Fear of God brings Knowledge and Wisdom

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Enhancing of Energy Efficiency and Comfort Through Building Integrated Photovoltaic (BIPV) Windows in Kampala City Buildings

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Abstract

Windows play crucial role in buildings, enhancing indoor environments with natural light and ventilation while presenting challenges (heat loss and discomfort). In rapidly developing urban areas like Kampala City, high-rise buildings with large window-to-wall ratios (WWR) increase energy consumption for air-conditioning due to solar radiation. One of the ways to use this resource is Building-Integrated Photovoltaic (BIPV) System. BIPV windows are multi-functional semi-transparent photovoltaic (PV) glazed integrated within windows applied to buildings which absorb partial solar and convert some of them to electricity while reducing solar heat gain and indoor delighting. In this study, BIPV windows were categorized into four categories, and the double-glazed BIPV windows with ventilated air layer showed more reliable due to the great potential of electricity produced to reduce building energy consumption significantly in the hottest months (January and February) in Kampala City. A novel mathematical model was developed to determine the solar intensity and cell temperature dependency of the PV module parameters. Therefore, BIPV windows are promising for existing and new build applications in Kampala City shopping malls, arcades and hotel buildings. This paper makes a unique contribution to the research arena by providing a conceptual model, and strategies to academics through the BIPV system.

Keywords: BIPV Windows, PV Glazing, Solar PV, VLT, SHGC, U-Value/U-Factor, Funding

Introduction and background

Solar energy is one of the most important renewable energy sources (RES) due to its wide availability, and one way to use these resources is by building- integrated photovoltaic (BIPV) systems (Zarate et al., 2023). In 2022, the global market for BIPV systems valued at 20 billion and is projected to maintain an annual growth rate (CAGR) of 21% by 20230 (Platio, 2023).

Moreover, in the developed countries, the statistics show that they already host a significant number of BIPV systems, but developing countries such as the Middle East and North Africa (MENA) are rapidly catching up (Sohani et al. 2023). Therefore, the quick development of infrastructure and construction in Uganda especially in urban areas like Kampala City, including new-built high-rise buildings with high window-to-wall ratios (WWR) significantly increases the energy consumption for air-conditioning (AC) systems due to solar radiation entering rooms through windows (Eric, 2022).

Building integrated photovoltaic (BIPV) is a smart production system that incorporates solar PV panels as part of the windows, roofs, facades, and shading devices. BIPV product development has been ongoing for the past 30 years but their practical application has been slow in comparison to conventional rack-mounted solar PV (Hazeem et al., 2023).

This paper considers BIPV windows which can replace traditional windows entirely, and promising ways to cut down cooling loads and generate electricity in buildings. Moreover, reducing solar radiation in rooms through windows is effective for many buildings to reduce cooling loads and energy consumption for air-conditioning Therefore, the International Energy Agency (IEA) indicated that more than 30% of global energy was consumed by buildings (Maghrabie et al., 2021), which is a great incentive to reduce building energy consumption (Yang & Athienitis, 2016).

[1] *This study was neither funded by any external source nor received a grant.*

Imagine, you stay or live in a small house with small traditional windows where it is too hot all night, tomorrow morning you go to work, and when you reach your office located in Kampala City you find the same situation as at home!

Uganda is endowed with vast solar energy sources and from an energy security view, solar is the most secure and safe of all sources, since it is abundantly available in Kampala City. Moreover, the impact of BIPV windows in Kampala City buildings was analyzed commonly as (a) electrical efficiency and electricity production per square meter, (b) solar heat gain coefficient (SHGC), and (c) heat transfer coefficient known as U-value (Danny & al., 2009), and (Lu & Law, 2013) all these are explained in the next sections.

A scientific map of BIPV systems and a comprehensive review of scientific literature are essential to be developed to identify future research directions. Moreover, in this research, BIPV windows are categorized into four (4) categories such as single-glazed BIPV windows (Fung, et al., 2008), double-glazed BIPV windows with closed/ventilated air layer (Han, et al., 2021), and PV vacuum glazed system (Huang, et al, 2018). The study showed that the double-glazed BIPV windows with ventilated air layer are more reliable due to the total heat gain through BIPV windows being less than the other three (3) and electricity produced showed that there is a great potential to reduce building energy consumption significantly in a hot climate in Kampala City.

BIPV windows are very promising for both energy-efficient retrofitting (Sureshkumar, et al, 2024) of existing and new build applications in Kampala City shopping malls and multi-functional (URA Tower, Worker's House, Stanbic Bank North Tower Kampala, Mapeera House Kampala), arcades and hotel buildings (Pearl of Africa Hotel Kampala). In this respect, a novel mathematical model was developed to determine the solar intensity and cell temperature dependency of the PV module parameters. Therefore, the results would be a benchmark of enhanced energy efficiency and comfort through BIPV windows in Uganda and the East African Community (EAC).

This research seeks to design and implement building-integrated photovoltaic (BIPV) windows for the best energy-saving efficiency by minimizing the amount of solar heat gain in the buildings and also maximizing the amount of light getting into a room (Eric, 2022; Masloub, et al., 2020 and Shaohang, et al., 2023). Furthermore, this research presents the method of selecting windows with comfort and proper specification which would result in a higher Mean Radiant Temperature (MRT) in winter and lower MRT in summer, improving occupants' comfort and productivity, reducing cooling loads, energy consumption for AC, and also generates electricity in the buildings as for an emergency.

Methodology

This research proposed a holistic approach to assess BIPV windows integration in Kampala City buildings (shopping malls and multi-functional, arcades and hotel buildings), using a life-cycle perspective that considered both environmental and economic aspects. By addressing not only technical feasibility but also the financial and aesthetic constraints, this study provided a nuanced understanding of BIPV's potential.

Methodology Approach

The relevant material for this research was obtained from the most accurate and available studies and data collected at international, national, and local levels journals, internet-published papers, conference proceedings, progress, and completed project reports of the real-time working on BIPV systems.

