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Comprehensive Analysis of Performance Determining Factors of Window-Integrated Photovoltaic Systems

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Abstract

The present review article deals with the critical factors affecting the energy efficiency of Building-Integrated Photovoltaic (BIPV) systems, especially Semi-Transparent Photovoltaic (STPV) windows. Initially, the relationship between module temperature and energy output is highlighted. It was found that with temperatures, the annual energy declines by 5% to 8%. The temperature coefficient of maximum power was found to range from 0.0026 to 0.0045 per °C. Factors like the STPV color of the module, atmospheric conditions, and mounting structures are also explored. Next, the role of local climate, incident spectrum, and radiation on STPV performance is addressed, stressing the importance of evaluating actual conditions. The discussion then shifts to the effects of the angle of incidence on energy production, emphasizing optical losses and reduced power generation at higher angles. Lastly, the influence of orientation, Window-to-Wall Ratio (WWR), and photovoltaic cell/module characteristics on energy performance are discussed, highlighting aspects like transparency, Solar Heat Gain Coefficient (SHGC), and U-value or the thermal transmittance.

Key Words: *Cell temperature; Local climate; Incident spectrum; Angle of incidence; WWR*

1. Introduction

In the global energy mix, the building segment consumes about 40% of energy [http://www.unep.org/sbci/AboutSBCI/Background.asp]. In the energy needs of buildings, the windows play a critical role. Further, natural daylight is crucial for comfort and an efficient working environment. Windows have an important role in maintaining natural daylight along with the view and fresh air for occupants [Yao and Zhu, 2012]. The energy generation and natural lighting through an STPV window system are determined by the window's size, glazing type, and orientation.

ABBREVIATIONS

Notation	Description	Notation	Description
a-Si	Amorphous Silicon	m-Si	Mono-crystalline Silicon
AOI	Angle of Incidence	NFRE	National Fenestration Rating Council
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	OECD	Economic Co-operation and Development
BIPV	Building Integrated Photovoltaic	p-Si	Polycrystalline Silicon
CdTe	Cadmium Telluride	PV	Photovoltaic
ECBC	Energy Conservation Building Code	SHGC	Solar Heat Gain Coefficient
CIGS	Copper Indium Gallium Diselenide	SNL	Sandia National Laboratory
CRI	Colour Rendering Index	RMSE	Root Mean Square Error
HIT	Heterojunction with an Intrinsic Thin layer	STPV	Semi-Transparent Photovoltaic
HPVT	Hybrid Photovoltaic Thermal	TCO	Transparent Conducting Oxides
IEA	International Energy Agency	VLT	Visible Light Transparent
IEC	International Electrotechnical Commission	WWR	Window-to-Wall Ratio
MPP	Maximum Power Point	ZEB	Zero Energy Buildings
MPPT	Maximum Power Point Tracking		

According to ASHRAE (2009), the functioning of a window is characterized by three properties, namely (a) U-value of the window assembly, (b) SHGC, and (c) VLT through the window. Besides the above elements, condensation defiance, and air leakage are also necessary to label the energy performance of a window system by the NFRE.

In several regions of the world, CG with a poorly insulated frame is used in the window. The U-value of the above types of windows ranges from 4.5 to 5.6 W/m^{2}K. On the other hand, most of the EU member countries targeted to achieve a U-value between 1 to 2 W/m^{2}K. Several countries in the OECD region have achieved a low U-value window, between 1.2 to 1.8 W/m^{2}K by using the Low-e coated glazing and low conductive frame. However, much R&D will need to be conducted to achieve the targeted U-values of the window recommended for ZEB.

Energy positive or ZEBs are the needs of the present time due to their ability to reduce carbon emissions, combat climate change, and enhance energy security by generating as much or more energy than they consume, thus promoting sustainable development and resilience in the face of environmental challenges. In the recent past, this type of building has become a reality through efficient devices and design. The incorporation of solar and other renewable technologies in buildings has a great role in realizing the ZEBs [Charron and Athienitis 2006]. The literature also reveals that the BIPV systems have a vital role to play towards achieving the goal of ZEB in the years to come [Kolokotsa et al., 2011; Baetens et al., 2012; Bureau of Energy Efficiency, 2017]. The importance of the integration of solar photovoltaic systems in buildings has also been emphasized in the recently published ECBC-2017 of India. The code has recommended meeting at least 4% of the total electricity loaded by solar or other renewable energy in the advanced buildings called super ECBC buildings [Yoon et al., 2013].

In buildings, the photovoltaic modules can be integrated as rooftop power plants, façade/windows, window overhangs, and skylights. Researchers have recently shown significant interest in STPV systems among various BIPV options [Jung et al., 2014; Wong et al., 2008]. One key factor is the ability of STPV module-embedded windows to decrease off-site electricity demand while also permitting daylight to illuminate interior spaces [Peng et al., 2011]. Further, the STPV integrated window systems maintain the primary purposes of a window similar to a conventional system. In many cases, the STPV integrated window systems show improved quality than the conventional windows.

