to energy wastage.
- Underutilized or misconfigured energy-saving technologies, leading to inefficiency.

With the new technology of solar windows [4]-[7], the technology allows modern looking for buildings while having capacity of electricity generation. This leads to the possibility of energy conservation or saving for buildings based on many Building Energy Codes (BEC) worldwide [8]-[11]. However, proper evaluation of solar window technology implementation for buildings based on the standard BEC criteria has not been examined and explored yet.

This research proposes the analytical evaluation for energy efficiency evaluation based on BEC codes of Thailand [11] and some parts from BEC of China as shown in Fig. 1 [12]-[13]. The case study of 3 skyscraper buildings in Nanning city, China, was investigated. These buildings were used because they locate in the hot summer warm winter zone of China which has many solar conditions similar to Thailand as shown in Fig. 2 [14], and thus the BEC codes of Thailand could be directly implemented. In this article, the development of mathematical models for energy efficiency evaluation was first presented. The buildings' information was then applied to the developed model while the output results were analyzed and compared. The details of the research findings were finally evaluated and summarized. The research focuses on China's regions with hot summers and warm winters, analyzing the performance of solar glass windows under these conditions. The study adheres to building energy codes from China and Thailand, offering insights into energy-efficient building designs in both geopolitical contexts [15]-[19].

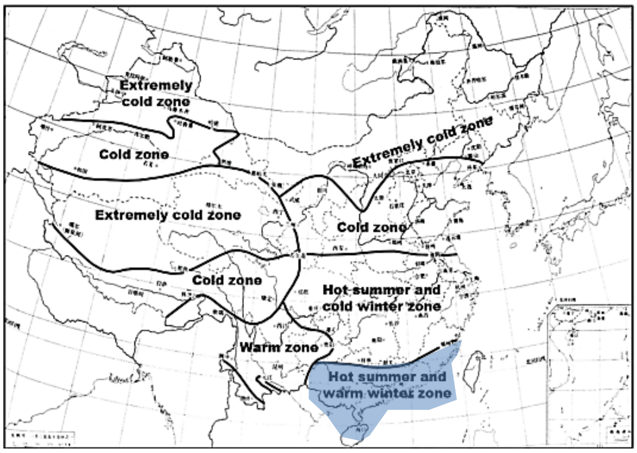


Fig. 1 Research study area (shadowed area): hot summer and warm winter zone of China [13]

This study offered mathematical models for energy efficiency aligned with building codes, invaluable for stakeholders, as well as, providing a comparative analysis between solar and conventional windows, offering empirical data vital for the scientific community, industry, and policymaking [20]. This research's outcomes could drive further innovation, influence building standards, and promote sustainable living spaces [21]-[23].

This comparative exploration delves into the solar potential and climatic nuances of Thailand and Nanning, Guangxi, China, revealing insightful patterns and distinctions. Situated in Southeast Asia, the geographical proximity of Thailand and Nanning becomes evident, despite their cultural differences. The solar landscape's shaping influence is crucial, prompting a meticulous investigation into their climate intricacies. Examining solar irradiance, Thailand registers 1600-1800 kWh/m²-yr, while Nanning records 1300-1600 kWh/m²-yr, indicating a comparable solar energy potential. Similarly, sunshine duration aligns, with Thailand experiencing an average of 6 hours per day and Nanning recording 5:36 hours. Temperature patterns exhibit seasonal similarities, emphasizing the likelihood of comparable solar potential. Both regions share a Köppen climate classification, reflecting observed climate similarities. Their geographical proximity at similar latitudes contributes to comparable solar radiation and temperature patterns. Seasonal variations further underline parallels, Thailand's tropical climate contrasts with Nanning's humid subtropical conditions. This comprehensive analysis, incorporating solar data, climate features, and geographic alignment, solidifies the argument for a shared solar environment between Thailand and Nanning, Guangxi, China.

