Circuit Connection Reconfiguration Of Partially Shaded BIPV Systems, A Solution For Power Loss Reduction

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Integrating PV panels as a source of clean energy has been a widely established method to achieve net-zero energy (NZE) buildings. The exterior envelope of high-rise buildings can serve as the best place to integrate PV panels for utilizing solar energy. The taller the building, the higher the potential to utilize solar energy by PV panels. However, shadows casting on the BIPV façade systems are unavoidable as they are often subject to partial shades from panels' self-shading as well as building walls. Partial shading or ununiform solar radiation on the PV surface causes a dramatic decrease in the current output of the circuit. For that reason, in BIPV facades the default circuit connection of manufactured PV panels does not output maximum power under partial shading conditions. This paper investigates the different circuit connections in the BIPV façade system to achieve higher energy yields while addressing design requirements. To this end, PV panel's power production in different circuit connection reconfiguration scenarios was explored both by simulation and experimentation in two levels of building integrated photovoltaics (BIPV) components: 1) PV cells, and 2) strings of PV cells. The results of simulations demonstrated that the maximum power generation occurred when the circuit connection between cells within a string is series, and the circuit connection between the strings within a PV panel is parallel. Comparing the results of Ladybug (LB) energy simulations with the proposed Grasshopper (GH) analysis recipe showed that the developed GH definition will increase the BIPVs energy simulation by 90%. To validate the simulation results, experimental tests were conducted. The measured power output indicated that the series-parallel circuit connection increased the energy yields of the BIPV facades 71 times in real-world applications compared to the manufactured series-series PV panels.

INTRODUCTION

In 2021, the U.S. set a greenhouse gas reduction goal of 40% by 2030 (USDepartmentofState 2021) and 80% by 2050 (Lefteris Karagiannopoulos 2021). The built environment is the dominant energy consumer in the U.S. using more than 38% of the total energy and 76% of the electricity (EIA 2015), which accounts for 40% of the total greenhouse gas (GHG) emissions in the country (EIA 2019). In 2021, U.S. commercial buildings consumed 17,410 trillion Btu of energy (EIA 2022). Therefore, decreasing building energy consumption while generating on-site electricity will be a highly effective solution to reduce GHG emissions. Currently, PV installed on rooftops is the most common approach for generating on-site solar energy (Isa Zanetti 2017). However, many buildings will not have sufficient rooftop area that is exposed to sunlight to install PV panels due to the overshadowing of block structures, electrical boxes, elevator bulkheads, etc. (Roberts, Simon 2009). Figure 1 depicts shadows cast on the rooftop of a tall building in the city of Charlotte in the month of February at 9 am, 12 pm, and 3 pm. This example highlights the efficacy of the façade surface to mitigate GHG emissions. With more than 6 million commercial buildings in the U.S. (EIA 2014), the total area of the exterior envelopes of those buildings has a great potential to integrate solar panels to offset electricity usage of the buildings' energy load demand.

This paper proposed the optimum BIPV façade systems' circuit connection for louvered PV panels that are integrated into the south façade, based on a robust analysis recipe to evaluate irradiance nonuniformity on the PV panel surface. The power output of partially shaded PV panels with different circuit connections between PV cells and strings of PV cells was calculated. The simulation and calculated results were validated by experiment tests. The remaining part of the paper proceeds as follows: Literature review and precedent case study, methodology, experiment, architecture design, results, conclusion and discussion.

LITERATURE REVIEW

Compared with ground-mounted PV panels, addressing partial shadows in a BIPV façade system is highly difficult. Currently, the tools and methods suggested by researchers to tackle partial shading problems are not applicable to BIPV façade systems as they are designed to be integrated into large-scale PV systems. The reason is that the radiation non-uniformity due to partial shadows in the BIPV façade systems happens on the scale of solar cells, which causes several limitations that make the BIPV façade systems improper to incorporate those