Figure 1 presents a comparison of the working of the STPV window and the conventional window.

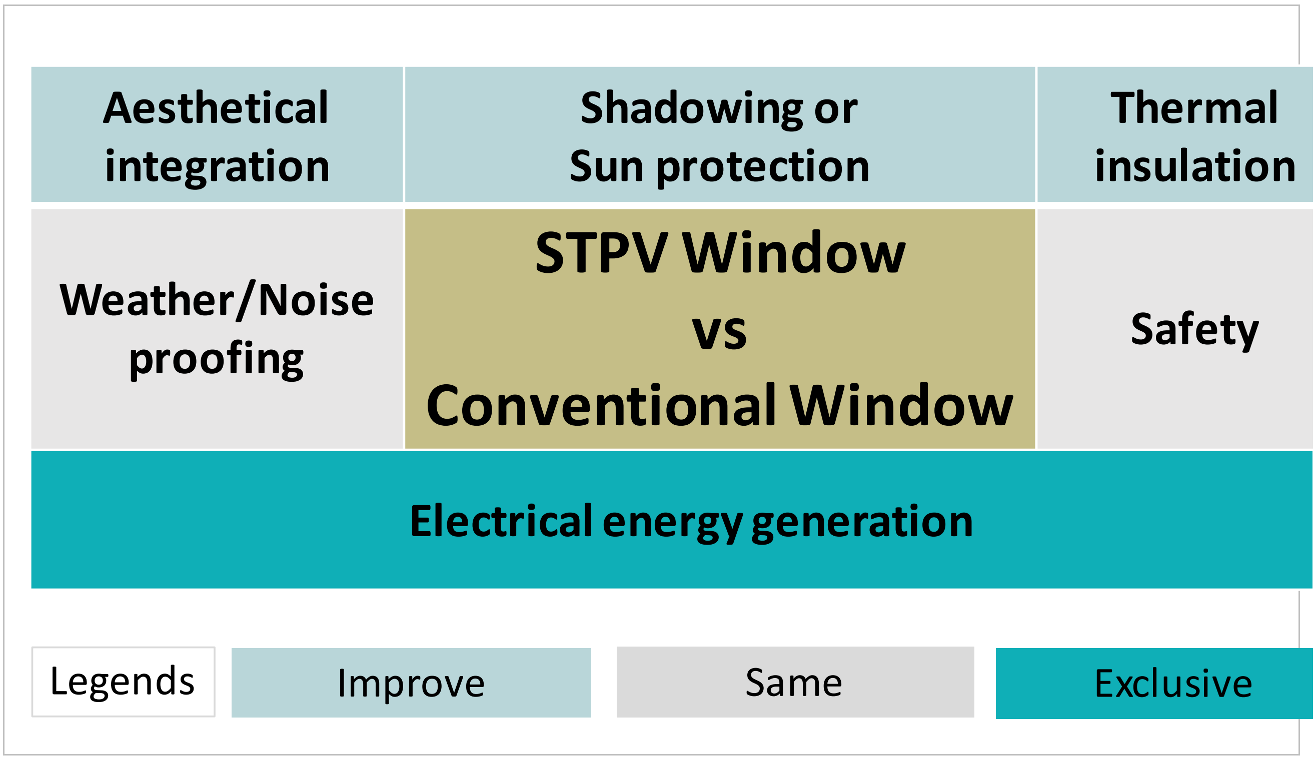

Figure 1: Working of the STPV window in comparison to conventional windows

In a BIPV system, the photovoltaic modules become an integral part of the building envelope [Chae et al ., 2014]. Because of the above situation, a complex relationship is established between the BIPV system and the building energy load. For example, an STPV module-based window system that *generates energy* also needs to pass daylight through it. The performance of STPV, similar to that of any other photovoltaic module, is influenced by factors such as installation location, design, and operating conditions [Miguel et al., 2002]. Moreover, the part of absorbed solar radiation, which doesn't get converted into electrical energy, leads to increases in the STPV module's temperature and releases heat into the surroundings. The release of heat into the occupant area contributes to the buildings' cooling demand. Further, due to constraints at the material level, a wide range of the solar spectrum doesn't convert into useful electrical energy. Therefore, particular attention is required in the selection and design of the STPV module-based window system. The present research included a comprehensive study on the performance-determining factors of the STPV window system.

