COMPUTATIONAL ANALYSIS OF POWER LOSS REDUCTION IN BIPV SYSTEMS CONSIDERING PARTIAL SHADOW CONDITIONS

by

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ABSTRACT

SEYEDEHHAMIDEH HOSSEINIIRANI. Computational analysis of power loss reduction in BIPV systems considering partial shadow conditions. (Under the direction of DR. KYOUNG-HEE KIM)

Implementing PV panels as a source of clean energy for the building sector is growing worldwide. Currently, PV materials are widely installed on building roofs; however, with more population and urban area growth, the rooftop of high-rise buildings is not sufficient to fulfill the electricity consumption needs of the entire building. Additionally, the rooftop of many buildings is further limited to installing PV panels due to the overshadowing of block structures, electrical boxes, elevator bulkheads, etc. Therefore, the façade of a building has the potential to generate a high amount of electricity. The higher the building, the more opportunities to respond to the building demand loads and reduce the building's carbon footprint. The BIPV façade systems are often subject to partial shades from panels self-shading, building itself, and surrounding objects. Therefore, traditional default circuit connections do not output maximum power for those systems. While available technologies to keep the current in the highest amount such as inverters and microinverter cannot be used for BIPV applications due to their relatively low current output compared to larger-scale PV systems such as solar farms, PV cells circuit connections have a significant impact on higher energy yields in BIPV façade systems. This study investigates the different array configurations and PV cell circuit connections to achieve higher energy yields in BIPV facade systems. According to the simulated results in this study, the series connection between PV cells within the string that receive similar solar radiation, the parallel connection between strings of PV cells within each PV panel, and the series connection between PV panels within an array increases the total power production of the BIPV façade systems. The outcomes of this study demonstrated that this circuit reconfiguration increases the energy yields by 10%.

ACKNOWLEDGEMENTS

I would like to offer my special thanks to my research supervisor, Dr. Kyoung-Hee Kim, for her constant support, guidance, and dedicated involvement in every step of my research. Her advice and immense knowledge always encouraged me during my time of academic study and daily life. I also appreciate all the support I received from my family, especially my husband. Without his unfailing support, this achievement would not have been possible.

DEDICATION

I am dedicating this thesis to my beloved parents. I received their support and encouragement all the time during my personal and professional life. Even when they were thousands of miles away from me, physical distance never put a stop to their constant support.

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NOMENCLATURE

PV	Photovoltaics
BIPV	Building Integrated PV
3D	Three-dimensional
DOE	Department Of Energy
GHI	Global Horizontal solar Irradiance
GW_{dc}	Gigawatts-direct current
GHG	Greenhouse gas
MPPT	Maximum Power Point Tracking
LMPP	Local Maximum Power Point
V_{mp}	Maximum Power Voltage
I_{mp}	Maximum Power Current
DNI	Direct Normal solar Irradiance
NZE	Net Zero Energy
EPW	Energy Plus Weather

INTRODUCTION

In April 2021, the U.S. set a climate target of power sector decarbonization by 2035 (Nadim Chakroun 2021) Based on the climate target goal, GHG emissions need to be reduced by 50% to 52% by 2030 and achieve net-zero emissions by 2050. (NewClimate Institute 2021) Decarbonization of the power sector, by replacing fossil fuel-based powerplants with renewable energy sources, can be a key lever for this ambitious GHG emission reduction goal in the U.S. To facilitate this transition, the electric power sector requires to simultaneously decarbonize, while adding approximately 40% of new electric generating capacity to the grid by 2035. (Nadim Chakroun 2021) Based on the U.S. annual addition of new electric generating capacity, solar energy has always ranked as the first or second largest new electric capacity addition. According to the USSMI report, the U.S. installed 23.6 GW_{dc} of solar capacity in 2021 which was 46% of the total new electric capacity added to the grid (figure 1). (Perea et al. 2020)