Moreover, this research involves the thematic analysis of various sorts of findings from different sources to make decisions about the enhancement of energy efficiency and comfort through building integrated photovoltaic (BIPV) windows in Kampala City buildings. Therefore, the primary method (mass observation (10 independent observers in a public place- Nakasero Market and Kampala Road), personal interview (12 people from Stanbic Bank, and Mapeera House using open and closed questions), and group interviews (12 Small groups of respondents from different places such as Kiseka Market, Parliament Avenue, Nasser Road, and Kikuubo Markets) and the secondary method to collect data (Nkwanga, et al, and 2023, ERA, 2023) were used.

Furthermore, the scope of the present research is to abreast the scientific community to know about:

- The most popular technology being used such as monocrystalline, polycrystalline, thin film, etc in such systems.
- The existing BIPV windows, sizes being used around the globe, efficiency, the effect of temperature, and dust on the efficiency.
- The integration of PV with buildings being used (façade or roof-top) globally and continentally.

Therefore, the strategy is not limited to public goods and activities but extended to the entire territory of Kampala and Greater Kampala. Kampala is not an island, so it is important to take into account the impacts generated by our activities beyond our borders to evaluate the contribution of external activities to Kampala and the Greater Kampala Metropolitan Area (GKMA). Thus, these data are the primary generic input data for the feasibility analysis that fits any infrastructure and construction. However, the input was based on the situation in Uganda-Kampala City, and the results (data) would be the main indicator for standards in the East African Community (EAC).

Findings and analysis

The buildings included in the study showcased a diverse array of housing types built over the past 5 years (Fig.1 to Fig. 6b) and highlighted rapid growth, including new-built high-rise buildings with high window-to-wall ratios (WWR) where the solar radiation entering rooms through windows significantly increases the energy consumption by air-conditioning systems. Therefore, arcades, shopping malls, hotels, and multifunctional buildings in Kampala City were predominant in this study.

Figure 1- The Pearl of Africa Hotel, Kampala- 24 Floors (Nakasero) at a height of 90m (2006-2017)

Figure 2- CADENZA RESIDENCE, 1 Katonga Rd, Kampala-24 floors at a height of 80m

Figure 3- Uganda Revenue Authority Tower-22 Floors at a Height of 79m (2015-2017)

Figure 4- Workers' House- 20 Floors at a Height of 72.33m

Figure 5- Stanbic Bank North Tower Kampala- 20 Floors at 72.33m (1970)

Figure 6- Mapeera House Kampala- 16 Floors at a Height of 68.71m (2007-2011)

Figure 6-b: Pension towers (The tallest Building in Uganda at a height of 155m)

Site and climate

Uganda has a Latitude of 1.37330 N, and a Longitude of 32.29030 E. Kampala has a Latitude of 0.3475960 N and a Longitude of 32.5825200 E. Bestriding the Equator, and there is a little year-round fluctuation in temperature. The hottest months are January and February where the average daytime range is 24-330 C (50-910 F) with peaks of up to 400 C (1040 F) in the far North. The rainy seasons are from March to May, and October to November. The dry seasons are from December to February, and June to August (Eric, 2022). According to Koppen-Geiger climate classification (2019), Kampala is a city with significant rainfall, even in the driest month; there is a lot of rain. The climate is considered to be a tropical rainforest climate (Af).

Kampala is in the middle and summers are easy to define, and the month with the most daily hours of sunshine is February with an average of 9.25 hours of sunshine. In total, there are 286.86 hours of sunshine throughout February. The month with the fewest daily hours of sunshine in Kampala is January with an average of 7.43 hours of sunshine a day. In total, there are 223.4 hours of sunshine in January. Around 3,071.35 hours of sunshine are counted in Kampala throughout the year. On average, there are 101.02 hours of sunshine per month (Eric, 2022).

BIPV System Designs

In urban areas (i.e. Kampala City), BIPV systems can be deployed in multi-story buildings and individual houses that are connected to the national grid/ an isolated system with diesel generators or battery power backup options. On the other hand in remote areas, BIPV systems can only be used as isolated systems with diesel generators or battery power backup options.

Description of a BIPV System

Uganda is geographically excellent position with its abundant sunshine with solar radiation of 1,825kWh/m2 to 2,500kWh/m2 per year (Nkwanga, et al., 2023). Therefore, the measurements presented in this research are for the Pearl of Africa Hotel-Nakasero at a total height of 90m, with 24 floors (This includes a variety of room types, such as the Deluxe Double Room, Deluxe Suite, Executive Suite, Junior Executive Suite, Presidential Suite, and Standard Double Suite).

This research presents the BIPV system of 3kWp with 25 polycrystalline PV modules produced 3,114.3kWh, with an efficiency of 12%, and a lifetime of 25 years (Table 1, Table 2, and Table 3).

Table 1-Summary of the annual energy output and efficiency of two BIPV systems

Type	PV-Module	Capacity (kWp)	Energy (kWh)	Efficiency (%)		Life -Time (Years)
				Low	High	
BIPV	Polycrystalline (Poly-si)	3	3,114.3	12.1	13.5	25
	Monocrystaline (Mono-si)	10	9,890.7	11.9	16.9	

Table 2- Coefficient of the façade component

SN	Climate Zone	Umax (W/m2.K)			Uref (W/m2.K)
		Opaque Walls	Roofs	Doors & windows	
1	Hot and Humid, and semi-humid (Cost/Coastal hinterland)	1	0.6	3	2.1
2	Semiarid/ Savannah (Central plateau)	2	0.7	6	2.3
3	Upland and Highland areas	1	0.6	3	2.1
4	High Lake regions	1	0.6	3	2.1
5	Hot and Arid	1	0.6	3	2.1
6	Desert	1	0.6	3	2.1

Photovoltaic (PV) Cell

A photovoltaic (PV) cell commonly known as a solar cell is a renewable energy power generation device that uses photovoltaic modules to generate electricity directly from solar radiation using the photovoltaic effect phenomenon as shown on the Figure7 (Mohd & al., 2017).