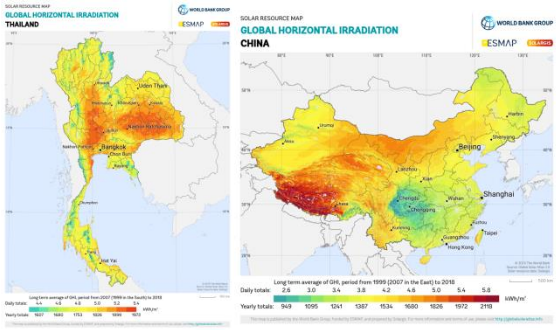


Fig. 2 Horizontal irradiation of Thailand and China

2. Research Materials

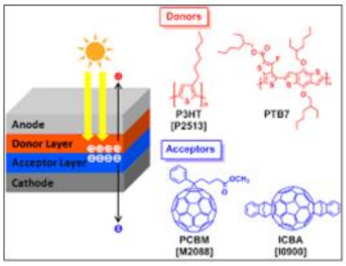
This sector presents full detail of the building energy codes, solar window technologies, buildings under this study, and related literature reviews.

2.1 Building Energy Codes

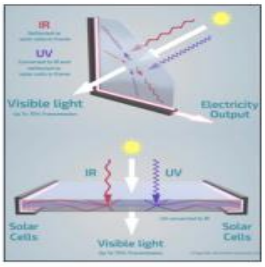
There are a number of building energy codes (BECs) in the world. In China, the PGB50189–2015 code mandates energy efficiency in public buildings, emphasizing thermal performance, HVAC system efficiency, and lighting system optimization. Criticisms include limited guidance on retrofitting existing buildings and potentially high initial costs. It's more exhaustive than standards like the U.S.'s LEED system. Alternatively, the GB/T 50378–2019 code is the comprehensive sustainable building practices code, covering energy, water conservation, building materials, and indoor environmental quality [24]. Critics mention a lack of focus on retrofitting older buildings and high compliance costs. However, in some zone of China such as a hot summer warm winter zone in Guangxi, located close to the northern part of Thailand, could be more interesting if the BEC for this zone using the BEC of Thailand due to the similar in weather and geography.[22-26] This is because of the fact that the BEC of Thailand addresses diverse building types and systems, with an emphasis on local climate and materials. It mandates compliance for new constructions but promotes voluntary retrofitting for older buildings. Criticisms include a weak monitoring system and high implementation costs for advanced technologies [27].

2.2 Solar Window Technologies

Solar windows are defined as transparent photovoltaic cells embedded into window glass, converting sunlight into electricity while also serving as windows as shown in Fig. They offer design flexibility, energy savings, and reduced reliance on traditional energy sources [11],[21]. There are few alternative technologies available for them. The main technologies include organic photovoltaic cells (OPVs) [15] with flexible characteristics, transparent luminescent solar concentrators (TLSCs) [7],[25] for balancing transparency and energy capture, and quantum dot solar cells, which offer versatile applications. Their surface coatings and integration with building systems enhance efficiency. The solar windows are ideal for high-rise buildings, commercial settings, educational institutions, industrial environments, healthcare facilities, and residential areas. They're especially promising for retrofitting existing buildings, aligning with energy-efficient building codes. The studies for these technologies usually focus on improving energy conversion efficiency. While OPVs are flexible, they have lower efficiency than traditional cells. TLSCs and quantum dots show promising potential, but challenges like long-term stability persist. In terms of economic considerations, high initial costs are a barrier to wide adoption. Research evaluates return on investment, suggesting that solar windows can become cost-effective in some scenarios. Financial models, including public-private partnerships and tax incentives, are proposed to accelerate adoption. However, regarding policy implications and environmental impact, the BECs could be continuously modified to better incorporate solar window technologies. [9],[10],[13] Lifecycle analyses evaluate the total environmental footprint of solar windows, emphasizing their potential in urban sustainability [24]. Research calls for standardized environmental impact assessment methodologies [26]-[27].