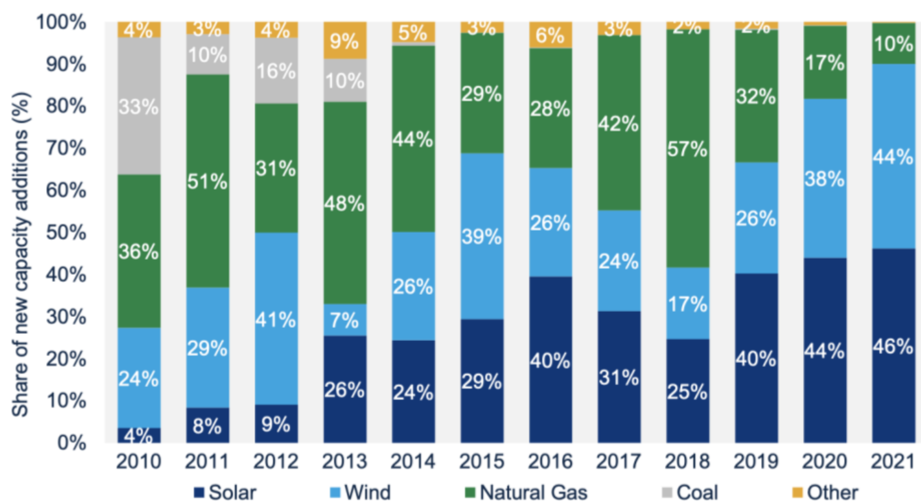
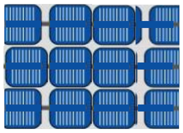
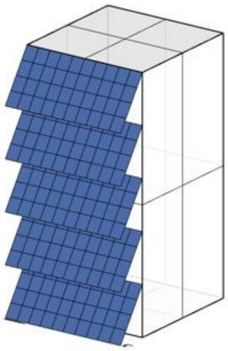


Figure 1: New power capacity additions during the last decade in the U.S. Source:(Perea et al. 2020)

A study was done by DOE in which a roadmap for achieving the climate target of GHG emission reduction has been demonstrated. According to that study, by 2035 the U.S. has to quadruple its yearly solar additions and maximize solar installation capacity by 1000 GW of power. Considering energy expenditure increment due to electrification in buildings, industry, and transportation sectors, decarbonizing the entire power sector, requires 3000 GW of solar by 2050. (DOE 2021) In February 2021, the U.S. had 48.8 GW of operating solar power systems which cover 654 mi^2 of land. To meet the decarbonization target of 2050, 13412 mi^2 of land will be required to install ground-mounted PV panels which is 43 times the area of the city of Charlotte in the state of North Carolina, U.S. (Lefteris Karagiannopoulos 2021) Although the land requirements to increase yearly solar installation capacity to 1500 GW over the next 15 years is only 1% of the total land area of the U.S., implementing economic projects within that footprint is exponentially challenging. (Nadim Chakroun 2021)

In addition, making that amount of land area suitable for installing ground-mounted solar panels means cutting a large number of trees, flattening topography, and destroying ecological systems which is contradictory to the main goal of solar energy as being a source of clean and eco-friendly energy. With more than 6 million commercial buildings in the U.S. (EIA 2015), the total area of the exterior envelops of those buildings has a great potential to integrate solar panels to offset electricity usage of the buildings' energy load demand.

Table 1: BIPV terminologies.

Term	**Graphic explanation**
Cell	
String	 
Panels	
Array	

BACKGROUND

With such a dramatic increase in PV development, the land area needed to mount PV panels will not be available, especially in countries with higher population rates and limited land use. On the contrary, there are available areas on buildings' exterior surfaces to install and integrate PV panels. The higher the building, the more opportunities to respond to the building demand loads. BIPV systems can be classified into two main categories based on where the PV panels have been installed on the exterior envelope of the building: roof and facade. Roof installed PV panels have been widely implemented in buildings during the past decade (figure 2). (Isa Zanetti 2017) However, with more population and urban area growth, the rooftop area of high-rise buildings is not sufficient to fulfill the electricity consumption needs of the entire building. Additionally, the rooftop of many buildings is further limited to installing PV panels due to the overshadowing of surrounding buildings, block structures, electrical boxes, elevator bulkheads, etc. Figure 3 is showing shadows cast on the rooftop of a two-stories building in London in the month of February at 10 am, 12 pm, and 2 pm. (Roberts and Guariento 2009)