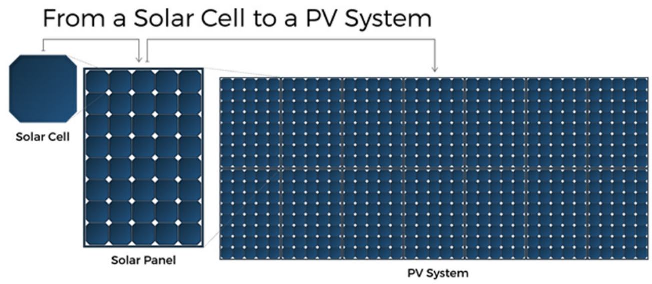

Figure 7-The Photovoltaic System as a Whole

Photovoltaic (PV) Cell operation

The operation of a photovoltaic (PV) cell requires three basic attributes: Photons in sunlight hit the solar panel and are absorbed by photovoltaic materials (Silicon) as shown on the Figure 8. Furthermore, the electrons negatively charged are charged, and current starts flowing through the material, and this is stored electricity, therefore, the panel known as solar cells converts the solar energy into direct current (DC) (Dubey & al, 2013).

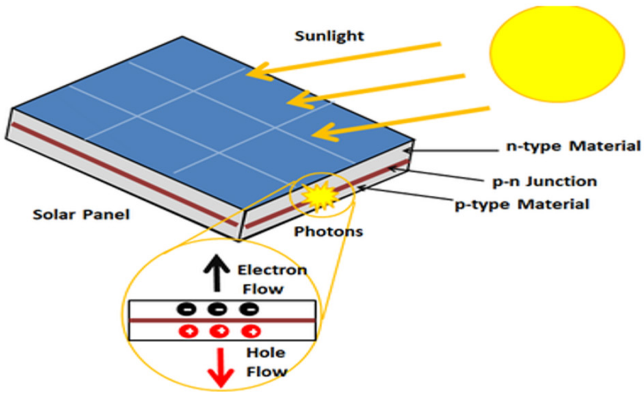

Figure 8- Internal reaction of photovoltaic (PV) cell to produce electricity

PV Potential Assessment

The power output of a PV array was based on solar irradiance and ambient temperature, and thus the model was calculated as:

$$P_{pv} = \eta_{pvg} A_{pvg} G_t \quad (3.1)$$

Where,

η_{pvg} - is the PV generation efficiency

A_{pvg} - is the PV generator area (m^2)

G_t - is the solar radiation in a tilted module plane (W/m^2)

Therefore, η_{pvg} is further calculated as:

$$\eta_{pvg} = \eta_r \eta_{pc} [1-\beta(T_c - T_{ref})] \quad (3.2)$$

Where,

η_r - is the reference module efficiency

η_{pc} - is the power conditioning efficiency (equal to 1 when MPPT is used)

β - is a temperature coefficient (0.004-0.006/0C)

T_c - is a cell temperature in oC

T_{cref} - is a reference cell temperature in oC

Therefore, (T_c) can be calculated as:

$$T_c = T_a + ((NOCT-20)/800)*G_t \quad (3.3)$$

Where,

T_a - is ambient temperature in oC

NOCT- Nominal operating cell temperature in oC

G_t - is the solar radiation in a tilted module plane (W/m^2)

The total radiation in the solar cell (considering both normal and diffuse solar radiation) is calculated as:

$$I_t=I_b R_b+I_d R_d+(I_b+I_d)R_r \quad (3.4)$$

BIPV Windows

BIPV system is an energy-producing building component that derives power from a renewable source (i.e. solar), it utilizes solar energy harnessed and converted into electricity by photovoltaic technology via solar cells which are integrated into the building envelope. BIPV windows are the semi-transparent photovoltaic (STPV) glazing integrated within windows applied to buildings while reducing solar heat gain and indoor delighting, BIPV windows have a photovoltaic effect that transforms part of the incident solar irradiation into useful electricity (Danny & al., 2009).

Therefore, BIPV windows can attenuate the solar radiation penetrating rooms, reduce the power consumption of air-conditioning systems, and mitigate light glare from windows. Furthermore, in Kampala City, the application of BIPV windows in arcades, and shopping malls should have the best energy-saving efficiency. Figure 9 illustrates how it affects building energy consumption (Mithraratne & al., 2013), followed by those on multifunctional buildings and Hotel buildings. Therefore, the impact of BIPV windows is analyzed in three dimensions: Optical performance, Thermal performance, and Electricity generation (Eric, 2022).

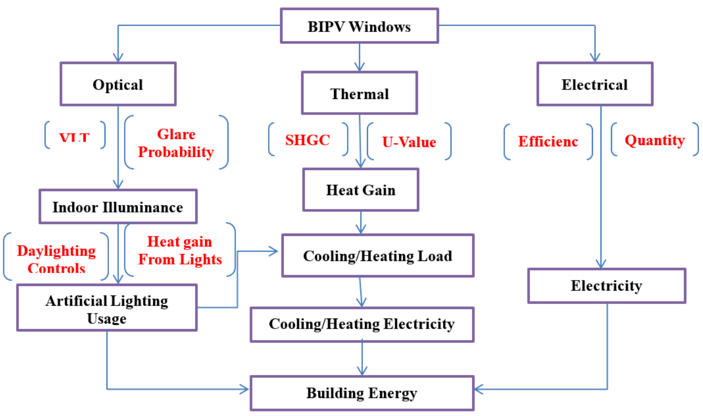

Figure 9- The effects of BIPV adoption on building energy consumption (Mithraratne & al., 2013)

The optical performance

The indoor visual effect and energy consumption of artificial illumination are affected by the optical performance including VLT (Visible Light Transmittance) and glare probability value (Sosten & Edson, 2012), (Guoqing & al., 2021), and (Yang & al., 2019).

The thermal performance

The thermal performance is mainly expressed in terms of Solar Heat Gain Coefficient (SHGC) and U-value (Heat Transfer Coefficient) (Peng & al., 2013). Thus, the value of SHGS determines the solar energy directly incident into the room through the window, and the U-value determines the heat gains/losses through the window due to the temperature difference between indoors and outdoors U-value or U-factor ratings generally fall between 2.2 and 1.2 (Chen & al., 2012), (Cuce & al., 2015).

Therefore, both SHGC and U-value significantly affect the heat gains/losses of the room. Hence, affecting the energy used for HVAC systems (Sosten & Edson, 2012), (Guoqing & al., 2021), (Peng & al., 2015).