(a)



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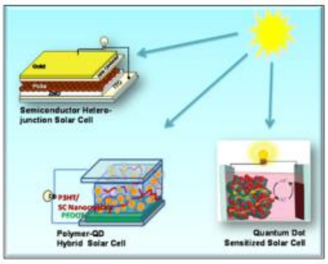


(c)

Fig. 3 Solar Window Technologies: (a) organic photovoltaic cells (OPVs); (b) transparent luminescent solar concentrators (TLSCs) and (c) quantum dot solar cells

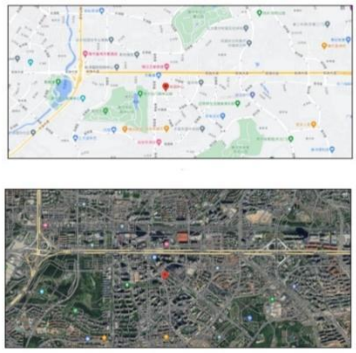
2.3 Buildings under Investigation

The 3 skyscraper buildings selected from Nanning city, Guangxi, China, were selected as they located in a summer zone resembling the northern of Thailand. The buildings are the China Resources Center, the Nanning Long Guang Century, and the Guangxi Financial Plaza. Details are as follows:

2.3.1 China Resources Center

The China Resources Center (location: 22.8103239°N, 108.3899491°E) locates in Nanning city, the business core ASEAN business district, the city's main road above the Nationality Avenue, 403 meters building height reconstruction of the Nanning city skyline. It is the tallest building of Guangxi, China, has geographical information as shown in Fig.3. This building is not only the landmark of the gesture of the reconstruction of the Nanning city skyline, but also the world's attention focus.

(a)



(b)

(c)

Fig. 4 The China Resources Center building, Nanning, China: (a) overview of the building, (b) location on the maps, and (c) different views of the building

2.3.2 Nanning Long Guang Century

The Long Guang Century building (location: 22.8092549°N, 108.3966541°E) consists of an 82-story super-high-rise hotel office building and a 54-story super-high-rise apartment office building. The total planned site area is about 22,669.62 m^2 and the total building area is 392,091 m^2. The two buildings are connected by a three-floor podium and a four-floor podium, with the podium mainly serving as a commercial building and the tower as a hotel office and apartment office. The functions of the site are townhouses, business, and finance.

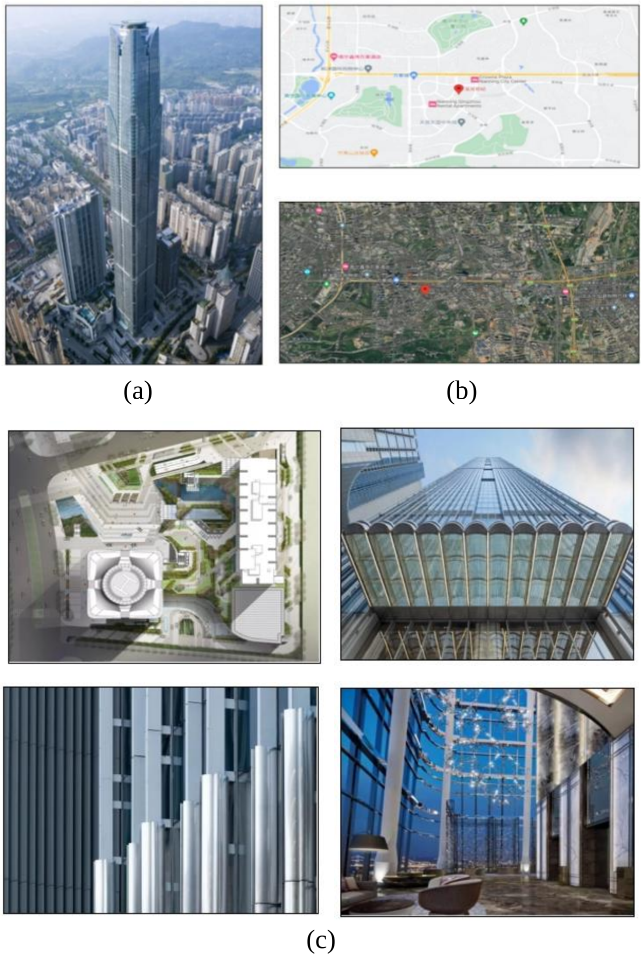


Fig. 5 The Nanning Long Guang Century building, Nanning, China: (a) overview of the building, (b) location on the maps, and (c) different views of the building

