PAPER

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 the 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 BIPV façade system to achieve higher energy yields while addressing design requirements. To this end, PV power production in different circuit connection reconfiguration scenarios was explored in two levels of BIPV components: 1) PV cells, and 2) strings of PV cells. Experimental tests conducted to validate the simulation results. The results of this study indicated 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. Results of the experimental tests shown that the series-parallel circuit connection increases the energy yields of the BIPV facades 71 times in real-world applications. The comparison analysis of the Ladybug energy simulations and the proposed analysis Grasshopper analysis recipe power output showed that the developed Grasshopper script will increase the BIPVs energy yields by 90% in simulations.

INTRODUCTION

In 2021, the US set the 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 takes account for 40% of the total greenhouse gas (GHG) emissions in the country. (EIA 2019) In 2021, U.S. commercial buildings consumed 17410 trillion Btu of energy. (EIA 2022) Therefore, decreasing building energy consumption while generating on-site electricity will be a highly effective solution to reduce the GHG emission. Currently, PV installed on rooftops is the most common approach to generate 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 is showing shadows cast on the rooftop of a three-stories building in 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.

LITERATURE REVIEW

Compared with ground-mounted PV panels, addressing partial shadows in a building integrated photovoltaic (BIPV) façade system is highly difficult. Currently, the tools and methods suggested by researchers to tackle partial shading problems in large-scale PV systems. 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)

Installing several bypass diodes in one PV panel to avoid the current (I) drop in PV cells was proposed by Hasyim et al. (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 inapplicable for BIPV façade systems due to their voltage input threshold of 30 V to 40 V. (Roy and Ayyanar 2018) Connecting PV panels that receive similar radiation intensity were suggested as one solution

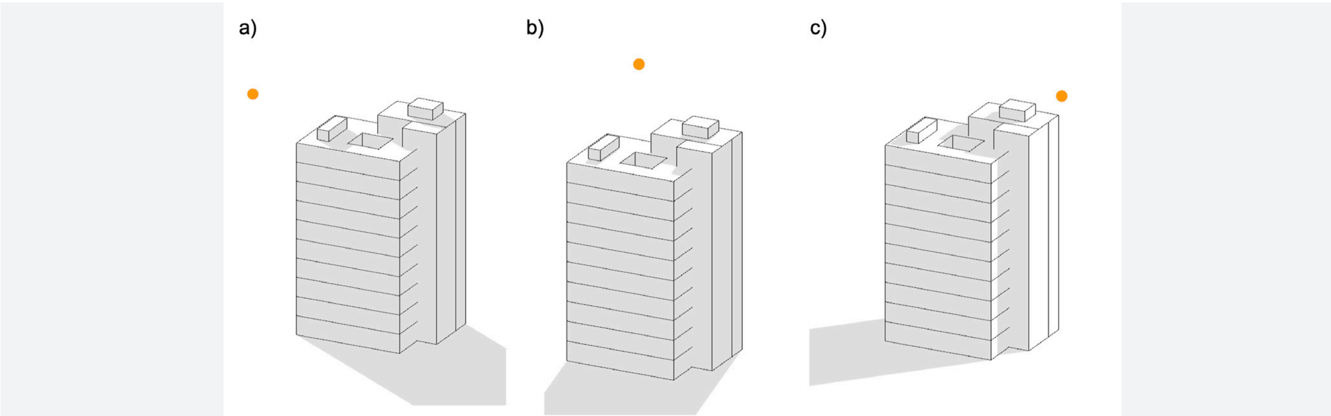

Figure 1. Sun path and shadow analysis of a building in Charlotte on February a) 9 am, b) 12 pm, c) 3 pm.

to address the power loss due to voltage and current drop in the circuit. (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.

A large number of researchers performed BIPV simulations without taking into account the shadow's negative effects on the power output. Therefore, the results of real-world application of the same design 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 shading. (Lee et al. 2017) Depending on 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 non-uniform 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, the 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)

Many studies have considered radiation nonuniformity in the scale of PV panels. Compared with the BIPV façade systems, the radiation nonuniformity happens on the scale of solar cells. Therefore, the proposed methods are inapplicable for BIPV facades. Connecting PV panels that receive similar radiation intensity were suggested as one solution for BIPV façade systems to address the power loss due to voltage and current drop in the circuit. (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 shadow 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)

This paper proposed the optimum BIPV façade systems' circuit connection for louvered PV integrated on 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 were calculated. The simulation and calculated results were validated by experiment tests. The next section describes the research methodology in detail.