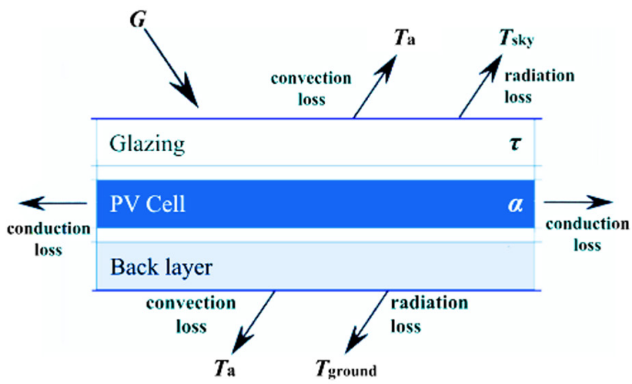

Figure 10: Thermal Processes in a PV Module (Santos & al., 2022)

Where, G - *Solar irradiance*; T_a - Ambient temperature; V_w - Wind speed

The electrical performance

The electrical efficiency and electricity production per square meter characterize the Electrical performance (Sosten & Edson, 2012), (Guoqing & al., 2021). Furthermore, BIPV windows can generate electricity which can be consumed in the buildings or connected to a grid which has realized building energy conservation to a certain extent. Therefore, the impact of BIPV windows on building energy consumption is determined by the trade-off between electricity generation performance, thermal performance, and lighting performance (Mithraratne & al., 2013).

General Description of BIPV Windows

BIPV windows absorb partial solar radiation and convert some of them to generate electricity. Hence, affects indoor heat gains and natural daylight (Chae, Kim, & Park, 2014).

Types of solar cells used in BIPV Windows

c-Si, a-Si/CdTe solar cells

The Cadmium telluride (CdTe) solar cells contain thin-film layers of cadmium telluride materials as a semiconductor to convert absorbed sunlight and hence generate electricity. Moreover, in these types of solar cells, one electrode is prepared from copper-doped carbon paste while the other electrode is made up of tin oxide or cadmium-based stannous oxide. Therefore, CdTe thin-film PV solar cells can be assembled rapidly and easily as long as an economical substitute for conventional silicon-based PV technologies (Gaetam & al., 2020). Furthermore, numerical analysis of a closed double PV glazing that used a-Si-based solar cells with a lower coating to evaluate the heat transfer by radiation and convection, and the internal airflow patterns in the middle air gap (Han, Lu, & Yang, 2021).

Poly-Si, Dye-sensitized Cells (DSSCs) and Perovskite solar cells

Here, window and glazing system choices are considered holistically. Therefore, the application of a new type of carbon counter electrode Perovskite solar cells used for BIPV windows and its optimum choice depend on many factors including the building use type, the local climate, utility rates, and building orientation (Ghosh & al., 2020).

Window Characteristics

The following characteristics specify the window system: a) Window U-value/U-factor, b) Window SHGC/Shading Coefficient (SC), c) Glass Visible Transmittance (Tvis-glass), and d) Tints (colors) and coatings for specific aesthetic and performance objectives (Ander, 2016).

U-value/ U-factor

U-value indicates the rate of heat flow due to the heat transfer law (conduction, convection, and radiation) through a window as a result of a temperature difference between the inside and outside (Ander, 2016). The higher the U-factor the more heat is transferred/lost through the window in winter.

*U-value is measured (Btu/hr*ft^2*^{0}F): Btus per hour per square foot per ^{0}F.*

The range of U-factors usually measured from a high of 1.3 (for a typical aluminum frame single-glazed window) to a low of around 0.2 (for a multi-paned, high-performance window with low-emissivity coatings and insulated frames) (Eric, 2022). A window with a U-factor of 0.6 will lose twice as much heat under the same conditions as one with a U-factor of 0.3. Therefore, total/net window U-factors can be considerably higher than the center-of-glass U-factors (Ander, 2016), & (Eric, 2022).

Solar Heat Gain Coefficient (SHGC)

SHGC indicates how much of the sun's energy striking the window is transmitted through the window as heat inside homes. As the SHGC increases, the solar gain potential through a given window increase (Eric, 2022). Therefore, the SHGC is a ratio between 0 and 1 (SHGC=0 means none of the incident solar gains is transmitted through the window as heat, and SHGC=1 means that all of the incident solar energy is transmitted through the window as heat). Typically, windows with SHGC values are desirable in buildings with high air-conditioning loads while windows with high SHGC values are desirable in buildings where passive solar heating is needed (Energy, 2022), (Burgess, 2022).

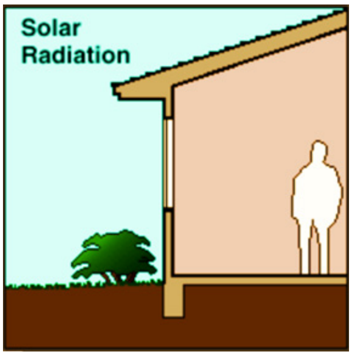

Figure 11-a: Solar radiation

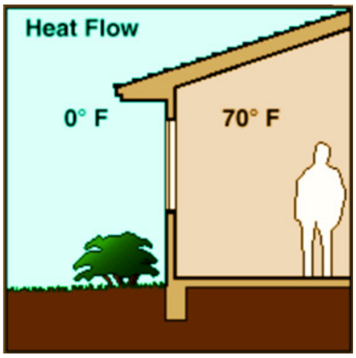

Figure 11-b: Heat flow

Generally, low SHGC windows should be considered for East and West-facing glazing as a means of controlling solar heat gain and increasing occupant comfort (Uganda Gazette No.35, Volume CXII, 2019). For large commercial structures specify low SHGC windows on the East, South, and West facades. SHGC for North-facing windows is not critical for most latitudes in the continent of Africa (Eric, 2022). For buildings where passive solar heating energy is desired, south-facing windows with high SHGC values coupled with low U-factors should be specified. Select windows with comfort. The proper specification of windows can result in higher Mean Radiant Temperature in winter and Lower MRT in summer, improving occupant comfort and productivity. MRT represents the average temperature occupant feels from radiant heat exchange with their surroundings (Elif & al., 2019).

