

Performance Assessment of a Multifunctional 3D Building Integrated Photovoltaic (BIPV) System

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ABSTRACT: The rooftop is a default location for photovoltaic solar panels and is often not enough to offset increasing building energy consumption. The vertical surface of urban buildings offers a prime location to harness solar energy. The overall goal of this research is to evaluate power production potentials and multi-functionalities of a 3D building integrated photovoltaic (BIPV) facade system. The traditional BIPV which is laminated with window glass obscures the view-out and limits daylight penetration. Unlike the traditional system, the 3D solar module was configured to reflect the sun path geometry to maximize year-round solar exposure and energy production. In addition, the 3D BIPV facade offers multiple functionalities – solar regulations, daylighting penetration, and view-out, resulting in energy savings from heating, cooling, and artificial lighting load. Its ability to produce solar energy offsets building energy consumption and contributes to net-zero-energy buildings. Both solar simulations and physical prototyping were carried out to investigate the promises and challenges of the 3D BIPV facade system compared to a traditional BIPV system. With climate emergency on the rise and the need for clean, sustainable energy becoming ever more pressing, the 3D BIPV facade in this paper offers a creative approach to tackling the problems of power production, building energy savings, and user health and wellbeing.

KEYWORDS: multifunctional 3D BIPV facade, net zero energy buildings, clean power production, health and wellbeing
PAPER SESSION TRACK: Technology and Design

INTRODUCTION

Buildings are one of the most important contributors to energy consumption and carbon emissions. The concept of net zero energy architecture and carbon neutrality has been around for a while. Recently, it has been gaining traction among architects, engineers, developers, and stakeholders alike. The net-zero energy architecture aims to produce as much energy as they consume by incorporating bioclimatic design, energy-efficient building service systems, and renewable energy sources such as solar panels. Carbon neutrality means that the carbon footprint of the building is balanced by a pollutant reduction through energy-efficient buildings while also offsetting energy use by renewable energy production systems. In order to reduce the environmental impacts, integrating photovoltaic systems (BIPV) into building designs can provide a sustainable solution toward carbon-neutral, net-zero energy architecture. Building surfaces are the prime location for integrating solar panels which can take any form from walls, roofs, and windows. The overall goal of this project is to develop a multi-functional solar facade for high-rise buildings to reduce carbon emissions and energy use, and improve occupant health and comfort through increased indoor environmental quality (IEQ). The proposed system outperforms traditional BIPV windows by providing maximum solar power output, summer shading, winter solar gain, year-round daylighting, and a view to outside.

1.0 SOLAR ARCHITECTURE

1.1 History of solar architecture

Photovoltaic cells convert solar radiation into direct current electricity. The history of cells can be traced back to the early days of the 20th century but it was not until the 1960s that they were used in a practical way. The first photovoltaic effect that light can generate electricity was discovered by a French scientist called Alexandre-Edmond Becquerel in 1839 (U.S. Department of Energy n.d.). In 1883, an American scientist Charles Fritts conducted the first experiment with solar cells made by placing selenium wafers between two metal plates and applying pressure but the cells were not very efficient and had to be in direct sunlight to work (U.S. DOE n.d.). In 1954, Bell Labs created silicon-based solar cells with a maximum of 11% conversion efficiency, which was a significant breakthrough because it is able to harness the sun to supply everyday electric devices (U.S. DOE n.d.). NASA launched the first satellite powered by a 470-watt photovoltaic array in 1964, beginning a new era for satellites with long-term power supply without recharging (U.S. DOE n.d.). Silicon solar cells are widely used today in most commercial applications of photovoltaic technology to provide sustainable architecture and generate electricity for the building. The US's BIPV market in 2020 was valued at \$1.9 billion and is expected to grow to \$7.8 billion by 2029 (Grand View Research 2020). This growth is largely due to the advent of new BIPV technologies with affordable prices which make BIPV easier to use and integrate into buildings. In addition, new construction markets are large and growing, offering large potential market opportunities for BIPV technology.