METHODOLOGY

SIMULATION

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. (Kaji Esfahani et al. 2021) Thus, the solar panels also perform as shading louvers while generating electricity during sun hours of the

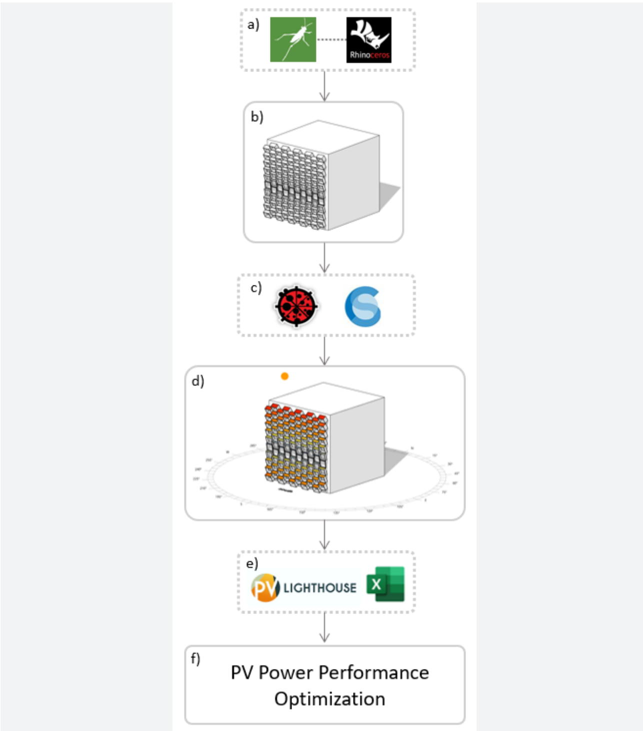

Figure 2. Workflow graphics: a) 3D modeling: Rhino and its plugin Grasshopper, b) Building geometry: integrating PV panels on the south façade, c) Shadows and solar analysis: Ladybug and ClimateCtudio, d) Power output evaluation, e) Maximum electricity output: by calculating I and V of different circuit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

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 facade system considering irradiance nonuniformity on the PV surface, the irradiance levels on the PV cells were simulated using Grasshopper, and other plugins such as Ladybug (LB), ClimateStudio (CS), PVLightHouse website (Keith McIntosh 2022), Python programing language and Excel (figure 2). Setting the grid size of the LB incident radiation component equal to 0.05 m, it creates the solar irradiance analysis grid exactly the same size of each PV cells that were used in the experimental tests. LB outputs the results based on kWh/m2. Since the total PV panel size were 1 m2, the output units of hourly irradiance simulation on the PV surface will be kW. Therefore, after multiplying the PV cells efficiency to those values, the BIPV power output will be calculated.

Calculating Imp and Vmp: It is obvious that the top PV panel of the array in a BIPV façade system 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, will receive less irradiance. However, the strings of the PV cells that are located closer on the exterior edge of the PV panel will receive higher irradiance level. Thus, to connect cells that receive 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 to gather. To reduce the time of simulations, a single PV panel that was located at the middle of the array chose to simulate the incident radiation and calculate the power output of the cells in different circuit connections. Maximum current (Imp) and maximum voltage (Vmp) 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 Grasshopper script were 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 cells during the sun hours of the entire year. Different circuit connections including 1) series connection between cells and series connection between strings, 2) series connection between cells and parallel connection between strings, 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.