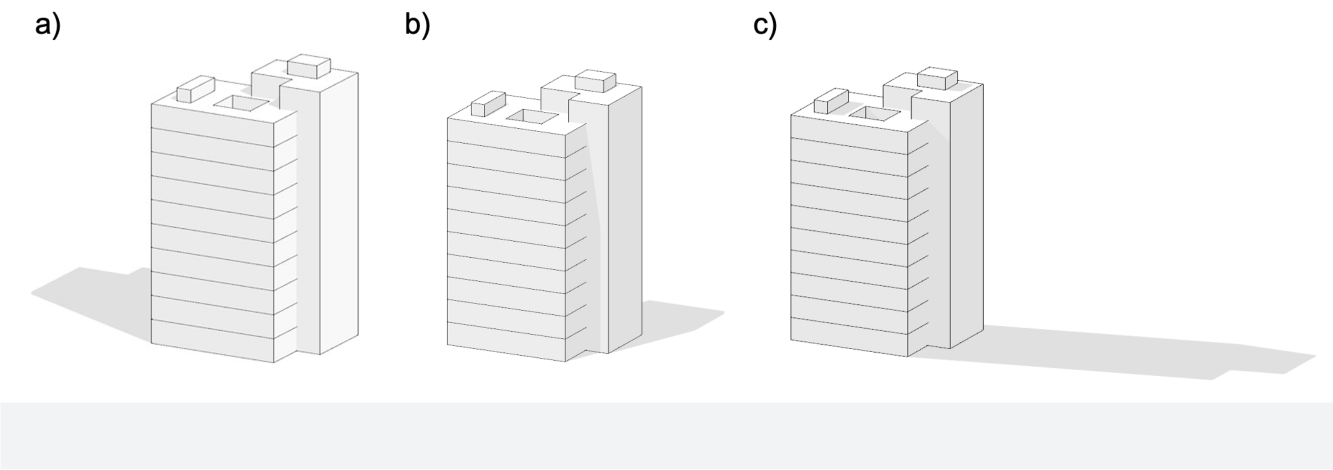

Figure 1. Sun path and shadow analysis of a building in Charlotte on August a) 10 am, b) 1 pm, c) 4 pm.

tools or methods.Ishaque et al. studied maximum power point (MPPT) tracking techniques for PV power systems considering partial shading conditions (Ishaque and Salam 2013). However, in smaller-scale PV systems like BIPV façade systems, partial shading on the PV panel surface causes multiple local maximum power points (LMPP), and integrating traditional MPPT techniques into the system leads to a significant power loss in a BIPV façade system (Satpathy, Jena, and Sharma 2018).

Another method, proposed by Hasyim et al., is installing several bypass diodes in one PV panel to avoid the current drop in PV cells' electric circuit (Hasyim, Wenham, and Green 1986); however, to this date, it did not meet the solar PV manufacturers' specifications standards due to unavoidable major costs (Dhimish et al. 2018). Apart from high costs, the bypass diodes cannot be applied on the scale of PV cells because of the cells' low output voltage (Pareek and Dahiya 2016). For the same reason, microinverters are not suitable for BIPV façade systems due to their minimum voltage input threshold of 30 V to 40 V (Roy and Ayyanar 2018).

Many of the BIPV and building applied PV panels (BAPVs) performance studies simulated either the PV systems' power output without considering the adverse effects of the shadows (Taveres-Cachat et al. 2019), (Mandalaki, Tsoutsos, and Papamanolis 2014), (Akata, Njomo, and Agrawal 2017), (Kumar, Sudhakar, and Samykano 2019), (Didoné and Wagner 2013). Researchers studied partial shadows on BIPV performance however they did not propose a solution to effectively address this challenge (Walker, Hofer, and Schlueter 2019), (Walker, Hofer, and Schlueter 2019), (Sun and Yang 2010). A number of studies investigated the effect of partial shadows on ground-mounted solar panels (Matam and Barry 2018), (Bana and Saini 2017), (Pareek and Dahiya 2016).

Since there is not a well-developed method to address the partial shadows on the PV panels in BIPV application, the results of real-world application of the same designed system will have a big shift compared with the simulated model. Based on a study conducted by Lee et al., shadows cast on a-Si thin-film solar cells on a south-facing double-glazed window reduced the annual energy performance to 1.52 h/day. However, this performance yield was about 2.15 h/day without considering the shading (Lee et al. 2017). Depending on the PV panel surface area, this shift can be escalated several times in larger-scale projects. Cannavale et al. investigated a BIPV case study in southern Italy. The results indicate that the energy performance was significantly diminished by 50% due to neighboring buildings casting shadows on the façade (Cannavale et al. 2017).