Visible Light Transmittance (VLT)

Visible Transmittance indicates the percentage of the visible portion of the solar spectrum that is transmitted through a given glass product (sunlight, ultraviolet (UV, visible and Infrared (IR), which is approximately 390 to 780 nanometers within the solar spectrum) transmitted through the glass (Windows, 2023). It is determined by the glass's color and thickness.

Figure 12- Visible Light Transmittance (Windows, 2023)

Therefore, the VLT range of clear float glass is 75% to 92% VLT; colored has 14% to 85% (Elif & al., 2019). For a given glazing system, the "Coolness Index (Ke)" also called the "Efficacy Factor", is the ratio of the Tvis-glass to the shading coefficient (SC):

$$K_e = T_{(vis\text{-}glass)} / SC \qquad (4.1)$$

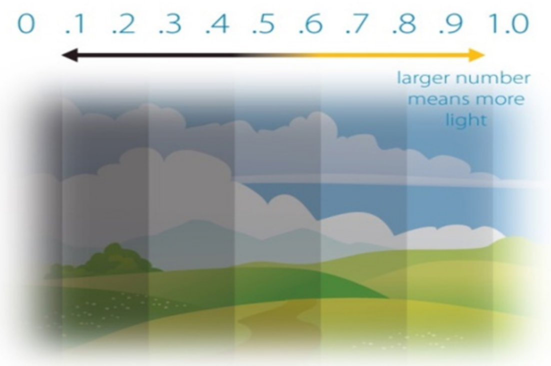

Figure 13- The amount of light entering a home (Windows, 2023)

In general cases, specify low U-factors (<0.40) for residential applications. Even lower values may be desired in extreme heating climates. Furthermore, when specifying Windows performance, take care to specify "whole product performance value" for U-factors and SHGC. For none residential buildings, high (>70%) Glass Visible Transmittance is desired, especially for daylighting applications (Table 4).

The daylight maximization

With modern high-performance glazing systems, it is possible to use low-E coatings to allow the greatest amount of light in, while rejecting the solar heat gain through the glass. Moreover, while we want to minimize the amount of solar heat gain, we also want to maximize the amount of light getting into a room. Therefore, the type of low-E coating that is appropriate for your specific house depends on your location, window orientation, and window area that is being used.

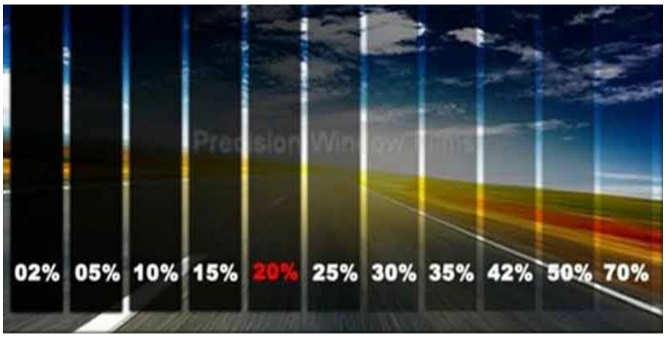

Figure 14- Solar heat gain through the glass

The VLT/TVW is just one of the measures that tell us how well a double-glazed window performs. Although maximizing the amount of light entering through a window is often desired, especially in colder climates, there is often an undesirable solar heat gain. High-performance windows with low-E coatings can reject the solar heat gain while allowing relatively high amounts of visible light to pass through the glass, however, the more solar gain is filtered out, the less (minimal) the transmittance. Tints can also be added to glass to decrease light transmittance (Eric, 2022).

Field Measurement

The test of the study was done at The Pearl of Africa Hotel- Nakasero, with a standard master bedroom medium in size of 26m^2 (4.65m X 4.61m) or (14'x 20') facing East-West, according to the Uganda Gazette No.35, Volume CXII, 2019, and was selected to study its energy output, heat gain, heat loss, and daylighting measurement. The room is on the 4th floor free from shading and obstacle to ensure it receives the maximum amount of solar irradiance. The measurements were done using a designed PV window to measure, evaluate, and validate the maximum power DC from the PV window module. The details of the electrical and thermo-optical characteristics of the PV module are shown on Figure15 and Table 3.

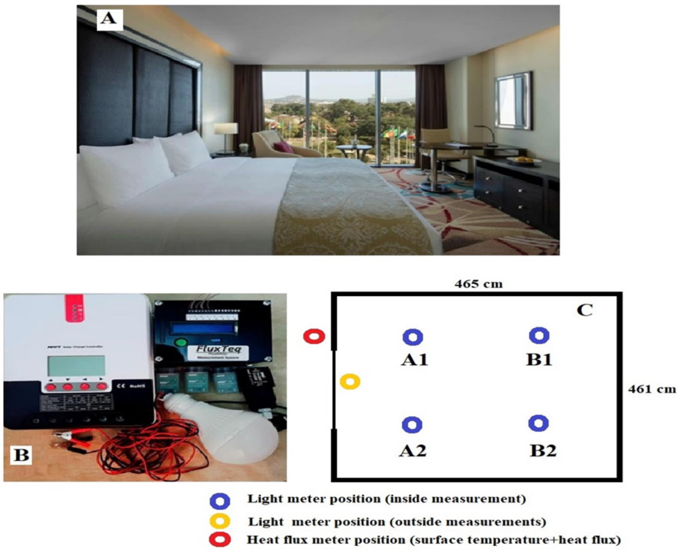

Figure 15: (A) *The tested BIPV window in the chosen room for the experiment,* **(B)** *the apparatus used during the test, and* **(C)** *the equipment's arrangements during the test.*

Table 3: Electrical and thermo-optical characteristics of the BIPV windows used in this study