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

For parallel connection,

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

and for serries 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 conducted to validate the simulation results. To determine the PV cells efficiencies, I and V of a string consist of 9 PV cells connected in series circuit connections were measured outdoor 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 efficiency of. The cells calculated which was 12%. Two panels, each consist of 36 mini monocrystalline solar cells were made by installing mini PV cells on a rectangle acrylic board. In one panel the PV cells were connected in series-series, demonstrating the conventional PV panels that are currently been using in the industry and BIPV construction (figure 4- a). The PV cells in the other panel were connected in a series-parallel

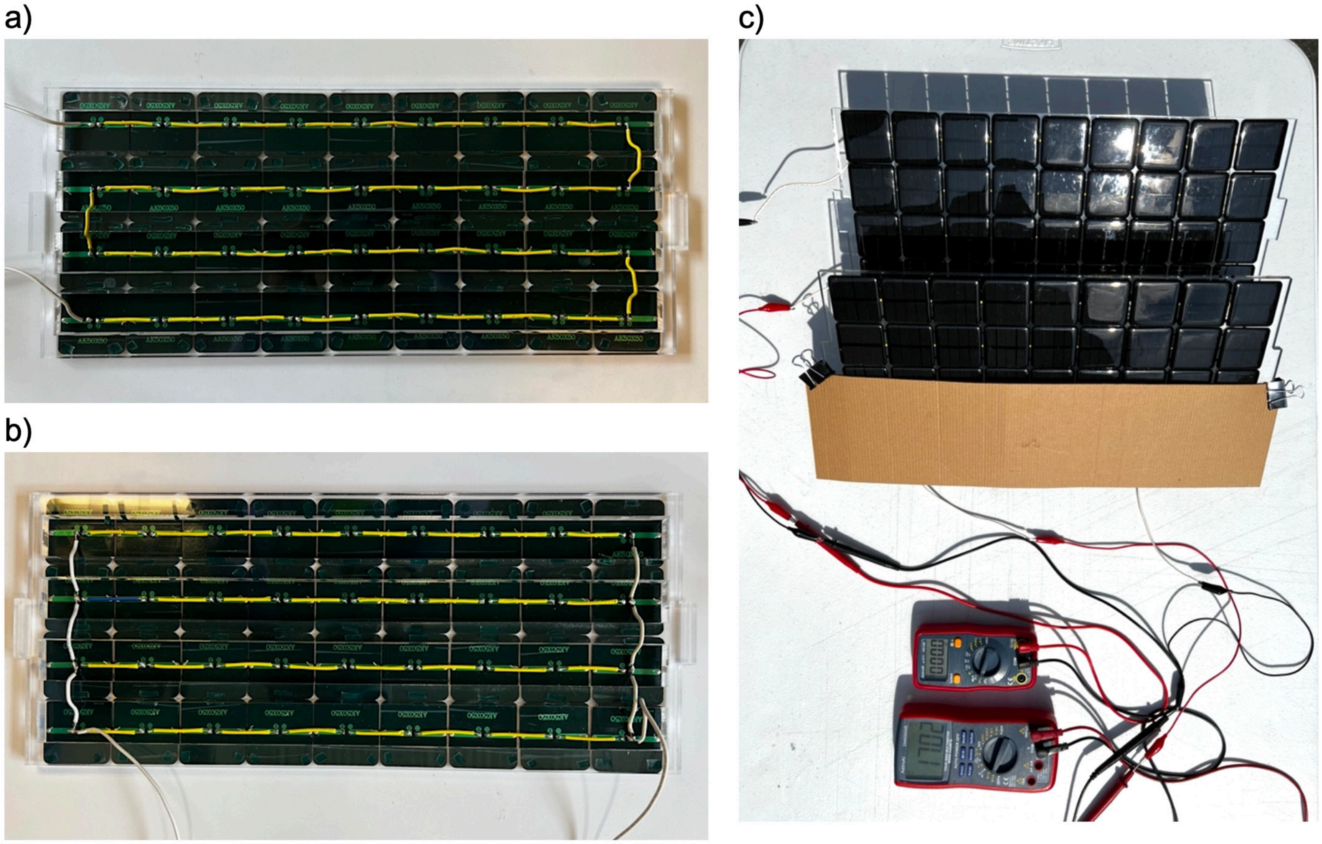

Figure 3. Experimental setup: a) series-series connection, b) series-parallel circuit connection, measuring the I, V, irradiance levels.

electric circuit where the PV cells in each row were connected in series, and the strings of PV cells were connected in parallel (figure 4-b). The tilting angle of the panels were 35.22 ° which is equal to the latitude of city of Charlotte. To make the experimental setup similar to the south façade, the panels located towards the south geographic direction (figure 4-c). While the panel in the front casted shadows on the 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 were exactly 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 results of the experiment tests showed that the conventional PV panel with series connection outputted 7.8 mA to 13.7 mA, and 77.8 v to 83.0 v 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. The overall irradiance levels during the experiment in those five days were changed from 210 W/m2 to 1020 W/m2.