Yadav et al. considered the shadow effect of the variables such as width, height, and horizontal distance of the adjacent buildings in the evaluation of the optimum tilt angle, insolation, and performance of the BIPV systems (Yadav, Panda, and Tripathy 2018). Bana and Saini investigated different uniform and nonuniform shading scenarios on the energy production of the PV modules in various interconnections. The result of their experimental tests demonstrated that uniform shading on 50% of the PV array decreased the energy yields by 60%. They concluded that while the power outcome reduction can be caused by several shaded modules or shaded areas and the position of the shaded modules in the whole PV array, higher energy yields can be achieved through reconfiguration methods that connect similar shaded areas together (Bana and Saini 2017) (Pareek and Dahiya 2016). Power output reduction of the PV array that is partially shaded is proportional to the area that receives the least amount of radiation (Matam and Barry 2018).

Since the PV cells in manufactured PV panels are connected in series, an electric current drop of one cell will reduce the

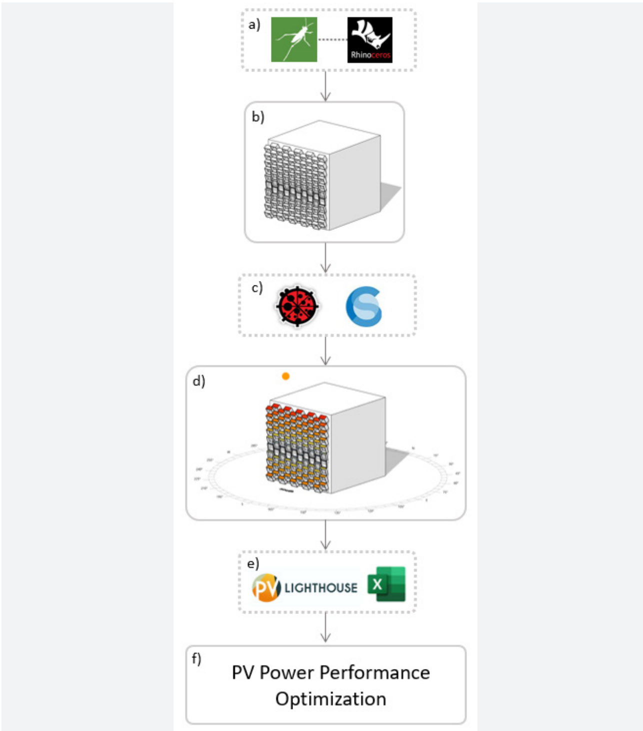

Figure 2. Workflow graphics: a) 3D modeling: Rhino and its plugin GH, b) Building geometry: integrating PV panels on the south façade, c) Shadows and solar analysis: Ladybug and ClimateCtudio, d) Power output evaluation, e) Maximum electricity output: by calculating I and V of different circuit connections, e) Final result: PV system power performance optimization based on shadow analysis and optimum circuit connection.

current output of the entire panel. Radiation on the PV panels' surface is the main source of current flow, therefore, partial shadows dramatically reduce the electrical current through the entire panel. Roberts and Simon introduced panels self-shading as the main issue of the BIPV façade systems (Roberts, Simon 2009). One solution to tackle this problem is to use a circuit connection between PVs in the BIPV façade components that are customized based on the shadow patterns to connect the PV area that receives similar irradiance, and as a result, prevent power loss (Matam and Barry 2018).

This method also extends the lifetime of the PV system since it reduces the possibility of mismatch losses (Zomer and Rüther 2017) and prevents unnecessary investment due to errors of system oversizing and downsizing. The Z3 building of Ed. Züblin AG in Stuttgart, Germany is an example of connecting PV cells based on solar intensity and shadow patterns. In the Z3 building, wooden lamellas on the façade surface cast shadows near the edges of PV modules. By dividing each vertical module into three separate zones based on shadow patterns and connecting the vertical divisions in a separate circuit, the negative impact of partial shadows on energy yield is reduced (Kuhn et al. 2021).

METHODOLOGY

Geometry: A typical office building, with PV panels installed on the south façade, was modeled in Rhino for the simulations' geometry. It is widely accepted that the south-oriented façade's PV panels should install horizontally on the façade surface with a tilting angle equal to the latitude of the site location (Duffie and Beckman 2013). Thus, the solar panels also perform as shadiing louvers while generating electricity during sun hours of the day and year. The geographical location was set to the city of Charlotte in the state of North Carolina, U.S.