Amorphous Silicon (ASG090)	
Dimension: Length (L), Width (W), Thickness (T)	**1,400 x 1,100 x 6.8 mm**
Electrical Properties (STC)	
Efficiency of Module (η)	6%
Maximum Power (P_{max})	100 Watts
Maximum Voltage (V_{pm})	78 V
Maximum Power Current (I_{pm})	1.16 A
Open Circuit Voltage (V_{oc})	100 V
Short-Circuit Current (I_{sc})	1.43 A
Temperature Coefficient (β)	-0.0033/^{0}C
Temperature Coefficient (α)	-0.0009/^{0}C
Temperature Coefficient (γ)	-0.002/^{0}C
Optical Properties	
Visual Light Transmittance (VLT)	20%
Thermal Properties	
U-value	4.0 at Summer Daytime
	5.8 Winter Night-time
Solar Heat Gain Coefficient (SHGC)	0.4

The system consists of 3 main components a PV window and battery with VLT, two solar charge controllers (MPPT), and a fluorescent lamp (load element) of 12 volts. Thus, all affect the daylighting measurements. Therefore, to achieve the minimum line of sight, the distance between the floor and the bottom part of the BIPV window showing the equivalent windows-to-wall ratio (WWR-eq) to avoid overheating was demonstrated using formula (4.2) and Tables 4 &5 below:

$$WWR_{-eq} = \frac{\sum Awi*SHGCwi*ASFwi}{Av+2*\sum(Asi*SHGCsi/Ah} \qquad (4.4)$$

Where,

Awi - is area of individual windows (m^2)

SHGCwi - is solar heat gain coefficient of the individual window (provided by the supplier)

ASFwi is the architecture shading factor of the individual window

Av-is area of all vertical surfaces (opaque walls+windows)(m^2)

Asi-is area of the individual skylight (m^2)

SHGCsi - is the solar heat gain coefficient of the individual skylight (provided by supply.)

Ah-is area of all horizontal surcafes (roof+skylight)(m^2).

Table 4- Performance of path building envelope requirements for residential/hotel buildings according to the climate (Uganda Gazette No.35, Volume CXII, 2019)

Window-to-Wall Ratio WWR (%)	U-value Roof W/m2.K		U-value Wall W/m2.K		U-value Window W/m2.K		SHGC*	
	Zones 1,3,4,5	Zones 2	Zones 1,3,4,5	Zones 2	Zones 1,3,4,5	Zones 2	Zones 1,3,4,5	Zones 2
≤15%	0.63	0.71	0.77	1.60	4.0	5.8	Not Required	Not Required
16-25%	0.63	0.71	0.77	1.60	4.0	5.8	0.7	0.7
26-35%	0.63	0.71	0.57	1.60	3.3	4.0	0.5	0.6
36-45%	0.55	0.71	0.57	1.26	2.6	3.3	0.4	0.4
SRR Skylight					**U- value Skylight W/m2.K**		**SHGC**	
≤2%					4.0	5.8	0.4	0.4
2.1-5.0%					3.3	5.8	0.2	0.2

*SHGC of the glazing of the proposed building can be multiplied according to the architectural shading factor (ASF) for exterior permanent solar shading (overhangs and fins).

*SRR is the skylight Roof Ratio which is the ratio of the total skylight area of the roof, measured to the outside of the frame to the gross exterior roof.

Table 5-Upper Limits for the equivalent window to wall ratio (WWR-eq) (Uganda Gazette No.35, Volume CXII, 2019)

Climate Zone	Max. Reference Window to Wall Ratio (WWR-ref)
Zone 1: Hot-arid	0.30** //0.22*
Zone 2: Hot- semi-arid/Savannah	0.25** //0.21*
Zone 3: Great Lakes	0.25** //0.21*
Zone 4: High Upland	0.30** //0.21*

Discussions

Designing a Photovoltaic (PV) system involved estimating its electricity production. Moreover, the considered PV performance was influenced by the environmental conditions and the resulting PV Cell operating temperature (TC) (Trinuruk & al., 2009). Therefore, a Thermal model was necessary to estimate the PV operating temperature. However, designing, implementing, and effectively monitoring PV system's performance was a difficult task due to the influence of factors related to the physics of solar cells and the environment (Leticia & al., 2022).

Types of BIPV windows to be used in the Republic of Uganda

BIPV windows were divided into single-glazed BIPV windows, double-glazed BIPV windows with/without ventilation, and vacuum BIPV windows based on the configurations of the glazing as shown in Figure 16.

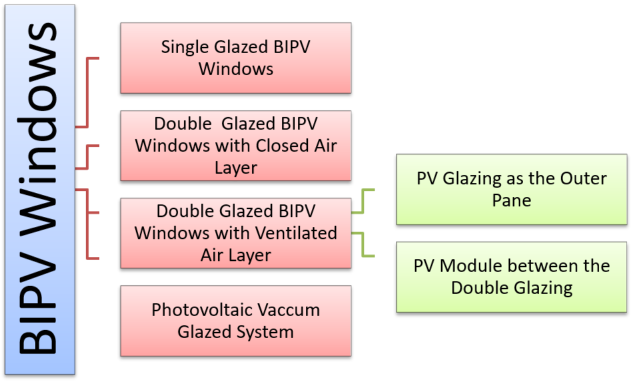

Figure 16- BIPV Windows classification

Single-glazed BIPV Windows

A single-glazed BIPV window refers to a window equipped with single semi-transparent PV glazing. As shown in Figure 17, the single PV glazing consists of two layers of glass panes and a series of thin-film solar cells which are enclosed between the two glass panes.

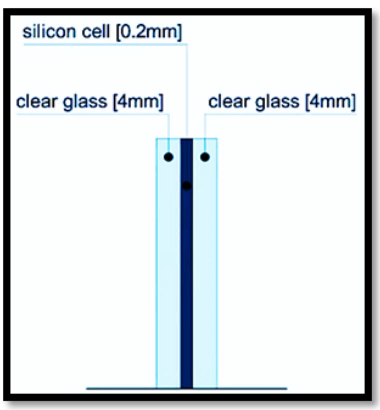

Figure 17- a: Single laminated glass BIPV section (Ugo, 2015)

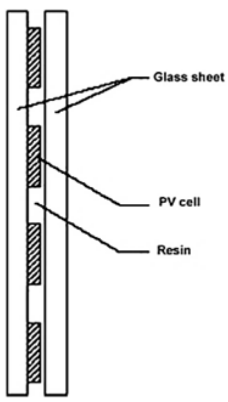

Figure 17- b: Structure of Single glazed BIPV windows

The single PV glazing can be used as a common glass pane in a window. This class of BIPV windows can produce electricity and reduce indoor solar heat gain as it converts part of incident radiation into electricity. Single PV glazing is the basic type of PV glazing and all the other classes of PV glazing are based on it whereby the thin-film solar cells are semi-transparent with a VLT (Visual Light Transmittance) usually ranging from 5% to 10% (Fung & al., 2008).