2. Performance determining factors of a STPV module-based window system

Like any other photovoltaic device, the BIPV’s performance is also influenced by various interdependent factors. Some of the crucial factors are module and ambient air temperature, place of installation, incident radiation and spectrum, AOI & tilt angle, orientation or surface azimuth, shading, soiling, and so forth. Another set of PV systems performance determining factors is the opto-thermal, electrical properties, type of material, and cell area in the module. The performance is also affected due to wiring, string diodes, partial shading, dirt accumulation, low &in-homogeneous radiation, cell mismatch, MPPT, and system failure [Singh and Ravindra, 2012]. In the following subsection, some of the factors and related research findings are explained in brief.

2.1 Module temperature

For a PV module, the fill factor and conversion efficiency decrease when the cell temperature increases [Makrides, et al., 2012]. These dependencies eventually reduce the energy generation capacity of the PV module. Depending upon the type of the PV material, the annual energy generation reduces in the range of 5% to 8% due to elevated operating temperature [Yamawaki et al.2001]. The reduction in power generation for per unit rise in temperature of the cell is represented by θ_k, known as the temperature coefficient of maximum power. The value of θ_k, varies with the change of material of the cell. Several researchers have calculated the value of at the cell/module as well as at the system level [Nagano, et al., 2001; Chow, 2003; Zondag, et al., 2003; Radziemska, 2003; Bakker, et al ., 2005; Tiwari and Sodha, 2006; Tiwari and Sodha, 2007; Assoa, et al., 2007; Hove, 2000]. The result of the above researcher's work reveals that, depending upon the applied material/system, the value of θ_k remains between 0.0026 per ^{0}C and 0.0045 per ^{0}C. Various correlations for temperature-dependent photovoltaic conversion efficiency have also been proposed in the literature [Bazilian and Prasad, 2002; Yamaguchi, et al., 2007; Zhu et al., 2004; Notton, et al .,2005; Chow, et al., 2006; Aste et al., 2008]. However, the temperature of photovoltaic modules in an STPV window/façade system varies with design and operating conditions. This variation demands the assessment of module temperature for a design or application. For a BIPV plant, the assessment of module temperature is also important due to its influence on the heat transfer into the occupant area.

Through an experiment, Park et al.,[2010] found that the colour of the STPV modules and the property of the back glass are some of the determining factors of module temperature. In the study, it has been reported that there is a 0.52% reduction in power generation for every degree of rise in cell temperature.

Armstrong and Hurley[2010] proposed a model by considering different atmospheric conditions, materials, and mounting structures. Jones and Underwood [2001] also gave a transient model for the module temperature. In both studies, the module temperature is found to be changed with atmospheric features like wind speed and incident solar energy. For example, the module temperature changes from 15.62^{0}C to 15.56^{0}C when wind speed changes from 0.77m/sec to 2.14 m/sec [Armstrong and Hurley, 2010].

Using an analytical method, the effect of packing factors on the cell temperature of roof-integrated PV modules has been investigated by Vats. et al., [2012]. They considered six different types of PV modules for the study. Two modules of different packing factors are shown in

Figure 2.

Figure 2:Crystalline Si photovoltaic module with different packing factors[Kamthania. et al., 2010]

In their analysis, up to 10°C reductions in cell temperature were observed for the decrease in packing factor by 49% in the case of m-Si, a-Si, and HIT. For the similar change in packing factor, the reduction in cell temperature was 11^{0}C for p-Si, CdTe, and CIGS materials. Similarly, Kamthania et al., [2010] found higher cell temperature in the case of opaque PV technology than that of the STPV module due to heat retention in the cell.

A photovoltaic module contains different layers. The sandwich structure prevents the direct measurement of cell temperature in the actual working conditions. Nayak and Tiwari, [2008] through an experimentally validated analytical model, developed a method to calculate the temperature of various layers of a PV module. They observed that compared to the backside Tedlar layer, the cell temperature remains higher by 3–4^{0}C.