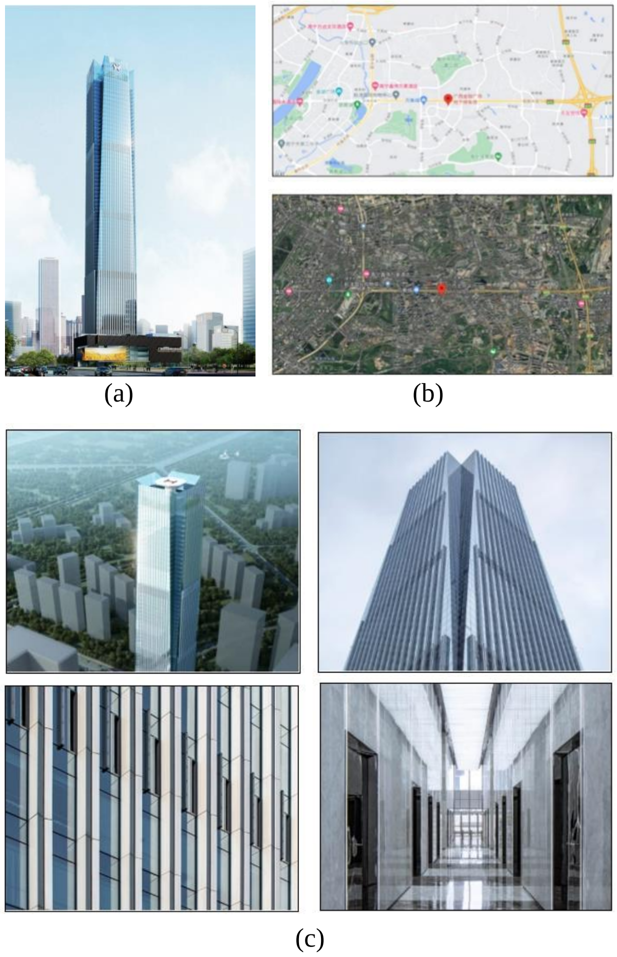


Fig. 6 The Guangxi Financial Plaza building, Nanning, China: (a) overview of the building, (b) location on the maps, and (c) different views of the building

2.3.3 Guangxi Financial Plaza

Guangxi Financial Plaza (location: 22.823289ºN, 108.4055702ºE) is one of the landmark super high-rise buildings in Nanning ASEAN business district. The program design pursues the high degree of unity of architectural function and structural design, the main tower facade adopts the three-layer inwardly closing frame structure step by step, which makes the building shape simple and upright, and through the cutting of the four corners of the top, it forms the visual gradient effect from bottom to top, from solid to virtual, which strengthens the upward trend of the building shape upright. The indoor depth of the building is 11 meters, and the structural design realizes a commercial office space without structural columns, so that the owner can freely separate it according to his needs to achieve the optimal efficiency of space use and realize the panoramic office of the super high-rise building.

3. Research Methodology

Fig. 7 shows the overall research procedure for this study. There were 4 steps: data collection, BEC formulation and calculation, data analysis, and result evaluation and comparison. The specific data of each building was firstly collected, including geographical location (latitude-longitude), solar absorptance (α), thermal transmittance of Wall (U_w), window-to-wall ratio (WWR), equivalent temperature difference (T_{Dex}), thermal transmittance of fenestration (U_f) temperature difference between the exterior and interior condition (ΔT), shading coefficient of fenestration (SC), and solar factor (SF).