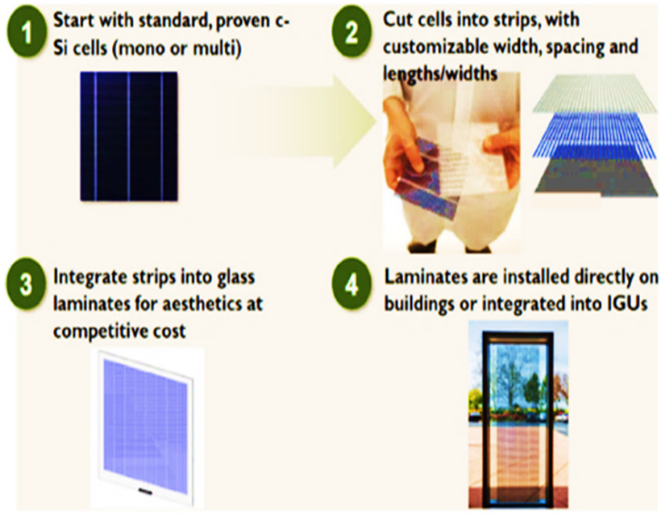

Figure 18: Specific Technical procedures of novel BIPV Module based on c-Si (Curcija & al, 2019)

Performance of Single-Glazed BIPV Windows

The total heat gain mainly comes from solar heat gain Figure 18, while other factors such as PV efficiency have little effect on it. (Fung & al., 2008)

Double-glazed BIPV Windows

The double-glazed BIPV windows with closed air layer refer to windows equipped with closed double PV glazing as shown in Figure 20. It consists of a single PV glazing as an outer pane, an ordinary single glass pane, and an air gap-sealed between the two panes. This system has also lower U-Values than Single-glazed BIPV windows. The silicon PV-based semi-transparent PV glazing remains regularly distributed opaque PV cells and offers transparent gaps between PV cells as shown in Figure 19 whereby incident solar radiation on the portion covered by opaque PV cell generates clean electricity, and the remaining part is absorbed by PV material. The transparent portion allows incident solar radiation, which allows solar heat gain, daylight, and viewing through the glazing.

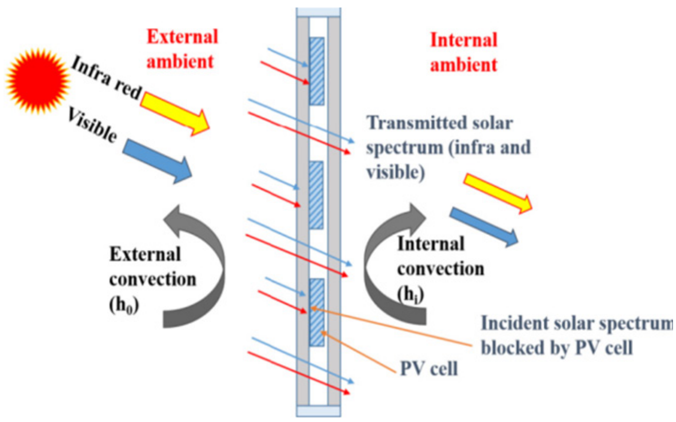

Figure 19-Schematic of silicon solar cell based on semi-transparent type PV glazing (Ghosh & al., 2020)

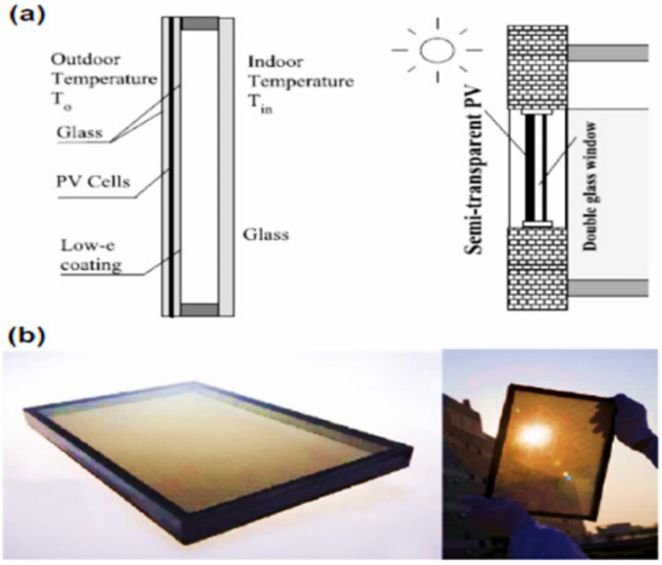

Figure 20 -Schematic diagram of double-glazed BIPV (Han, Lu, & Yang, 2021)

The proportion of light transmitted by glazing is specified by the Visible Light Transmittance, which is recorded as either TV_W (visible transmittance of the window) or VLT (visible light transmittance). While the VLT/TV_W rating varies between 0 and 1, most double-glazed windows rate between 0.3 and 0.7, which means that between 30% and 70% of the available light, passes through the windows.

A simple way to consider this:

Low TV_W = too dark inside = lights on =higher energy bills.

High TV_W = brighter inside + better views outside

Performance of Double-Glazed BIPV Windows

According to the experiment, the surface temperature of double-glazed BIPV windows in summer daytime and winter night is 1oC lower and 2oC higher than that of ordinary windows, due to the effect of the thermal insulation respectively.

Double Glazed BIPV Windows with ventilated air layers

It consists of external single glazing, a middle air layer, internal glazing, and two vents located at the top and bottom respectively as shown in Figure 21. The airflow extracts heat produced by the PV module, thus decreasing the PV temperature effectively, whereby the shielding effect of PV and the outdoor air flowing into vents reduce the solar energy entering the indoor space.