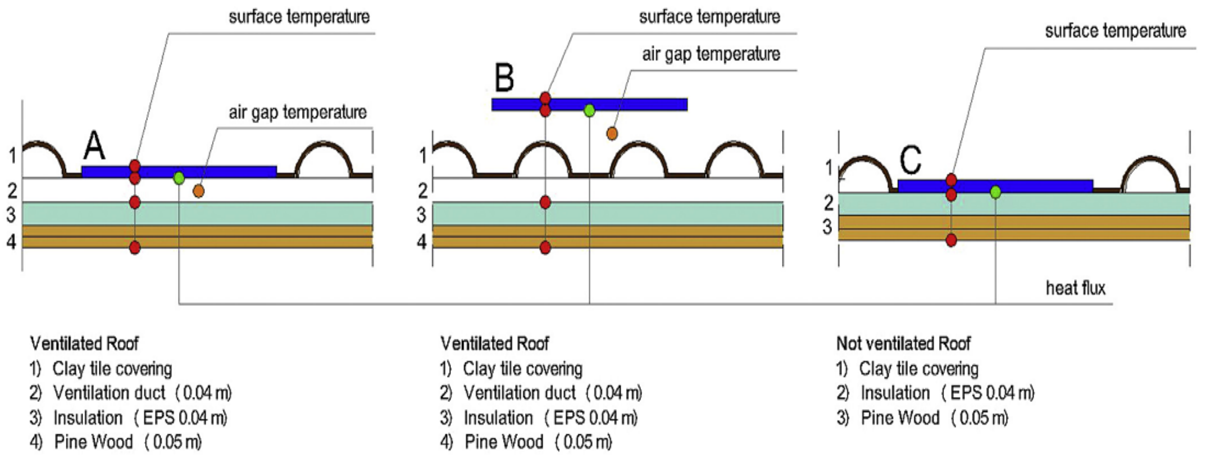

Figure 3: Experimental setup for temperature measurement of roof-mounted photovoltaic modules in different configurations [D'Orazio et al., 2014]

. The formula for operating cell temperature developed by SNL is widely used in photovoltaic research. Another widely used formula is NOCT. D'Orazio et al., [2014] compared the experimental values of cell temperature with these two standards. For this purpose, they experimented with the roof-mounted PV module. The cross-section of the setup used in the experiment is shown in Figure 3. Three different configurations were considered in the experiment. The studied configurations were a) rack-mounted, b) roof-integrated without ventilation, and c) roof-integrated system with ventilation ducts between the module and insulation. They observed that for the rack-mounted systems, both NOCT and SNL methods could predict the temperature quite accurately. However, for the combined systems, the SNL could predict more closely to the experimental results. For example, for the integrated system without any ventilation, the RMSE values between the observed and predicted average cell temperature with NOCT and SNL are ±6.3 and ±4.3, respectively. A summary of the above discussion is given in Table. 1

Table. 1

Reference	Type of study	Aim of the study	Important findings
George et al. (2012)	Outdoor experiment	To examine the influence of temperature on the energy yield of PV technologies	Due to cell temperature, the annual energy generation is reduced from 5% to 8%
Park et al., (2010)	Experimental work	To analyze the electrical characteristics of STPV modules and their temperature variation	Power generation decreased by 0.52% for a one-degree rise in the temperature of the cell.
Vats et al., (2012)	Analytical work	To investigate the influence of the packing factor of the STPV in a module, room air temperature, electrical efficiency	Depending upon module technology, the temperature is reduced by 10^0C to 11^0C with a decrease in packing factor by 49%.
Kamthania et al., (2011)	Numerical analysis	To assess the performance of the HPVT double pass structure for room heating	The cell temperature remains higher in an opaque PV module compared to the STPV
Nayak and Tiwari (2008)	Experimental work with numerical analysis	To experimentally validate the energy and exergy thermal model of the PV module	Cell temperature remains higher than the backside tedlar layer by 3^0–4^0C.

2.2 Local climate, incident spectrum, and amount of incident radiation

The air mass of a particular climate is determined by water vapor, clouds, and other climatic factors. The air mass is found more than 1 AM in numerous locations of the globe [Åsbjørn et al., 2011]. The air mass and consequently the spectral features of solar energy vary with time and geographical location. Further, a solar cell cannot absorb the whole spectrum of the incident radiation. The photovoltaic module's responses to the incident spectrum vary depending upon the type of the cell material.

For example, modules with a cell of a-Si material are more sensitive to the incident spectrum than that of the p-Si due to the narrow working wavelength range [Minemoto, et al.,; Virtuani et al., 2015]. The incident spectra also influence the power loss of a photovoltaic cell [Peharz and Ulm, 2019]. This factor can incorporate a loss range from 1 to 5 percent [Kumar et al., 2019].

Water vapor is virtually transparent in wavelength range, which is effective for CdTe photovoltaic panels [Nelson et al., 2013]. The transmittance of water vapor remains almost 100% between 320nm to 800nm, with a slight dip at 715nm to 725nm wavelength. Consequently, the conversion efficiency of the CdTe module in the monsoon and post-monsoon seasons is more compared to the other seasons. However, a high-conversion efficient module with more incident solar radiation only results in more power generation.

In the actual operating condition, the amount of incident radiation changes from location to location. It also changes with the state of the receiving surface. Li and Lam, [2004] have proposed an approach to estimate the sun radiation values on different planes considering the available sky irradiance data. Further, Aaditya et al., [2013] carried out an experimental inquiry on the working of the roof-integrated photovoltaic system in the temperate climate of (Bengaluru) India. In the study, they found that besides the cell material and mounting method, the working of the PV system is affected by incident solar irradiance along with the ambient temperature. Further, in the experimental analysis, Li et al.,[2005] found that more incident radiations with lower operating temperatures (16.5^{0}C) produce more energy in the winter compared to the summer season.

Therefore, to know the economic perspective, performance evaluation of a PV system in actual functioning conditions is essential in addition to the data provided by the manufacturer [Silverman, et al., 2004].