1.2. Current state-of-the-art

Conventional BIPVs include crystalline solar cells and thin films laminated with soda-lime glass. Vertical applications of BIPV windows result in power reduction due to the cosine loss as compared to roof or ground installations. The lamination of the PV cells within a window assembly lacks rear ventilation that increases module temperatures and further reduces system performance and longevity (Radziemska 2003). Opaque crystalline BIPV windows are good for shielding summer sun but are not energy efficient because they block winter sunlight into the interior space. The thin film solar cells allow for daylight penetration but their optical clarity is not truly transparent, often obscuring view-out and causing occupant dissatisfaction. Conventional BIPV made of soda-lime glass have been susceptible to shorter longevity and performance degradation due to potential induced degradation (PID) (Naumann et al. 2015). The commercially available BIPV has limited flexibility in architectural aesthetics, limiting a wide range of architectural applications. Table 1 shows potential BIPV solutions in real world deployment. There are opaque cladding and transparent glass applications. The integration of BIPV with glass modules acts like a shading device and renders it possible to minimize solar gain. On the other hand, the view and daylight penetration are minimized.

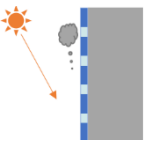
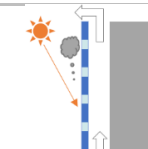
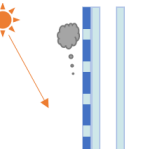
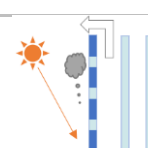
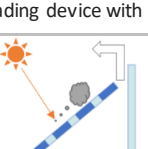
BIPV types	PV integration with building enclosures	Performance characteristics/ Differentiators
BIPV wall	 Without backside ventilation	• Cell heat up • Dust accumulation • Harsh environmental loading (i.e., rain, sunlight, wind) • No maximum power output due to cosine loss • No view-out/No daylight
	 With backside ventilation	• Less cell heat-up • Dust accumulation • Harsh environmental loading • No maximum power output • No view-out/No daylight
BIPV window	 PV integrated with a window without backside ventilation	• Cell heat up/ dust accumulation • Harsh environmental loading • Permanent shading (i.e., no winter sun penetration) • No maximum power output • Little view-out/ Little daylight penetration
	 PV as a shading device with backside ventilation	• Less cell heat up • Dust accumulation • Harsh environmental loading • Permanent shading • Little daylight penetration • Little view-out
	 PV as a permanent shading device (static or dynamic) with backside ventilation	• Less cell heat up • Dust accumulation • Harsh environmental loading • Permanent shading • More view-out
Proposed 3D BIPV system	 Encapsulation of a 3D solar module inside of a closed-air cavity	• Cells are cooled • No moisture buildup • No dust accumulation • Optimized shading and daylighting • Winter sunlight penetration • View out

Table 1: Potential BIPV solutions in real-world applications

Research data indicated that every 1°K increase in solar cell temperature reduces approximately 0.65% output power and 0.08% conversion efficiency of the PV module (Gok et al. 2020). Every 100 W/m² increase in solar irradiation decreases electrical efficiencies by about 0.33%, 0.51%, and 0.84% for amorphous, polycrystalline, and monocrystalline PV cells, respectively (Ugwuoke et al. 2012). Air cooled modules increase efficiency from 9.75% to 10.41% (Siecker et al. 2017). Wind around PV cells reduces the surface temperature of the module, but it can result in decreased efficiency if the wind lifts dust, creating shading and poor efficiency (Zaihidee et al. 2016). The proposed BIPV system, on the other hand, is functionally innovative in that it is integrated within a closed air cavity system where solar cells are installed in a conditioned air cavity to improve the conversion efficiency and longevity of the solar cell by preventing heat build-up, dust accumulation, and moisture infiltration. The system incorporates a patent-pending solar cell interlayer that balances summer solar blocking, winter solar gain, and year-round daylight illumination.

2.0 3D BIPV SYSTEM

2.1. Proposed BIPV system

Our 3D BIPV facade consists of a single pane glass at the exterior side of the assembly and insulated glass unit (IGU) at the interior side of the assembly and a closed-air cavity created by the external glass pane and the internal IGU. The 3D solar modules – a network of solar cell units – are suspended in the closed-air cavity where the PV cells are protected against harsh outdoor environments. The 3D BIPV facade is configured as a prefabricated curtainwall system for speedy installation and quality control.