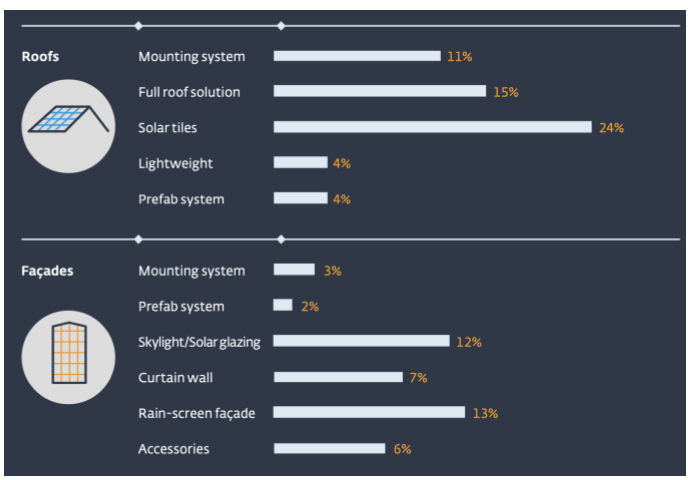


Figure 2: BIPV façade classification based on where the PV panels were installed and the materials that have been used. Source: (Isa Zanetti 2017)

a) b) c)

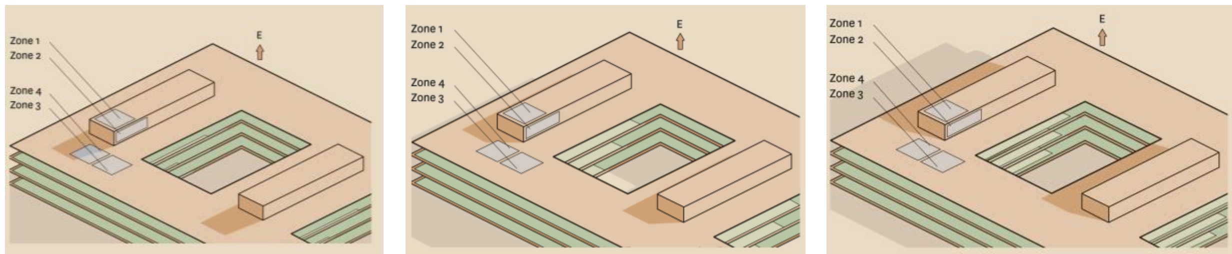


Figure 3: Sun path and shadow analysis of a building in London on February a) 10 am, b) 12 pm, c) 2 pm. Source: (Roberts and Guariento 2009)

Although the façade of the building is the best place to install PV panels due to the larger available area and adequate sunlight exposure, there are several challenges that need to be considered during the early stages of the design, such that BIPV façade systems can operate in real-world applications with more accuracy and higher energy yields as they are intended to perform in the design process.

PROBLEM STATEMENT

The BIPV façade systems are often subject to partial shades from surrounding objects such as trees, adjacent buildings, the building structure itself, modules frames, self-shadowing of modules, etc. that are drastically affecting the real-world power performance of the BIPVs. Shadows casting on the PV panel surface not only reduce the accuracy of the system performance in simulations during early design stage but also significantly affects the voltage and current in the PV panel electric circuit and consequently, drops the power output of the whole system. Roberts and Simon introduced panels self-shading as the main issue of BIPV sunshades. (Roberts and Guariento 2009) Figure 4 is demonstrating how shadows cast on one single cell of a PV module can significantly reduce the electricity output. Therefore, traditional default circuit connections between each cell in a PV panel do not output maximum power for BIPV façade applications.

Since shadows casting on the PV panels are unavoidable in BIPV façade applications, incorporating MPPT into the system leads to shutting off a large portion of the system due to the inability of tracking local MPPT, therefore, wasting a lot of material and oversizing the system which is not economically efficient. Other tools such as microinverter and bypass diodes are inapplicable for BIPV façade systems because most of the time, the current (I) output of the panels is lower than the current (I) threshold of the microinverter. Since in large-scale solar PV systems, each PV panel is connected to a microinverter, the voltage input threshold of the microinverter is from 30V to 40V. (Roy and Ayyanar 2018).

Previous literature has focused on the circuit connection and array reconfiguration of PV panels. However, the BIPV systems array reconfiguration and circuit connection primarily need to be defined at the PV cells scale. This study aims to contribute to the growing area of solar PV systems especially BIPV facades, by exploring suitable circuit connections of the BIPV façade system to maximize energy production, minimize discrepancies in power estimates between simulation results and real-world applications, and minimize power curtailment in MPPT systems.