ARCHITECTURE DESIGN

The PV panels integrated in the façade will alco perform as a shading device to reduce cooling loads, carbon emissions and glare problems while offering view out, on-site clean energy. Figure 3 is illustrating one typology of the BIPV façade systems and its simulated performance.

RESULTS

This paper investigated the optimum circuit connection for BIPV façade systems through simulation and experiment tests. After an in-depth shadow analysis, the simulations were conducted in two methods, 1) using LB incident radiation component and applying PV material efficiency to calculate the power output, 2) a Grasshopper script were developed 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 LB simulations can be considered for series-series circuit connection. Figure 5 is visualizing the annual power generation of LB and grasshopper 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 unapplicable for the BIPV

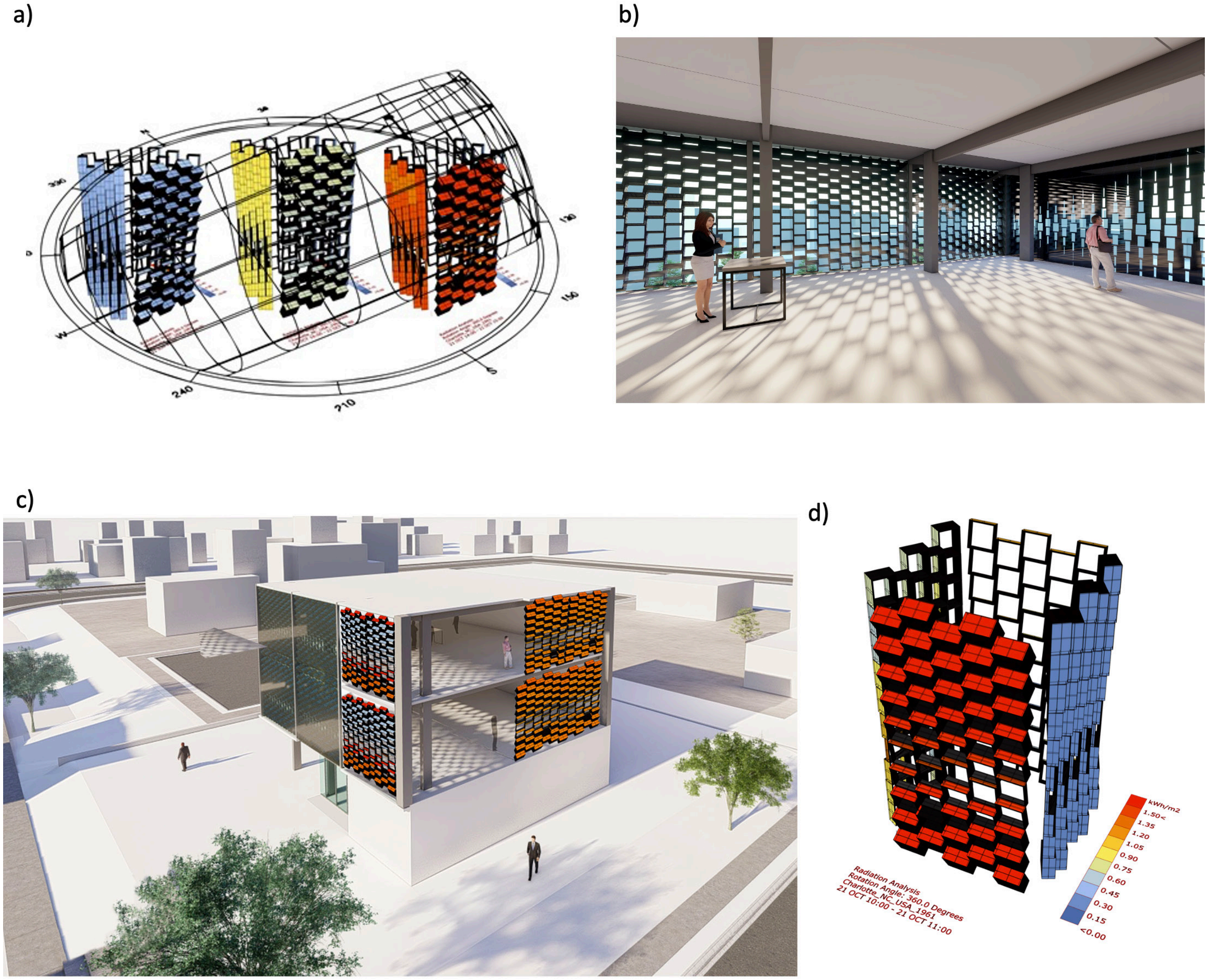

Figure 4. The proposed BIPV façade system architecture design: a) incident radiation on PV surface simulations on Oct 21st at 8pm, 5 pm, 2 pm from left to right respectively, b) interior view, c) bird eye view, d) incident radiation on PV surface simulations on Oct 21st at 10 am.

systems due to significantly low voltage output that will not meet the minimum required voltage input of the microinverter.

The results of the experiment tests were compared with the simulated circuit connections' power output in the corresponding day of the year. The LB incident radiation simulation results on Oct 8th at noon were 61 W. After applying the cells efficiency, 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 are 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 Oct 8th, were 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 measured in the experiment. The power output result of the series-parallel circuit connection that the Grasshopper 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.

CONCLUSION AND DISCUSSION