The sun constantly moves from the east and west during the day and its altitude and azimuth change across the seasons. The geometry of the solar unit mimics the sun's path to maximize solar exposure to produce electricity while regulating solar gains and penetrating daylight. The solar module blocks the summer sun and admits the winter solar gain. It is hypothesized that the curved solar unit following the sun path diagram yields better energy performance compared to a traditional flat BIPV window. The closed air cavity offers optimum environments for the solar module, keeping away from HAM (heat, air, and moisture) and dust accumulation and leading to the longevity and performance of the solar module.

We observed that while the closed cavity system yields high performance for the PV cell, it causes condensation in the air cavity in winter and heat build-up in summer. We also noted that the air cavity depth and height played a role in energy consumption for the air cavity operation. Therefore, we need to introduce an active system to condition the air cavity while optimizing solar module geometry and cavity dimensions depending on different climate zones and building orientations. We utilized an integrated multi-objective optimization using a genetic algorithm and Energy Plus performance simulation to estimate energy savings and power production. Figure 1 shows an overall configuration of the proposed BIPV system and its potential use for high-rise curtainwall construction.

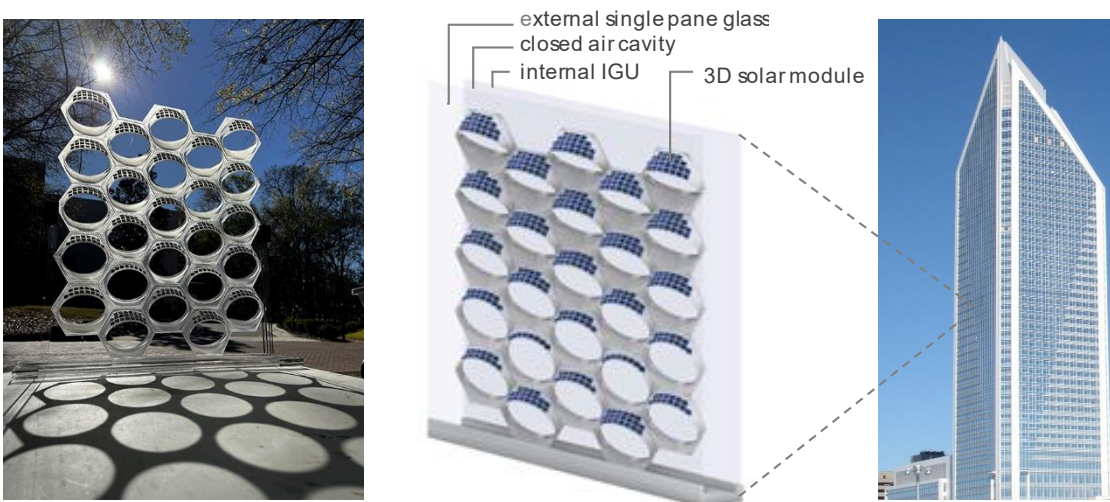


Figure 1: An overview of a multifunctional 3D BIPV system consisting of a 3D solar module, external glass, closed air cavity, and internal IGU; it is configured as a prefabricated curtainwall system for speedy installation and quality control.

2.2. Geometric rationalization

Building facades provide much more than just visual appearance. Well-designed building facades should provide comfort to the occupants while consuming minimal energy. In this research, we propose a facade system that can balance PV electricity generation, solar heat gain, daylighting, and view-out. This facade system is built on a hexagonal grid with circular openings. The geometries of the 3D solar module are parametrically controlled such that the overall performance can be optimized based on different climate conditions and façade orientations.

It is well known that high performance shading devices can reject solar radiation during summer when sun angle is high while admitting solar heat during winter when sun angle is low. In addition, horizontal shadings are more effective on the south facade while vertical shadings are more effective on east and west when sun angle is low. Figure 2 shows that the proposed 3D solar module combines these solar-responsive design principles to provide optimal shading efficacy and solar exposures based on orientation. Between the south and east/west facades, the geometries smoothly transform from horizontal to vertical. With this formation, the southern facade functions similar to an overhang while the east and west facade function similar to vertical fins to maximize shading efficacy. In addition to the shading aspect, to provide occupants with maximum view-out, the openings at eye level are larger and gradually reduced to the size for optimum shading and energy production when moving up to the ceiling and down to the floor.