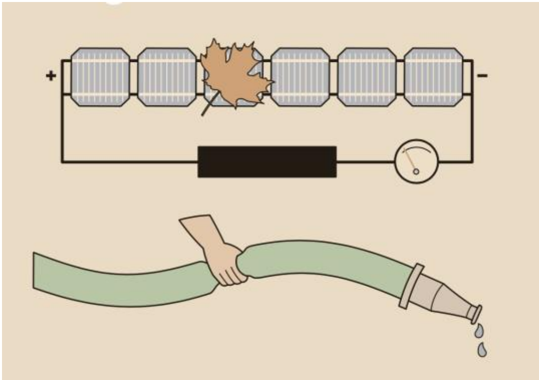


Figure 4: Emphasizing the importance of considering shading analysis in BIPV energy performance. Source: (Roberts and Guariento 2009)

GAP AND CHALLENGES

A large number of researchers performed BIPV simulations without taking into account shadow's negative effects. Therefore, the results of real-world application of the same model 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)

Shadows casting on the PV surface reduce the power output by not only decreasing the solar radiation on the PV cells' surface but also reducing the current of the circuit. There are available technologies to keep the current in the PV systems circuit high such as microinverter, MPPT, and bypass diode. Available microinverters are not applicable for BIPV façade systems because BIPV façade applications are not generating a higher amount of output than a large-scale system such as a solar farm.

Architects are accountable for taking 80% of the early-stage design decisions that affect the buildings' energy performance. (Freitas et al. 2020) In traditional design workflow, architectural solutions for design decisions are defined by iterating through the variables defined based on designers' knowledge, experience, and rules-of-thumb approach. (Jakica et al. 2019) However, in interdisciplinary projects such as BIPV applications, architects, designers and engineers need a robust and accurate analysis method so they will be able to perform in-depth shadow analysis and understand design constraints in both architecture and engineering fields.

Currently, to the author’s knowledge, there is not any available software, tool, or method to consider all of the variables and detailed constraints and provide an applicable solution for BIPV façade systems especially under partially shaded conditions.

RESEARCH HYPOTHESES

The hypothesis of this research was defined as follows:

- The power output of series-connected PV cells that are receiving a similar amount of solar radiation within each panel, is higher than parallel connection between PV cells.
- Parallel connection between the strings of PV cells within each PV panel outperforms other configurations.
- Series connections between PV panels within an array outperform other circuit connections.
- By using this reconfiguration, BIPV façade systems achieve 10% higher energy yields.

PRECEDENT

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 (figure 5). By dividing each 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)

Figure 5:Partial shading on PV modules of Z3 building of Ed. Züblin AG in Stuttgart, Germany. Source: (Kuhn et al. 2021)

LITERATURE REVIEW

SOLAR ENERGY

The amount of solar energy available on a surface depends on the following factors: The incident angle which defined as the angle between the cell surface and the sun's rays. The incident angle depends on the surface tilt angle and the sun's position in the sky. In figure 6 tilt angle is β which is measured from the horizon. (Bowden 2019)

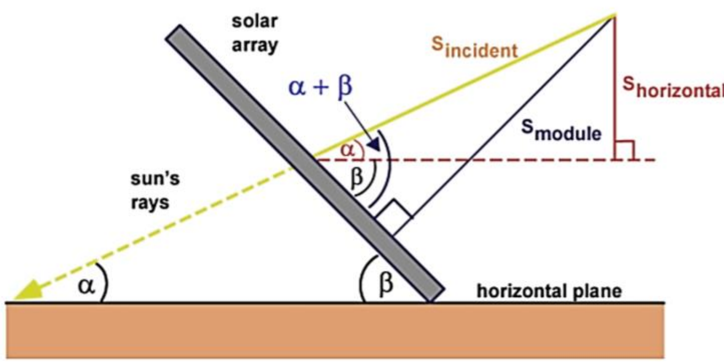


Figure 6:Tilt angle. Source: (Bowden 2019)

Panel orientation which called azimuth angle (γ). The azimuth angle is the compass direction that the module facing towards, i.e., north, east, south, and west has the azimuth angle of 0,90,180, and 270 degrees, respectively (figure 7). (Bowden 2019) The orientation of the module surface and its tilting angle determines the amount of direct and diffused light reaching the PV cell surface and that is constantly changing by different daily and annually sun positions. (Kuhn et al. 2021)