The working inquiry in a particular climatic condition proves the appropriateness of a given PV technology for that site [Sharma, et al ., 2018]. The working analysis of the STPV plant in a site is also vital to build assurance amongst the designer and architect. It helps in applying energy calculation tools in the novel smart buildings. Chae et al., [2014] assessed the energy functioning of the STPV window in six different locations in the USA. They summarised that besides the transformation efficiency, the opto-thermal properties of the PV module and place of installations

Table 2

Reference	Type of Study	Aim of the study	Important findings
Minemoto et al.,2007	Outdoor experiment	To study the effects of spectral irradiance distributions on the performance of PV modules	a-Si solar cell is more sensitive to the incident spectrum than that of the p-Si
Peharz and Ulm, 2019	Theoretical, simulation using Matlab	To quantify the impact of colors on the power loss of PV module	Power loss associated with different colors is different
Kumar et al., 2019	Simulation work using PVGIS	To investigate the performance of the photovoltaic module in BAPV and BIPV	Incident spectrum can incorporate a loss from 1 to 5%
Aaditya et al., 2013	Experimental work	To analyze the real-time performance of BIPV	Solar irradiance, ambient temperatures are performance-determining factors besides the material and mounting method
Li D et al., 2005	Experimental work	To investigate the performance, efficiency characteristics of the PV system	High incident radiation with a low module temperature produces more energy in the winter
Chae et al., 2014	Simulation work using EnergyPlus	To investigate the effects of electro-optical properties of the photovoltaic cell on the energy performance of a window	Besides conversion efficiency, the performance of the BIPV window also affected the thermo-optical properties of the cell, place of installation, etc.

are also important in the working of the STPV integrated system. For instance, they observed a variation of 27.4% in annual energy generation with the change in installation place. A summary of the discussion is given in Table 2 above.

2.3 Angle of incidence and tilt angle:

For a given site of the globe, the Sun's location keeps changing all over the day. For this reason, solar radiation falls at a different AOI on a stationary plane. However, in the laboratory, the radiation is maintained at normal incidence during the characterization of photovoltaic modules. On the other hand, the reflection as well as transmission of surface changes with AOI. Therefore, when a photovoltaic module is installed in the actual field, the deviation of solar radiation from the normal incidence incurs a loss in power production. These types of loss are known as optical or angular loss. Two factors contribute to this loss of energy generation. The factors are the cosine effect and the optical characteristics of the module surface [Suryanarayana, 2013]. Orientation, local climatic features, and latitude are the decisive elements of the angular loss of photovoltaic energy production [Martin and Ruiz. 2001]. In a tropical country, the solar radiation is mostly incident at a higher angle on the building window/façade. Therefore, the loss of energy generation due to the AIO becomes significant in the case of BIPV vertical systems such as windows/façades.

Martin N. and Ruiz J.M. have studied the effects of AOI on photovoltaic module energy generation using an analytical model [Martin and Ruiz 2002; Martin and Ruiz. 2005]. Three different versions of a model have been proposed to calculate the AOI effects depending upon the type of data available to the users. The calculated periodic optical loss of an m-Si module installed at two diverse angles in different locations is shown in Figure 4.

In some earlier research also, the AOI has put an emphasis on the calculation of photovoltaic module performance [Martin and Ruiz 2002, Martin and Ruiz 2005; Schaub et al ., 1994; Preu et al., 1995; Wohlgemuth, 2012].

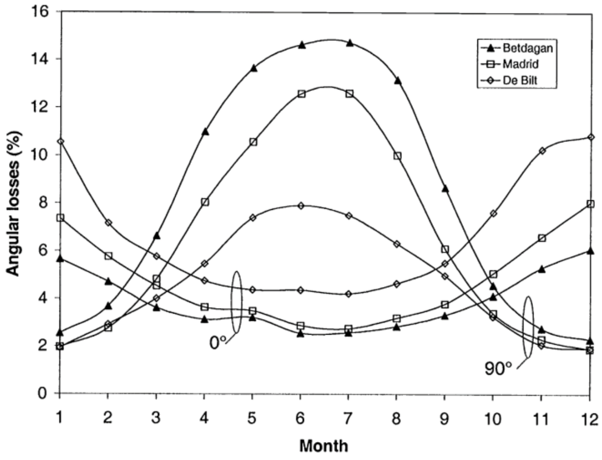

Figure 4**:** Monthly angular losses of a m-Si PV at different places (latitude) installed at ⁰ and 90⁰ tilt angle [Martin, and Ruiz. 2001]