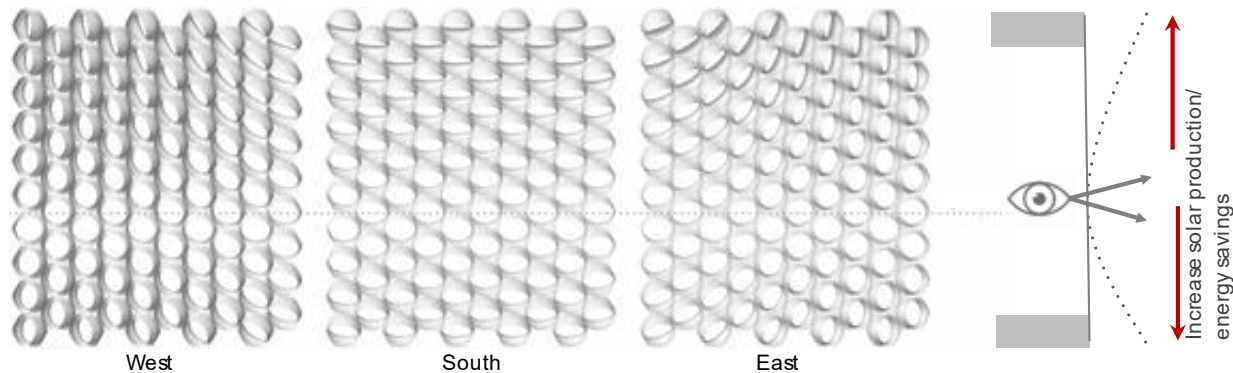


Figure 2: 3D solar module geometries facing different orientations: west (left), south (middle), and east (right) elevations; it balances solar energy production, energy savings, and user satisfaction through solar regulations, year-round daylight penetration, and view to outside.

As shown in Figure 3, each hexagonal cell contains an upper surface and a lower surface. The upper surface functions as a shading device while generating electricity with PV cells that are installed on the top of the surface. The curvature of the upper surface is parametrically controlled to optimize electricity generation based on the solar altitude of the building location. In Figure 3, the blue rectangles represent sections of PV cells and the arrows represent the normal direction of the cells. When the normal of the PV cells is aligned with the sun angle, the PV cells are at their maximum efficiency. Therefore, the curvature of the upper surface can be effectively changed depending on solar positions when each cell can produce the maximum electricity. Detailed performance analysis for electricity generation is explained in section 3 below. Although this system is a static system, meaning that the geometry of the facade does not change once manufactured and installed, the curvature of the upper surface and the lower surface vary based on the solar angle and climate conditions of the site. The optimum surface curvature can be determined by running optimization algorithms such as exhaustive search or Genetic Algorithm.

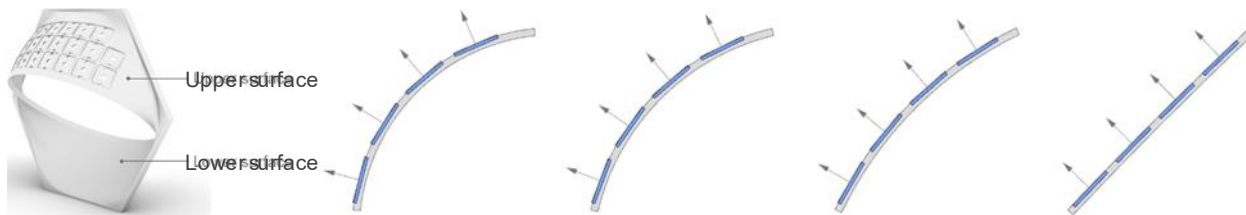


Figure 3: Various curvatures of the upper surface integrated with PV cells to adapt to different façade orientations and climate conditions.

The lower surface of the hexagonal solar unit can function as a light shelf to redirect visible light deeper into the space. For a traditional light shelf, the sunlight landing on a flat panel is reflected onto the ceiling, and is reflected again by the ceiling deeper into the space (Figure 4, left). In this research, the curvature of the lower surface is parametrically controlled to improve the daylighting quality. As shown in Figure 4, convex and concave light shelves can bring daylight into the space deeper with wider spread compared to conventional flat light shelves. The curvature of the convex or concave surfaces can be adjusted to redirect more light toward where it is needed. In figure 4, while the convex light shelf can effectively bring light deeper into the space, the curvature of the concave light shelf is designed to distribute more light toward the space further away from the window where more daylight is needed. This can be seen in figure 4 that the reflected arrows on the concave light shelf are denser toward the deeper end of the space. This shows that this facade system has potential to effectively distribute daylight to where it is needed.