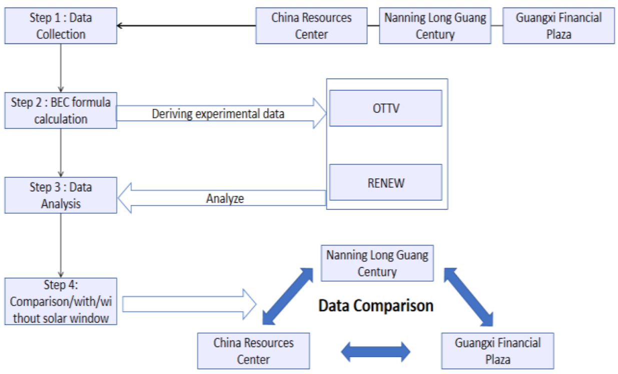


Fig. 7 Procedure for this research study

All the data obtained from the step 1 were then put into BEC of Thailand for calculation and consideration in terms of the overall thermal transfer value (*OTTV*) and renewable energy usage (*RENEW*) via Eq. (1) and (2), respectively.

$$OOTV = \alpha[(U_w \times (1 - WWR) \times T_{Dek}) + (U_f \times WWR \times \Delta T) + (SC \times WWR \times SF)] \quad (1)$$

$$RENEW = \frac{\text{Renewable Energy Generated}}{\text{Total Energy Consumed}} \times 100\% \quad (2)$$

Besides the BEC analysis, economic analysis in terms of net present value (*NPV*) and return of investment (*ROI*) were also considered. These values can be calculated by using Eq. (3)-(4).

$$NPV = \sum_{t=0}^{n} \frac{Rt}{(1+r)^t} - C \quad (3)$$

$$ROI = \frac{\text{Net Profit from Investment}}{\text{Total Cost of Investment}} \times 100\% \quad (4)$$

where R_t refers to the net cash flow in period of t, r to discount rate, C to the initial investment cost, t to the calculation period. The net profit from investment includes the cumulative financial benefits accrued over the defined period and total cost of investment encompasses all associated costs (procurement, installation, and necessary modifications).

4. Results and Discussions

Table 1 shows the collected data and conditions from the first step of the research procedure. Fig. 6 shows the overall research procedure for this study. All the building constructions and materials used were based on BEC of Thailand's parameters and location of Nanning city, Guangxi, China. All the buildings under this study used the same materials for the buildings and thus were ideal for comparative study and evaluation.

Table 1 Data about China Resources Center.

Parameter	Description	Building			Unit
		China Resources Center	Nanning Long Guang Century	Guangxi Financial Plaza	
Latitude	Geographical data	22.8103239	22.8092549	22.823289	ºN
Longitude	Geographical data	108.3899491	108.3966541	108.4055702	ºE
α	Solar absorptance	0.7	0.7	0.7	-
U_w	Thermal transmittance of wall	0.9	0.9	0.9	W/㎡ K
U_f	Thermal Transmittance of Fenestration	5.5	5.5	5.5	W/(㎡ K)
WWR	Window-to-Wall Ratio	0.4	0.4	0.4	-
T_{Dex}	Equivalent Temperature Difference	6	6	6	℃
ΔT	Temperature Difference	23	23	23	℃
SC	Shading Coefficient	0.8	0.8	0.8	-
SF	Solar Factor	480	480	480	W/㎡

For economic analysis, the average cost per unit of energy for commercial buildings in Nanning City was estimated to be 1 RMB/kWh. Calculation cycle of 20 years while the prevailing discount rate in China for the year 2023 is 2.65%. Table 2 shows the acquisition of cost data for ordinary glass buildings and solar window buildings.