Power output calculation: To define the optimum circuit connection of the BIPV façade system in scenarios where the PV surface receives nonuniform irradiance, the irradiance levels were simulated using GH and other plugins such as LB and ClimateStudio (CS), the PVLightHouse website (Keith McIntosh 2022), and Excel (Figure 2). Setting the grid size of the LB incident radiation component equal to 0.05 m made the solar irradiance analysis grid the same size as each PV cell that was used in the experimental tests. LB outputs the results based on kWh/m2. Since the PV panel area was 1 m2, the output units of hourly irradiance simulation on the PV surface will be kW. Therefore, after multiplying the PV cells' efficiency by those values, the output will be panel power generation.

Calculating I_{mp} and V_{mp}: It is obvious that the top PV panel of the array in a louvered BIPV façade will always receive the highest amount of solar radiation. Studying the simulated shadow patterns on the PV surface of the louvered PVs–excluding the first panel–installed on the south façade showed that the string of PV cells that is closer to the building exterior surface received less irradiance. However, the strings of the PV cells that are located closer to the exterior edge of the PV panel received a higher irradiance level. Thus, to connect cells that receive the same range of irradiance on their surfaces, the cells in the analysis grid rows should be connected in one circuit and then each row should be connected together. To reduce the time of simulations, a single PV panel located in the middle of the array was selected to simulate the incident radiation and calculate the power output of the cells in different circuit connections. Maximum current power (I_{mp}) and maximum voltage power (V_{mp}) output of a 1 cm2 PV cell in different irradiance levels were extracted from the PVLighthouse website (PVLightHouse, 2022). Using the PVLighthouse website data, a GH definition was developed to calculate the hourly power output of one partially shaded PV panel based on the Imp and Vmp of the irradiance received on each analysis grid cell during the sun hours of the entire year. Different circuit connections include the following: 1) series connection between cells and series connection between strings, 2) series connection between cells and parallel connection between strings, and 3) parallel connection between cells and parallel connection between strings. In this paper, series-series, series-parallel, and parallel-parallel circuit connections refer to the mentioned circuit configurations, respectively.