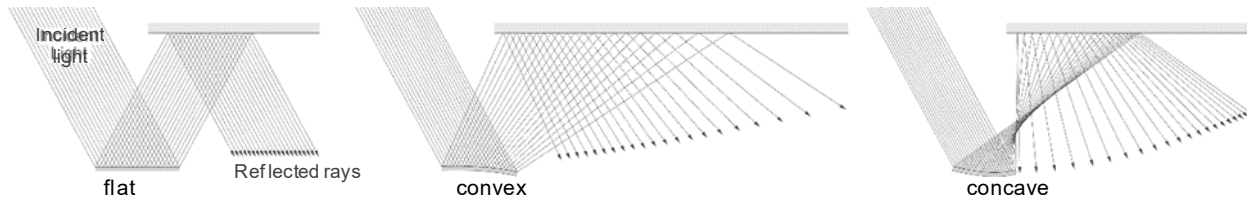


Figure 4: Curvatures of lower surface and their efficiency as light shelves.

2.3. Prototyping

To verify the energy performance of the façade design and test solar cell installation, we used additive manufacturing technology to prototype twenty-five oculi units. Using this prototyping technique, we were able to produce a performance mock-up with higher accuracy and precision which would have been difficult with traditional methods. Selected from the overall computational result of the geometry rationalization discussed in Section 2.2, each hexagonal solar unit measures 12.20 cm (h) x 14.22 cm (w) and is interconnected to form a network of the multi-functional solar module. Solar units have adjustable opening sizes for view-out and the upper surface of the unit allows a maximum of twenty-six and a minimum of eight 1cm x 1cm micro solar cells to be installed. In order to ensure the proper placement of micro solar cells and their wiring, we have developed a novel approach that incorporates inset surfaces and grooves. These geometric features provide a precise registration point that allows the solar cells to be installed in the correct locations while ensuring secure soldering connections.

Although additive manufacturing and laser cutting are allowing for precise and accurate tolerance, construction tolerance is an important consideration to ensure solar cell installation within the inset surface. To accommodate material and fabrication tolerances, the insets on the physical model for the solar cells to be inserted into are 110% of the cell size (Figure 5 middle), with connecting grooves on all sides which allow various configurations of cell soldering connections. In addition, a 0.22cm wide groove for the wire path is embedded along the border of each oculi unit (Figure 5 right). Due to the unique geometry of each of the solar units, 3D printing the entire prototype was selected as the method for physical prototyping. The units were printed one at a time by a Form 2 printer (FormLabs) using clear resin. The thickness of the units is optimized both for achieving a short printing time and ensuring surface properties for assembly. The average printing time for the prototype is 5.5 hr/unit, and each unit needs an average of 60 ml liquid resin including model supports automatically generated for printing.

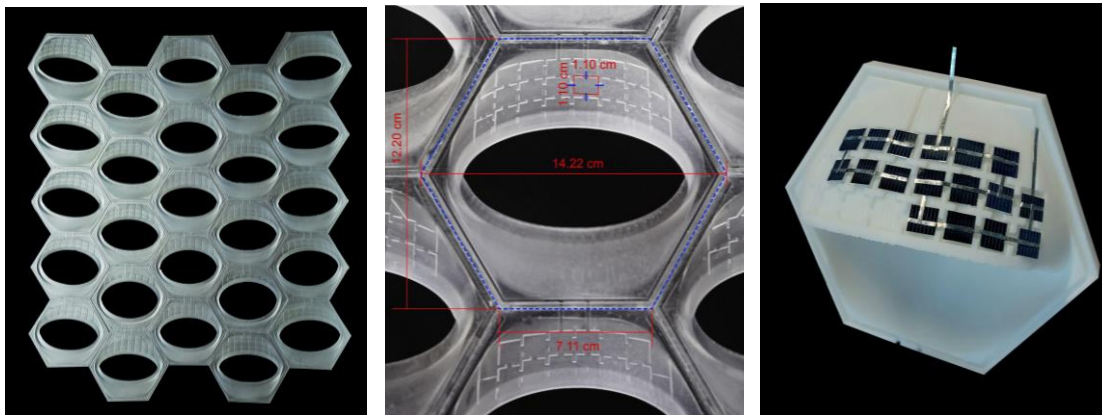


Figure 5: 3D printed 25 solar units using clear resin (left), a detailed view with dimension (middle) and a 1cm square micro solar cell with ribbon wire test-fit on a 3D printed white PLA module (right).