To measure the effects of AOI on photovoltaic module performance, the International IEC has suggested a procedure in IEC 61853-2 [Wohlgemuth, 2012]. One of the major statements of this standard is that for plane glass superstrate PV module, the value of a flat glass-air boundary can be applied without performing the AOI test [Knisely, 2013]. The SNL has also developed a procedure to check the effect of AOI on non-glass or non-planar photovoltaic modules [King, et al., 2004]. Subsequently, Knisely et al.,[2013] have experimentally found similar results for five different photovoltaic module technologies. Fanney et al., [2003] have examined the influence of AOI on energy production by applying the SNL's empirical model. Their findings indicate that the effects of AOI above 60^0 could be severe for photovoltaic energy generation. Similar observations have also been drawn in another work of the same researchers [Brain et al., 2005]. Significant reflection losses beyond 50^0 AOI have also been observed by Fanni et al., [2011] and Chen et al.,[2012] have found as high as 50% reduction in power generation of the STPV module at 60^0 AOI in comparison to the normal incidence. They used the indoor calorimetric hot box for the above experiment. Also, a significant loss in energy generation at a higher incident angle has been detected in a field study by Song et al.,[2008].

The influence of the slope of the PV module on the surface temperature has been experimentally studied by Yoon et al.,[2013]. They noticed that compared to clear glass, the innermost surface temperature remains lower by 1^0C for the STPV window in the summer daytime. On the other hand, the STPV window surface temperature remains 2^0C more on the night of the winter season.

The quantity of solar energy received by photovoltaic modules also changes with the slope of the module. Elminir et al., [2001] have experimentally found that the photovoltaic modules don't receive maximum solar radiation at the same slope, in all the seasons. In the winter season, the optimum slope is more by 15^0 than the local latitude. In the summer season, the ideal tilt is less by 15^0 than the local latitude. A summary of the above discussion is given in Table. 3.

Table. 3

Reference	**Type of study**	**Aim of the study**	**Important findings**
Martin and Ruiz 2002	Analytical work	To obtain a universal model for angular loss of PV	Near the pole, the annual angular loss is high for low tilt angle, while at the equator it is vice versa
Fanney et al., 2003	Experimental work	To investigate the long-term performance of different components of the BIPV system	The influences of AOI on energy production become severe above 60^0
Fanni et al., 2011	Indoor and outdoor experiment	One of the objectives is to analyze the optical loss of power generation due to the tilt angle	Angular loss in energy generation becomes significant for AOI beyond 50^0
Song et al.,2008	Simulation work using TRANSYS & experiment	To characterize the power output of PV at different incidence and azimuth angle	The power generation decreased significantly for a tilt angle above 70^0.
Yoon et al.,2013	Experimental work	To measure the long-term surface temperature characteristic of thin film BIPV	In the summer daytime, the innermost surface temperature of an STPV window remains 1^0C lower than clear glass. While it is 2^0C higher in the winter
Elminir et al., 2001	Experimental work	To analyze the effects of atmospheric factors on PV module performance	For maximum solar radiation, the best tilt angle is ± 15^0 to the local latitude in winter and summer respectively.

2.4 Orientation and WWR

Orientation-wise, the south-facing STPV window of a building generates the maximum energy [Chen et al., 2019; Vulkan et al., 2018; Yoon et al., 2011]. It occurs due to more incident radiation on the south-facing window. With the variation in the window directions from the south to the east and west, the power generation decreases. However, in the case of BIPV application, orientations other than the south are not completely forbidden [Yadav et al., 2018]. It is observed that in a tropical country like Singapore, besides the south orientation, the other surfaces also create a good potential for vertical STPV windows. The effects of orientation on the power generation of the façade integrated BIPV (a-Si) system have been investigated by Yoon et al.,[2013] also. For this purpose, they conducted a long-term experiment (2 years) on a BIPV system installed in an institutional building. The photovoltaic integrated wall of the experiment is shown in Figure 5.

Figure 5: Application of thin-film Photovoltaic modules in institution building, (a) building front view, (b)part of the building having Photovoltaic modules [Yoon et al., 2013].

They found lower energy generation than the expected value due to the constraint in surface azimuth angle and shading effects by the other parts of the building. However, when the ESPr simulation was performed by removing the effects of azimuth angle and shading, then they observed an improvement in the energy generation by 47%. In an urban area, the performance of a BIPV system gets adversely affected due to shading [Yoon et al., 2013].

The WWR and orientation are interdependent. In a cooling-demand country like India, a small WWR is preferred in the orientation that receive higher solar radiation. However, to get more energy

from the STPV window, a larger WWR is preferable. Therefore, the optimization of WWR is done by considering the overall energy performance. Yun et al.,[2007] have studied clear glass and opaque photovoltaic modules integrated windows of different areas using ESPr software. The findings of the analysis show that the optimum WWR changes with the building location, the applied insulation, and heat gain from the artificial lighting. In the EnergyPlus simulation study, Xu et al., [2014] have observed that STPV modules with higher cell areas are suitable for buildings with deep rooms and large WWRs. The optimum value of WWR changes with the window glass transparency also. Miyazaki, et al., [2005] obtained that the STPV window of 50% WWR and 40% module transparency provides the best energy result. A similar combination of transparency and WWR was also found by Cheng, et al.,[2018]. A summary of the above discussion is given in Table. 4.