Despite the building façade accounts for up to 80% of the building surface area, currently architectural integration of solar energy has largely focused on roofs. 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 energy yields of the BIPV façade systems while minimizing discrepancies between simulation results and real-world applications performance. In this paper simulation and experimental power output of the partially shaded PV panels in different circuit 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 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 current drop in the electric circuit caused by partial shadows in a BIPV system so the designed BIPVs perform in real-world applications as they were intended during the design stage of the project.

In addition, the circuit connection of the PV cells in panels that are currently been manufactured in the industry will not output the maximum power in the BIPV façade systems. Since other methods that have been using to prevent the power loss and current drop in the circuit are not applicable for the BIPV façade systems, the best approach is to reconfigure the circuit connections between PV cells and strings of PV cells in a PV panel based on an in-depth analysis of the shadow patterns on the PV surface. Since the PV panel with parallel-parallel circuit connection will output the voltage equal to the voltage of one single PV cell, this type of circuit connection is not applicable for BIPV façade systems. To increase the power output while balancing out the I and V the optimum circuit connection reconfiguration will be series-parallel.

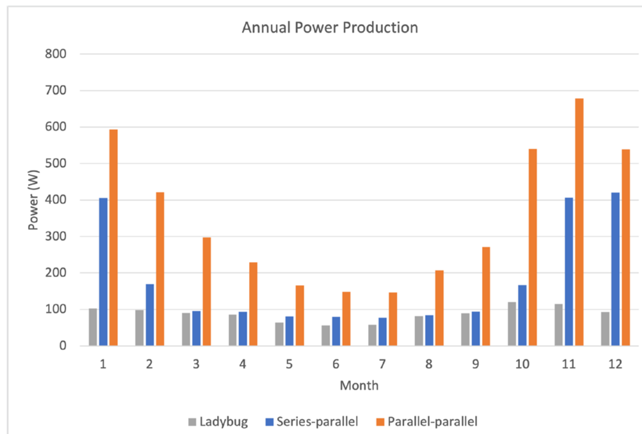

Figure 5. annual power production of different simulation methods

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

Although the results of the series-parallel circuit connection in Grasshopper script was close to the measured power output of the PV panel with series-parallel circuit connection in experimental tests, the reason of disparity can be the inconsistency between PV cells' efficiency in the PVLighthouse data and the efficiency of the PV cells that were used to conduct the experiments.

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ENDNOTES

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