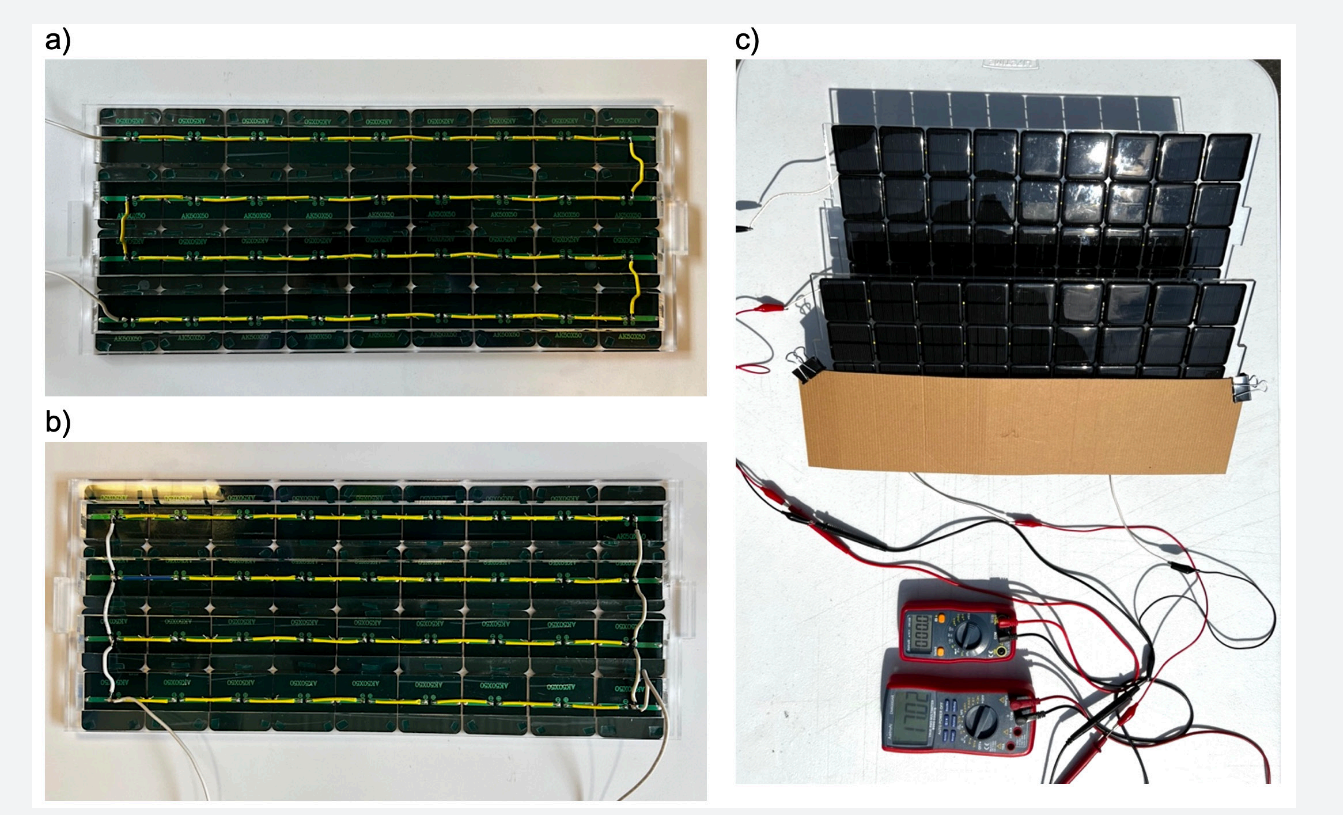

Figure 3. Experimental setup: a) series-series connection, b) series-parallel circuit connection, measuring the I, V, irradiance levels.

The GH definition determined the Imp and Vmp of the grid cells based on the kW irradiance range that each analysis grid received. Afterward, by having Imp and Vmp associated with each cell, the power output (P) of the circuit connections can be calculated using the formulas below.

For parallel connection,

$$P = (I_1 + I_2 + \cdots + I_n) \times V_{min}$$

and for series connection,

$$P = I_{min} \times (V_1 + V_2 + \cdots + V_n)$$

where n is the number of cells in the electrical circuit.

EXPERIMENT

Experimental tests were conducted to validate the simulation results. To determine the PV cells' efficiencies, I and V of a string consisting of 9 mini monocrystalline PV cells connected in series circuit connections were measured outdoors in 1000 w/m2 irradiance condition. Comparing the I and V output with the I and V provided in the PV cells data sheet, the calculated efficiency of the cells was 12%. Two panels, each consisting of 36 PV cells, were made by installing the cells on a rectangular acrylic board. In one panel the PV cells were connected in series-series, demonstrating the conventional PV panels that are currently being used in the industry and BIPV construction (Figure 3-a). The PV cells in the other panel were connected in a series-parallel electric circuit (Figure 3-b). The tilting angle of the panels was 35.22°, which is equal to the latitude of the city of Charlotte. To make the experimental setup similar to the south façade, the panels were located toward the south geographic direction (Figure 3-c). While the panel in the front casted shadows on half of the panel in the back, a piece of cardboard was used to cast shadows on the same area of the front PV panel. The distance between PV panels was the same as the simulation's geometry. The irradiance levels on the PV panels' surface were measured using the day star meter sensor. I and V output of the panels were measured by multimeters. All of the measured data were recorded every 15 minutes from 11:30 am to 12:30 pm for five days from October 5th to October 9th. The irradiance levels during the five days of the experiment were between 210 W/m2 to 1020 W/m2. The measured output of the panel with series-series circuit connection, which was representing the industry-manufactured panels, ranged from 7.8 mA to 13.7 mA and 77.8 v to 83.0 v for current and voltage, respectively. However, the PV panel with a series-parallel circuit connection generated 1.07 A to 3.3 A and 19.6 v to 21.5 v of current and voltage, respectively.

ARCHITECTURE DESIGN

The louvered PV panels integrated into the façade will also perform as a shading device to reduce cooling loads, carbon