3.0 ENERGY PERFORMANCE

3.1. Simulation set-up

Two generic office buildings with a 3D BIPV façade and a flat vertical BIPV façade on the south-facing wall were modeled in Rhino software to simulate how the 3D BIPV façade outperforms the flat vertical BIPV on power production. To compare the power output results of the 3D BIPV façade with the traditional BIPV flat window, a vertical PV surface facing towards the south, with an area equal to the total PV cells area in the 3D BIPV window was modeled. The geographical location of the analysis building was set to be the city of Charlotte in the state of North Carolina, U.S.

Equinoxes and solstices are four key days during the year that can provide insight into the solar power potential of the BIPV facades, and therefore, these four days were chosen for the analysis period. By analyzing these four seasonal days, we can gain an understanding of the amount of solar energy produced by the system throughout the year. Hourly average irradiance on the PV cells was simulated in those four days, using Grasshopper, Ladybug (LB), and ClimateStudio (CS) plugins. The analysis grid size of the LB incident radiation component was set to 1 cm which is exactly the same size as the PV cells of the physical prototype, allowing for accurate results and fast simulation process (Figure 6).

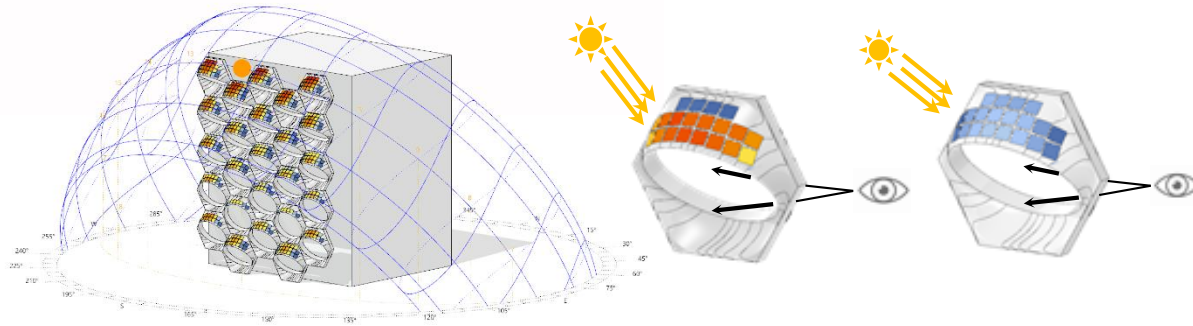


Figure 6: Simulation set-up of the solar modules facing the south orientation (left); irradiance level on fall equinox at 1 pm (left), summer solstice at 1 pm (middle), and winter solstice at 1 pm (right).

3.2. Performance simulations

Higher conversion efficiency of the solar module and its improved longevity result in lower electricity costs and a quick return on investment. In other words, the initial investment in BIPV systems can be quickly recouped through substantially lower electricity bills during the building use phase, contributing to economic and environmental sustainability. Conventional BIPV windows have been placed in vertical surfaces for years, but their power production has been limited due to the cosine effect. The cosine effect reduces conversion efficiency when sunlight is not perpendicular to the surface of the BIPV, limiting the amount of energy that can be collected and converted into usable electricity. To minimize cosine loss and maximize annual energy production, the proposed 3D BIPV system incorporates sun path-like curved geometries, which are optimized for the more prevalent summer design day. This new approach promises to be more energy-efficient than the traditional BIPV system.

Our analysis results indicated that the 3D BIPV façade on the south orientation outperformed across the seasons and the power production improvement was significantly higher during summer. In comparison to a conventional vertical BIPV system, the proposed BIPV facades yielded 72% greater power production during the summer solstice, about 25% during the equinox days, and similar power production during the winter solstice. Assuming that the PV cells have 15% efficiency, the 3D BIPV facade can output a daily average of 450 Wh/m² energy while the traditional vertical PVs generated 350 Wh/m² per day. Yearly solar energy comparison has shown that 3D BIPV offers 30% more electricity generation compared to the vertical BIPV, and produces 7% less energy than a horizontal BIPV. The analysis has revealed that a BIPV system with 3D-shapes that reflects the different positions of the sun significantly enhances energetic performances while being able to provide daylight provision and views to the outside. The 3D curved geometry maximizes their exposure to the sun and therefore, increases power production. Additional energy savings are achieved by providing shading in the summer and solar heating in the winter. The solar cell geometry is configured in response to the climate and environment depending on the site location and façade orientation, balancing solar exposure, shade in cooling seasons, winter solar gain, and daylight illumination. Figure 6 presents energy production comparisons between the 3D BIPV façade and a BIPV vertical façade.