Table 2 Economic analysis parameters and their values collected from the previous projects of Jungkai Hi-Tech Venture Center, Lijiazui 96 Plaza and Guangzhou Pazhou International and Exhibition Center

Standard glass cost case study table

Building Name	building height (m)	Curtain wall area (㎡)	Initial cost (¥)	Total price of materials (¥)	proportions	Labor and its installation costs (¥)	proportions	Equipment and other costs (¥)	proportions	Glass unit price (¥)
Jungkai Hi-Tech Venture Center	66	21738.91	22891072.23	16023750.6	70.00%	2289107.2	10.00%	4578214.4	20.00%	1053
Lujiazui 96 Plaza	18	22000	18832000	14124000.0	75.00%	1883200.0	10.00%	2824800.0	15.00%	856
Guangzhou Pazhou International Convention and Exhibition Center	250	165000	110000000	82500000.0	75.00%	9900000.0	9.00%	17600000.0	16.00%	666.7

Solar glass cost case study table

Building Name	building height (m)	Curtain wall area (㎡)	Initial cost (¥)	Total price of materials (¥)	proportions	Labor and its installation costs (¥)	proportions	Equipment and other costs (¥)	proportions	Glass unit price (¥)
Building 7, Western China Science and Technology Innovation Port	15	2755	5622955	4048527.6	72.00%	449836.4	8.00%	1124591.0	20.00%	2041
Ezhou Shunfeng Huahu Airport	21	5773	10524179	7998376.0	76.00%	736692.5	7.00%	1789110.4	17.00%	1823
Guangzhou Art Museum	45.4	70000	110000000	81400000.0	74.00%	12100000.0	11.00%	16500000.0	15.00%	1670

From the above case, it can be calculated that the three major components included in the initial cost, "Total price of materials, labor and its installation costs, equipment and other costs, respectively, account for about 75%, 10%, 15%. This provides a certain basis for the next step of cost analysis of the research object.

4.1 Results: OTTV and RENEW

After using the BEC calculation program provided by Ministry of Energy, Thailand, the overall thermal transfer value (OTTV) and renewable energy ratio (RENEW) parameters could be calculated obtained as shown in Table 3-4 and Fig. 7-8, respectively.

Table 3 OTTV results obtained for each building under this study.

Building Name	Overall Thermal Transfer Value (OTTV)		
	Standard Glass (W/㎡)	Solar Windows (W/㎡)	Reduction Rate (% (times))
China Resources Center	145.20	29.30	- 395.6% (-4.96 times)
Nanning Long Guang Century	134.90	34.72	- 288.5% (-3.89 times)
Guangxi Financial Plaza	167.33	40.49	- 313.3% (-4.13 times)

Table 4 RENEW results obtained for each building under this study.

Building Name	Total Energy Consumption (MWh/year)		Renewable Energy Ratio (RENEW)	
	Standard Glass (MWh/yr.)	Solar Windows (MWh/yr.)	Standard Glass (%)	Solar Windows (%)
China Resources Center	4,793	4,614	0	97.0 (4,475 MWh/yr.)
Nanning Long Guang Century	5,100	4,911	0	92.2 (4,526 MWh/yr.)
Guangxi Financial Plaza	4,232	4,058	0	87.0 (3,525 MWh/yr.)

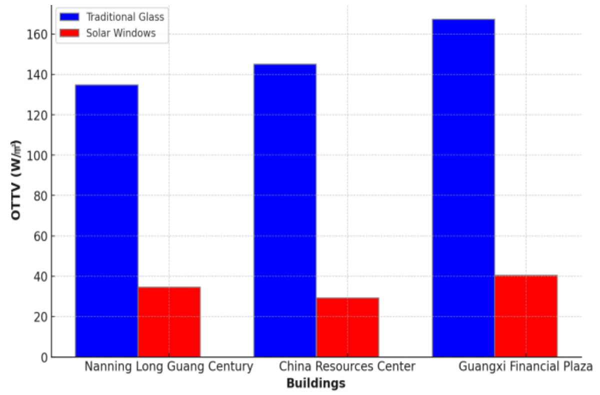


Fig. 8 Comparison of OTTV (W/m^2) values for each investigated building when using standard (traditional) glass windows and solar windows.