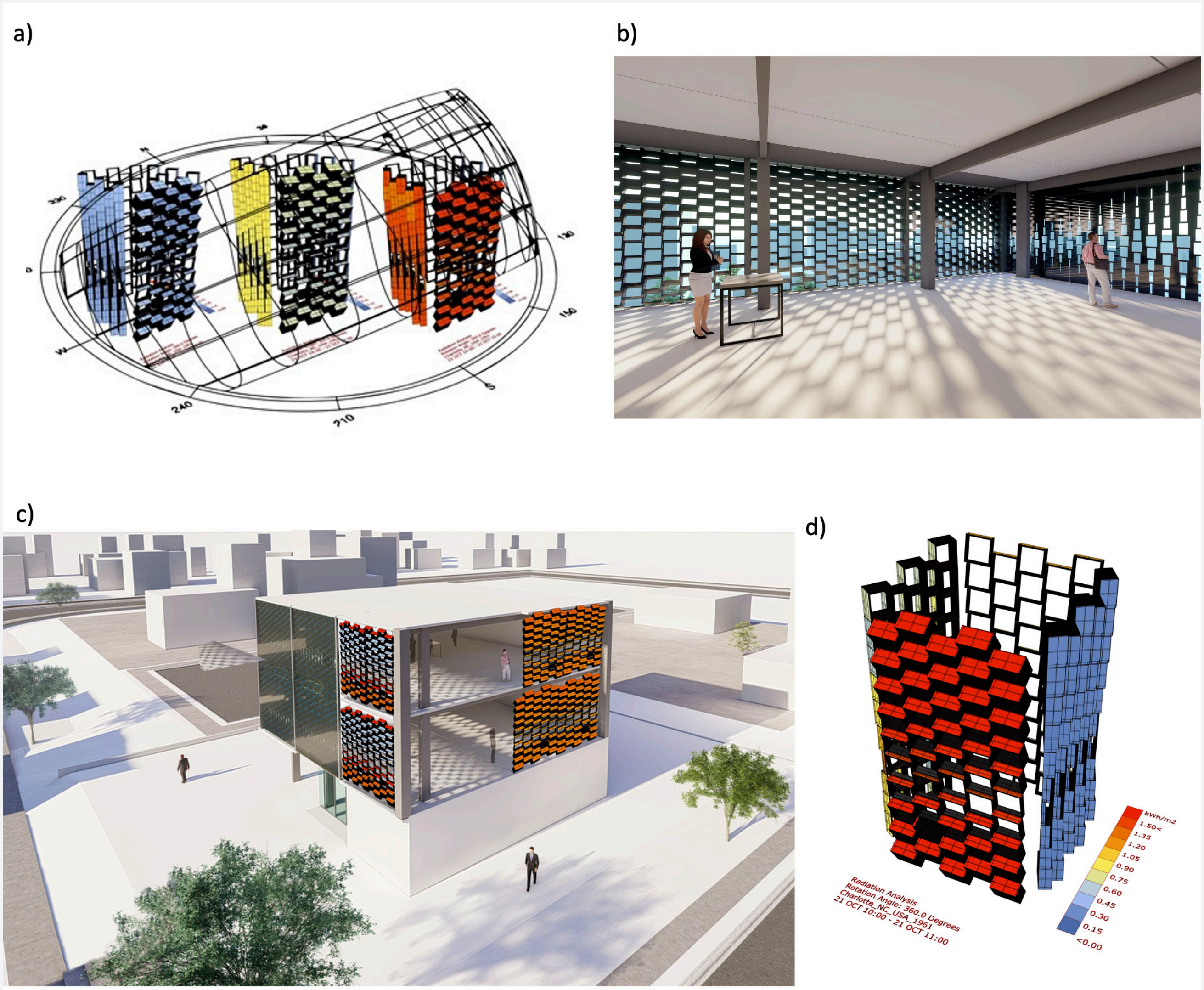

Figure 4. The proposed BIPV façade system architecture design: a) incident radiation on PV surface simulations on Oct 21st at 8 pm, 5 pm, and 2 pm from left to right respectively, b) interior view, c) bird eye view, d) incident radiation on PV surface simulations on Oct 21st at 10 am.

emissions, and glare problems while offering view-out, on-site clean energy. Figure 4 illustrates one typology of the BIPV façade systems and their simulated performance.

RESULTS

This paper investigated the optimum circuit connection for BIPV façade systems through simulation and experimental tests. After an in-depth shadow analysis, the simulations were conducted using two methods, including 1) using LB incident radiation component and applying PV material efficiency to calculate the power output and 2) developing a GH script to define the current and voltage output and calculate the power output of the panel of different circuit connections including series-parallel and parallel-parallel. Since the PV cells in PV panels are connected in series in today's manufacturing industry, the results of the LB simulations can be considered for series-series circuit connection. Figure 5 visualizes the annual power generation of LB and GH script for two circuit connections of series-parallel and parallel-parallel. Although the power output of the parallel-parallel circuit connection is higher than the series-series and series-parallel connection, it will be inapplicable for the BIPV systems due to the significantly low voltage output that will not meet the minimum required voltage input of the microinverter.