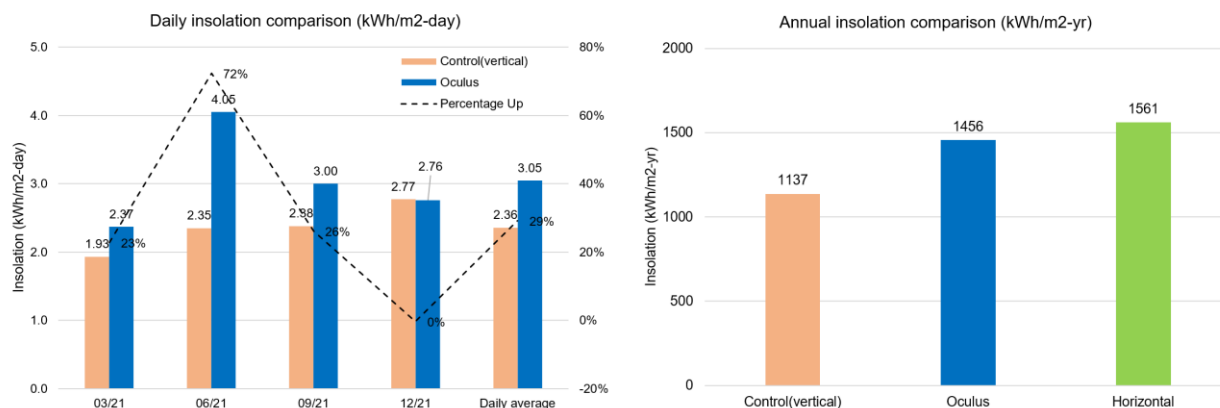


Figure 6: 3D BIPV and traditional BIPV power output comparison: Daily insolation (left) and annual insolation (right).

CONCLUSION

Buildings are primary contributors to fossil fuel consumption and pollutant emissions. BIPV facades can provide a sustainable solution to reduce their carbon footprint and achieve a net zero energy goal. Low-performing windows, in particular, are important in indoor environmental quality, energy bills, and occupant comfort. By integrating solar modules within a window assembly, the BIPV facade not only provides energy savings but also improves the comfort level of their interior spaces. We proposed a 3D BIPV facade as an innovative way to achieve carbon-neutral net zero energy buildings.

The proposed 3D BIPV system consists of a network of solar units with varying angles that balance power production, building energy efficiency, and view out. Because the path of the sun moves along with the spherical surface, our solar unit geometry takes into account the path of the sun, allowing maximum sun exposure throughout the day and across all seasons. The proposed BIPV facades on the south orientation yielded an average of 30% more power production year-round compared to a vertical BIPV. During summer seasons, the 3D BIPV facades produced 70% more power than a conventional BIPV system, 25% more during equinox seasons, and similar energy production during winter seasons.

The system offers a unique approach to solar module protection by installing them in a closed cavity air created between two panes of glass. This closed air cavity is conditioned to prevent heat build-up, moisture penetration, and dust accumulation on solar cells, thus providing the solar modules with higher power production and system longevity. In addition, it is expected to yield high thermal attributes, shading efficacy, and daylighting penetration, reducing heating, cooling, and artificial lighting load respectively. Unlike a traditional BIPV facade, the 3D BIPV façade offers an improved user experience by providing view contact with the outside and better sound insulation. Clean power production, building energy conservation, and user healthy and well-being are hallmarks of the proposed solution.

Further investigation is necessary to run comparative simulations for all building orientations and different sites. This will help provide a more comprehensive understanding of energy production potentials from the 3D BIPV system. In addition, field experiments are necessary to validate the simulation data. This data validation will result in a more reliable and accurate prediction of power production. Finally, the use of simulation and experimentation makes it possible to create a decision support tool, which helps evaluate the holistic energy performance of the 3D BIPVs in different facade orientations and site locations.

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