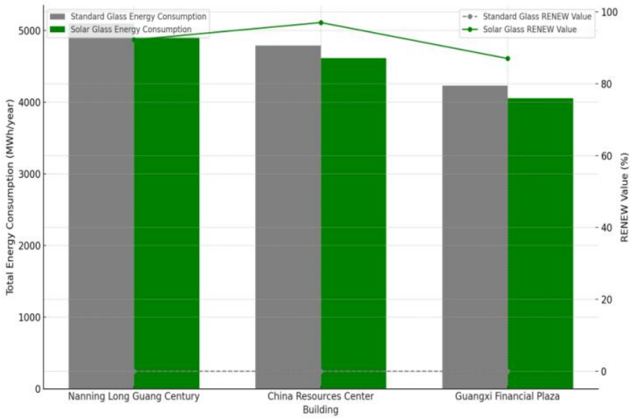


Fig. 9 Comparison of RENEW values for each investigated building when using standard (traditional) glass windows and solar windows.

Based on BEC-Thailand's OTTV standard, the buildings operate for 8 hours a day (offices or educational institutions) are limited to be lower than the maximum value of 50 W/m²; for those functioning 12 hours (theaters or department stores) of 40 W/m², and 24 hours (hotels or hospitals) of 30 W/m². As all the buildings under this study were considered as the offices and thus these buildings could not pass the evaluation for efficient energy building because they had OTTV of 145.20-167.33 W/m², which were over the limit of 50 W/m². In turn, using solar windows could achieve significantly better efficiency (29.30 – 40.49 W/m^2). The reduction rate of OTTV was in the range of -288.5% to –395.6% or 3.89 – 4.96 times.

For RENEW, the metric was employed to evaluate the proportion of renewable energy in each building's energy portfolio. For the Nanning Long Guang Century, the RENEW value showed enhancement from 0% with standard glass to 16.5% with solar windows. Similarly, the China Resources Center experienced an increase from 0% to 18.6%, and the Guangxi Financial Plaza observed a boost from 0% to 17.5%. The installation of solar windows not only led to a direct generation of renewable energy but also fostered an environment conducive to energy conservation by reducing overall energy demand.

4.2 Results: Initial Investment Cost and NPV and ROI

Fig. 9 shows comparison of the initial investment cost and the net present value (NPV) for each building under this study. It can be seen that the cost of the implementation of solar windows was approximately double compared to the conventional standard glass windows. Similarly, the NPV for all buildings in the dataset were negative (-64,552,297.66 RMB, -61,948,370.63 RMB, and -42,426,234.98 RMB). This indicates that, from a purely financial perspective, the initial investment costs associated with the installation of solar windows are not offset by the discounted future cash flows from energy savings and renewable energy generation. The negative NPV reflected the net loss expected from the investments over the time frame considered. This would be a challenge for researchers and engineering for further research in order to decrease the initial investment cost and the NPV for the implementation of solar windows.

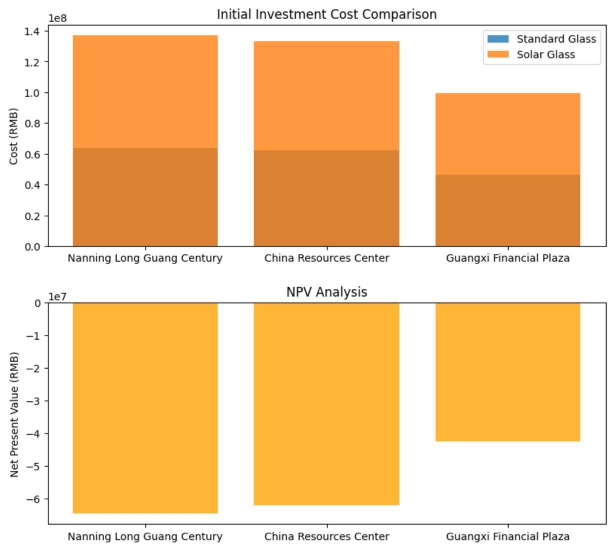


Fig. 10 Initial Cost and NPV Histogram

Return on Investment (ROI): The ROI values are negative across all buildings, which suggests that the investments lead to losses when comparing the gains from the investment to its cost. The results of this study are shown in Table 5. The ROI figures (-96.559%, -96.5134%, -96.2742%) demonstrate a substantial shortfall in recouping the initial outlay for the solar glass installation.