The results of the experimental tests were compared with the simulated circuit connections' power output on the corresponding day of the year. The LB incident radiation simulation results on Oct 8th at noon were 61 W. After applying the efficiency of the cells, the simulated power output will be 7.32 W. However, in the experimental tests, the measured I and V of the partially shaded panel with series-series connection were 0.011 A and 83 v respectively. Therefore, the power output of that PV panel in real-world applications will be about 1 W. To make sure that the comparison between the LB incident radiation output and the experimentation results is accurate, the least value of the simulated incident radiation list, which is related to the grid cell of the analysis grid that receives minimum amounts of incident radiation on October 8th was extracted. After applying the PV cells' efficiency, the power output of that specific cell was calculated. The calculation result was 2.8 W, which is close to what was measured in the experiment. The power output result of the series-parallel circuit connection that the GH script calculated was 78 W. The measured I and V of the PV panel with the series-parallel circuit connection were 3.3 A and 21.5 v respectively. Therefore, the generated power was about 71 W.

Results of the experimental tests show that the series-parallel circuit connection increases the energy yields of the BIPV façades 71 times in real-world applications. Additionally, the GH analysis recipe that this paper presented for the circuit connection reconfiguration will increase the BIPV façades energy yield by 10.6 times, which will not only help architects and designers make better decisions in the early stages of the design but also prevent wasting resources to scale up the PV system size to meet the building energy requirements.

CONCLUSION AND DISCUSSION

Despite the building façade accounting for up to 80% of the building surface area, the current architectural integration of solar energy is largely focused on roofs. The façade of a building is a great place to harness solar energy and enhance the building's overall energy performance. However, the BIPV façade systems are often subject to partial shadows from panels' self-shading and building walls. Therefore, traditional default circuit connections do not output maximum power for BIPV applications. This study focused on maximizing the energy yield of the BIPV façade systems while minimizing discrepancies between simulation results and real-world application performance. In this paper, simulation and experimental power output of the partially shaded PV panels in different circuits and connections were investigated. Comparison analysis of the results of the LB incident radiation simulations and the measured data in the experiment setup showed that there is a great difference between simulation results and the real-world performance of the partially shaded solar panels. LB does not consider the current drop due to the nonuniform irradiance levels on the PV surface under partially shaded conditions. Therefore, architects and designers need to consider the impact of the current drop in the electric circuit caused by partial shadows in a BIPV system so the designed BIPVs perform in the real-world application as they were intended during the design stage of the project.

The investigation of the BIPV facades and circuit connections in this paper is an important step toward implementing net zero energy architecture practices. The findings of this research are expected to provide design guidance to both researchers and professionals about how photovoltaic systems perform with different design options and surrounding contexts, especially under partial shading conditions. This would also help BIPV designers in the decision-making process to find optimum solutions while focusing on creative aspects of BIPV design. By using correct circuit connections, BIPV facades maximize renewable energy production while also ensuring the safety and longevity of the system.

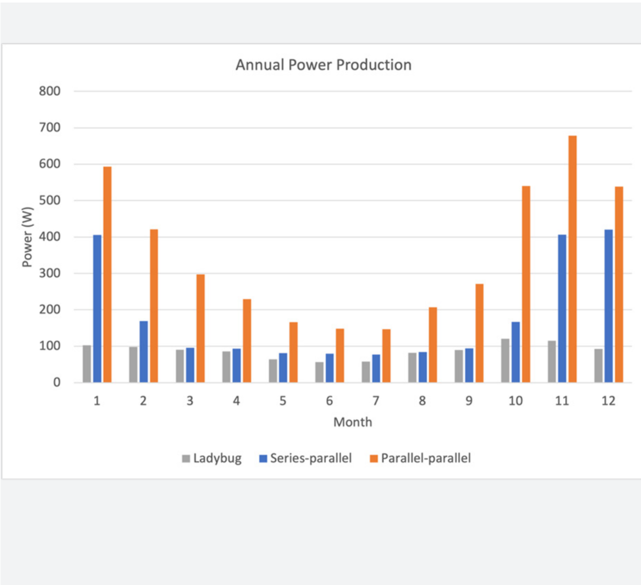

Figure 5. the annual power production of different simulation methods.

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