2.5 Photovoltaic cell/module characteristics

STPV module’s optical, electrical, and thermal features have a significant influence on the energy performance of a BIPV system. Various researchers have studied these features from a different point of view.

Moralejo-Vázquez et al.,[2015] found that the STPV module’s transparency is less dependent upon the cell material than the laminated material. Degradation of the laminated material influences the transmissivity of the STPV module though it does not affect the CRI inside the room. TCO is an integral part of STPV modules. However, the width of the TCO coating influences the transparency of a PV module. Lim et al.,[2013] have developed hydrogenated a-Si and a-SiGe solar cells with a varying width of TCO. The proposed optimum thickness of TCO is 300 to 500nm. Olivieri et al., [2014] studied the performance of STPV glazing with transparency from 10% to 40%. The decrease in electrical outputs with module transparency was observed in the survey. However, they concluded that transparency is not the sole electrical output determining factor. Furthermore, Kapsis and Athienitis [2015] examined the influence of module transparency on building energy demand. They noticed that the STPV unit with 10% VLT provided the best inclusive energy functioning. Chow et al.,[2007] had also investigated the effects of module transparency on the load-saving potential of the STPV double-pane ventilated window. For this purpose, they developed an energy balance model and found that the module transparency of between 45% to 55% delivered the best electricity savings

Table. 4

Reference	Type of Study	Aim of the study	Important findings
Chen et al., 2019	Experimental and numerical analysis	To evaluate the potential application of the PV window in southwest China	The south-facing window generates the maximum energy
Yoon et al., 2013	Experiment and simulation using ESPr	To investigate the influence of orientation on power generation of PV façade	Due to shading and azimuth angle, the energy generation loss was 47%
Xu et al., 2014	Theoretical model and experimental validation	To find the optimal PV cell area in terms of the overall energy consumption of office buildings	For buildings having deep rooms and large WWR, STPV modules with higher cell areas are suitable as window/façade
Miyazaki et al.,2005	Simulation work using EnergyPlus	To find the optimum module transparency and WWR of PV window for best energy savings	STPV window with 50% WWR and 40% module transparency provides the best energy performance
Cheng et al.,2018	Simulation work using EnergyPlus and experimental validation	To investigate the day-lighting and overall energy performance of STPV facades	For the best energy savings, the optimum transparency and WWR is 50–60% and 40–50%, respectively

Solar cell thickness and surface property are the determining factors for the electrical, optical, and thermal functioning of a BIPV plant. Chae et al,. [2014] grew three hydrogenated a-Si semi-through solar cells of different thicknesses with and without texturization. Besides electrical properties, the performance of the solar cells was observed to be affected by the place of installation, primary energy used, environmental impact, etc. Therefore, they concluded that the solar cell customized as per the applied location delivers the best results in BIPV applications.

Lighting color has a significant role in visual comfort and aesthetics. For an STPV module, the material and the cell thickness determine the color of the light passing through the window. Selj et al.,[2011] developed solar cells of various colors by depositing multiple-layer ARC. Subsequently, they studied the behavior of the light that passes through them. Lynn, et al., [2012] experimentally investigated the CRI of different a-Si and ~~a-~~micro-morph solar modules regarding visual comfort and aesthetics. In the investigation, the CRI of a-Si modules was found to be above 90 for all AOI, while for the micro-morph module, it was less than 90. Tak, et al.,[2017] showed that a changeable organic STPV cell window can provide better optical comfort than the conventional STPV window.

Among several aspects, SHGC has a special role in deciding the thermal functioning of glazing. It dominates the total heat ingress through the photovoltaic window [Fung and Yang, 2008]. But this property changes from module to module and with the working scenario. Kuhn [2014] at Fraunhofer, Germany, noticed that in the measurement of angle-dependent SHGC, the movement of the light source or the sample gives the same values. The calorimetric measurement of SHGC has also been performed in some other research. Chen et al. [2012] observed that the reduction in SHGC becomes rapid for AOI above 45^0, and it can be as high as 20%. They also noticed that the SHGC decreases with the connection of load in the STPV systems. Further, Olivieri. et al. [2015] observed that the SHGC changes depending upon the state of working of the STPV module. The SHGC of the same photovoltaic module is reduced by 11% when it works at MPP instead of working at a short circuit state. Along with the SHGC, the U-value has also a key impact in the thermal functioning analysis of a ventilated PV window/façade. Sánchez-Palencia et al.,[2019] have suggested a thermal model which calculates the U-value of the STPV window in actual operating conditions. Infield et al., [2006] have proposed four theoretical formulae for U value and g-value. In developing the formulas, the U value and g-value are divided into two components. The U-value has been divided into the recovered loss coefficient (U_{vent}) and transmission loss coefficient (U_{trans}). Similarly, the g-value has been divided into the constant transmission coefficient (U_{trans})and indirect solar gains to the ventilation (g_{vent}). The parameters are shown in Figure 6.