Table 5 ROI results obtained for each building under this study.

Building Name	China Resources Center	Nanning Long Guang Century	Guangxi Financial Plaza
ROI value	-96.5%	-96.60%	-96.30%

In summary, the juxtaposition of buildings with and without the integration of solar windows offers a compelling narrative on the transformative capabilities of this technology. The data clearly delineates the tangible benefits of solar windows, both in terms of thermal performance (as evidenced by the OTTV values) and the integration of renewable energy sources (as indicated by the RENEW values). This comparative analysis not only underscores the technological prowess of solar windows but also foregrounds their potential in redefining sustainable architectural paradigms. Furthermore, the substantial reduction in energy demand and the increased harnessing of renewable energy accentuates the pivotal role of solar windows in achieving energy-efficient design goals. Considering burgeoning global concerns about energy conservation and sustainability, the findings presented herein underscore the imperative for wider adoption of such renewable technologies in architectural designs. Solar windows, as evidenced by our analysis, can be instrumental in bridging the chasm between contemporary energy consumption patterns and a sustainable architectural future. In addition, these results meticulously elucidate the results of our case studies, underscoring the indubitable impact of solar windows on the energy efficiency metrics of buildings in Nanning city, China. These findings, rooted in rigorous analysis, reiterate the transformative potential of solar windows in both enhancing thermal performance and magnifying the integration of renewable energy sources. As the architectural world pivots towards a more sustainable trajectory, solar windows emerge as a quintessential component in this evolution, offering a confluence of energy efficiency and sustainability. However, the financial assessment of the transition from standard glass to solar glass for energy consumption in buildings presents a complex picture. The current financial analysis suggests that the implementation of solar glass technology in the buildings under study does not constitute a financially viable project at this stage. This conclusion is particularly relevant to stakeholders and investors who prioritize short-term financial returns. However, it is important to note that the analysis is constrained by the time horizon and cash flow estimates provided. The financial metrics do not capture the potential increases in property value, environmental benefits, or social goodwill that may accrue from utilizing renewable energy technologies.

5. Conclusions and Future Work

Throughout this research, our focus was centered on evaluating the tangible benefits of solar windows in comparison to traditional glass windows, especially in the context of three pre-selected buildings. The results were illuminating, both literally and figuratively. By employing solar windows, a significant reduction in OTTV values was observed, which, in essence, translates to enhanced thermal performance and energy efficiency. Moreover, RENEW values showed a commendable rise with the integration of solar windows. This increase not only indicates a direct contribution to power generation but also an overall reduction in the energy demands of a building, which is instrumental in driving the sustainability agenda forward. An intriguing dimension of our research was the application of Thai standards. While this might initially seem incongruous, the rationale was grounded in the striking similarity between the climatic conditions of Nanning and Thailand. The Thai standards, given their relevance and adaptability to such climates, provided a robust framework to assess the efficacy of solar windows in Nanning's context. The article included a study of its economics, using two key metrics, initial investment cost, NPV, for analysis, but the results were negative, surfacing the fact that at this stage the whole-building solution of using solar glass is not feasible in terms of economic investment.

While our research has shed light on the potential of solar windows in enhancing energy efficiency, several avenues remain unexplored:

- Material innovation by exploring advancements in materials for better performance.
- Local adaptation of standards as the tailor guidelines for Nanning, Guangxi-China, for a more contextual framework.
- Broader climatic studies by focusing on study efficiency in varied climatic conditions for global applicability.
- Incorporate sensitivity analysis by assessing the impact of key parameters on economic feasibility.
- Evaluate non-financial benefits, including consideration of environmental impacts and long-term societal benefits.
- Explore cost reduction strategies by investigating the possible ways to reduce costs and explore incentives for the promotion of solar window utilization.

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