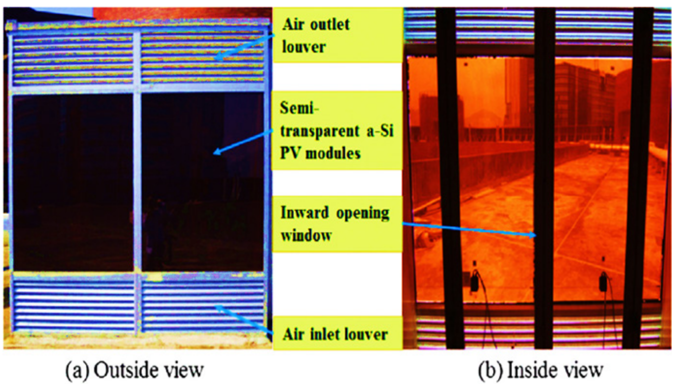

Figure 21-a: Double–glazed BIPV window with ventilation (Peng & al., 2015)

Figure 21-b: Actual inside view of Pearl of Africa Hotel with normal windows

Figure 22 shows another type of PV Vacuum glazing and heat transfer that temperature distribution and total heat transfer coefficient, whereby its results show and suggest that the best performance of PV vacuum double glazing can be achieved in four configurations when both PV module and U-Value are considered.

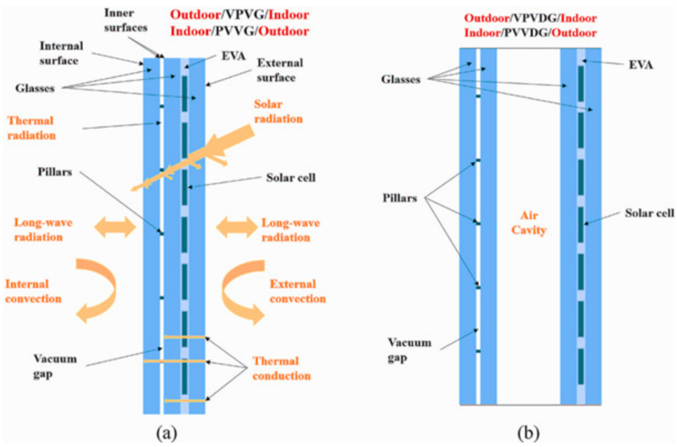

Figure 22: PV Vacuum glazing and heat transfer illustration (Huang & al., 2021)

Figure 23: Double–glazed BIPV window with ventilation before and after installation on facades

Mathematical Model

Different approaches of circuit models are adopted for parameter extraction of PV modules, and PV devices can be represented by an equivalent electric circuit as shown in Figure 24. (Duffie & al., 2013), and this considered circuit model is a one-diode five-parameter model with a solar intensity-dependent current source (Iph), a p-n junction diode, and two resistances (Rs, and Rsh). The resistance plays the role of the dissipative effects and construction defects which cause parasite currents within the PV module (Orioli & al., 2013).

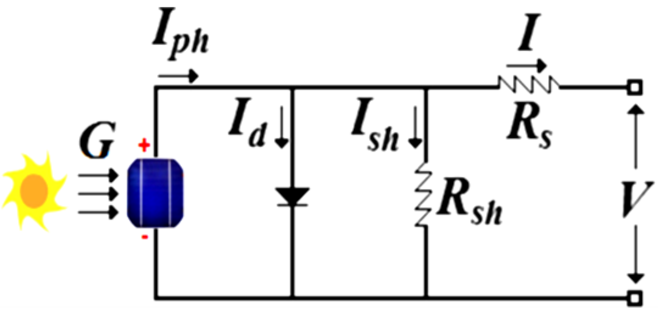

Figure 24: One-diode equivalent circuit for a PV Module (Erden & al., 2017)

$$I = I_{ph} - I_{Rs}\left[exp\left(\frac{qV}{kT}\right) - 1\right]$$ - *The Shockley's Ideal Diode Equation* (Sse & al., 2023) *(5.1)*

I_{ph}- The Photocurrent generated by the incidence of light
I_{Rs}- The reverse saturation current
T- The Temperature
k- The Boltzmann constant
q- The Electron charge

$$V_T = \frac{kT}{q} = I_{Rs}\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \qquad (5.2)$$

***Where VT**- Thermal Voltage is the last three terms grouped into one single parameter.*

Figure25- Double–glazed BIPV window with ventilation before and after installation on walkways

Conclusions and recommendations

The article discussed hot research issues and has research value. In the Republic of Uganda, the BIPV Windows in Arcades and shopping malls are the best energy-saving efficiency, followed by those on multifunctional buildings and Hotel buildings in Kampala City. While we want to minimize the amount of solar heat gain, we also want to maximize the amount of light getting into a room. Poor window design can reduce the amount of daylight entering the house. The type of low-E coating that is appropriate for your specific house depends on your location, window orientation, and window area that is being used whereby the VLT/TVW is just one of the measures that tell us how well a double-glazed window performs. When specifying Windows performance, take care to specify "whole product performance value" for U-factors and SHGC. Use of "glass-only" U-factors should be avoided as they can be 10% to 40% better than the whole product value.

The performance of BIPV windows is closely connected with local weather and climate, and the distribution of locations, whereby low SHGC windows should be considered for East and West facing glazing as a means of controlling solar heat gain and increasing occupant comfort. For large commercial structures specify low SHGC windows on the East, South, and West facades. SHGC for North-facing windows is not critical for most latitudes in the continent of Africa. For buildings where passive solar heating energy is desired, South-facing windows with high SHGC values coupled with low U-factors should be specified. Select windows with comfort, the proper specification of windows can result in higher Mean Radiant Temperature in winter and Lower MRT in summer, improving occupant comfort and productivity.

The efficiency of the solar cells used in a photovoltaic system in combination with latitude and climate determines the annual energy output of the system. Also, you have to find the annual radiation incident on your PV panels with your specific inclination (slop, tilt) and orientation (Azimuth). The condition under which efficiency is measured must be carefully controlled to compare the performance of one device to another. Window and glazing choices should be considered holistically. The optimum choice of window and glazing systems will depend on many factors including the building use type, the local climate, utility rates, and building orientation.

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