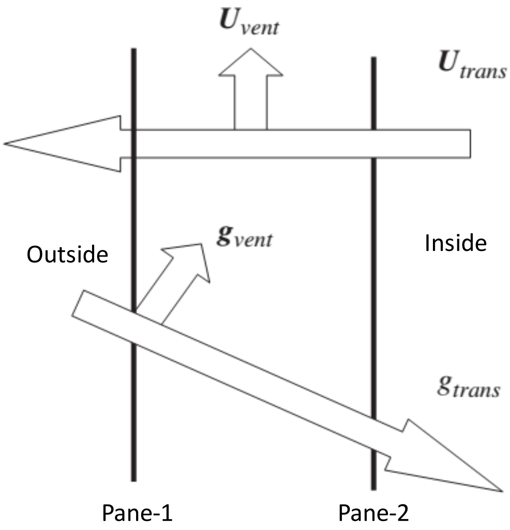

Figure 6: Energy flow of a ventilated façade [Infield, et al ., 2006]

Software like WINDOW and THERM is also applied to estimate the U and g values of STPV modules. Chen and Wittkopf,[2012] found similar values of heat transfer in calorimetric hot box measurement as calculated by WINDOW and THERM software. Further, among various characteristics of the STPV module, the cell area affects the most in the heat transmission across the module. The dominant role of the cell area in the heat transfer through the STPV module was also found by Xu, et al.,[2014]. A summary of the above discussion is given in the Table. 5.

Table. 5

Reference	Type of study	Aim of the study	Important findings
Moralejo-Vázquez, et al.,2015	Experimental work	To characterize the optical properties of PV modules for building integration	The STPV module’s transparency is less dependent upon the cell than the lamination
Lim, et al.,2013	Experimental work	To develop and characterize the thin film a-Si: H and a-SiGe: H STPV cells	The thickness of TCO in the STPV should be between 300 to 500nm,
Kapsis and Athienitis. 2015	Simulation work using Matlab	To investigate the role of optical properties in the performance of STPV windows	STPV module with 10% VLT provided the best overall performance
Tady, et al.,2008	Theoretical work with experimental validation	To develop a transient heat transmission method for assessing the heat dissemination of STPV modules	The solar cell area of an STPV module considerably influences the heat gain of the module
Olivieri, et al.,2015	Indoor experimental work	To design and development of a thermal testing facility for glazing components	The SHGC of a photovoltaic module is reduced by 11% when it works at the maximum power point.
Sánchez-Palencia, et al.,2019	Theoretical work with experimental validation	To develop thermal modeling for calculation of U-Value in real operating conditions	U-value of a PV window can be less than 35% than a conventional window for radiation 1000 W/m^2,

3. Conclusions

The research indicates a significant interest in buildings that incorporate STPV window/façade systems, aiming to attain low or net-zero energy structures. Numerous scholars have explored photovoltaic vertical systems from diverse perspectives. To summarize, here are some of the primary findings from the study:

Module temperature is a key performance-determining parameter. With the increase in module temperature, the annual energy generation was found to be decreased by 5% to 8%. The performance characteristics of building integrated STPV systems are highly location-dependent. For instance, the annual energy generation of a system may vary by 27.4% with the change in place of installation. This character demands the necessity of proper optimization of an STPV system before installation. WWR has a direct influence on the building's energy load. It has also a direct relationship with the energy generation of an STPV integrated window. Therefore, a WWR is optimized with respect to the transparency of the STPV module, orientation, etc. delivered the best energy results. Finally, the photovoltaic cell or module characteristic is found to influence not only the energy generation but also the heat gain into the occupant area.

4. Future research prospects

Incorporating the STPV module within the building envelope offers numerous benefits, enhancing both the energy efficiency of the structure and the comfort of its occupants. Additionally, it elevates the visual appeal of the building. Nevertheless, room for technological advancement remains. Some suggestions for further exploration are

In the case of vertical BIPV systems, such as window/façade, the AIO remains high most of the time of a year. As a result of this, a large part of incidence radiation gets reflected from the exterior of the system. Research can be carried out to reduce the reflected radiation for useful applications.

The photovoltaic modules convert a particular range of wavelengths into electrical energy. The remaining wavelengths of the incident radiation produce heat. So, the curtailment of the non-useful wavelengths before reaching the photovoltaic cell will lower the building energy demand, especially in cooling demand locations, besides enhancing the photovoltaic efficiency.

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