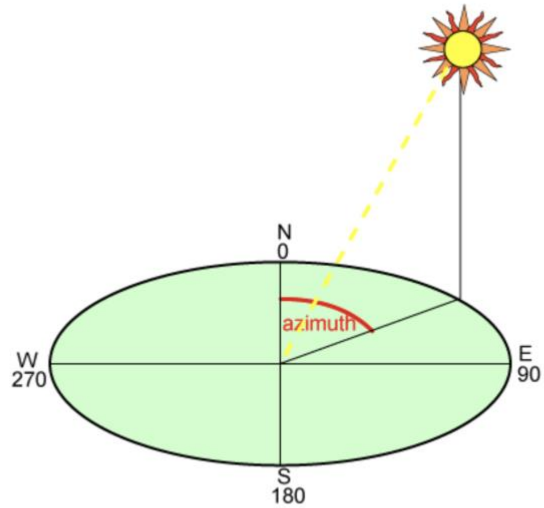


Figure 7: Sun path during the day and azimuth angle. Source: (Bowden 2019)

PV SYSTEM CIRCUIT RECONFIGURATION

Unlike ground-mounted PV panels, partial shadows casting on the PV surface is one of the biggest challenges in BIPV systems which causes power output reduction. Several methods such as array reconfiguration, modifying design variables and different circuit connections have been proposed in the literature to reduce the power reduction of the PV systems under partial shades. 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) Power output reduction of the PV array that is partially shaded, is proportional to the area that receives the least amount of radiation. By connecting the PV panels with similar radiation intensity, the power output will not only increase (Matam and Barry 2018) but also prevent system oversizing and downsizing. In addition, the aforementioned connection method will extend the lifetime of the PV system since it reduces the possibility of mismatch losses. (Zomer and Rüther 2017) 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%. Finally, 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)

In addition to Shadow patterns and the type of circuit connection between arrays, the location of shaded and unshaded panels within the array can also affect the PV system's power performance. (Pareek and Dahiya 2016) Other than basic circuit connections of series and parallel, researchers have studied more complex connections between PV panels to understand the impact of the circuit connection type on the PV system power output (figure 8). The primary problem of the series and parallel connection is either low current or voltage output. As figure 8 is showing the connection model type c, which is a serries-parallel connection, first connects PV panels in series to increase the voltage, and then each group is connected in parallel to achieve a higher current. (Bana and Saini 2017) The Serries-Parallel method has been widely accepted and used in PV arrays. (Satpathy, Jena, and Sharma 2018)

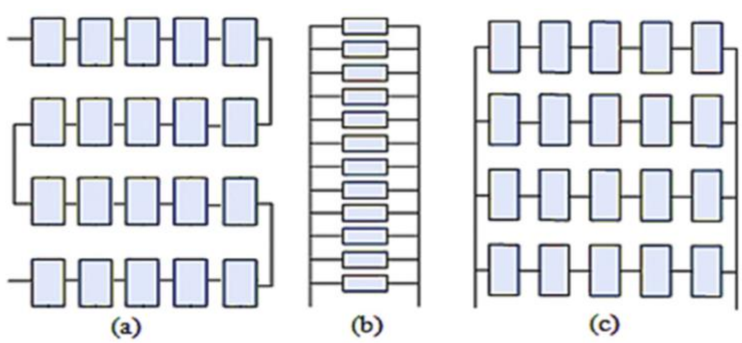


Figure 8: Different circuit connections. Source: (Bana and Saini 2017)

Although much literature focused on MPPT, not all of them considered partial shadings and nonuniform insolation in the BIPV systems. Ishaque et al. studied MPPT techniques for PV power systems considering partial shading conditions. (Ishaque and Salam 2013) Partial shading on the PV panel surface cause multiple LMPP and integrating traditional MPPT techniques into the system lead to a significant power loss. (Satpathy, Jena, and Sharma 2018) Nonetheless, those studies have considered radiation nonuniformity in the scale of PV panels. Considering the shadow patterns in BIPV façade systems, the radiation nonuniformity happens on the scale of solar cells. Therefore, the proposed methods are inapplicable for BIPV facades.

One might suggest installing several bypass diodes in one PV panel to avoid the current (I) reduction in PV cells. This method has been proposed by Hasyim et al. (Hasyim, Wenham, and Green 1986) However, it did not meet the solar PV manufacturers' specifications standards due to unavoidable major costs. (Dhimish et al. 2018) Other than 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) Satpathy et al. investigated I-Vcharachteristics of PV systems considering partial shading conditions but their experimental model and analytical method have been done using an array of PV panels. (Satpathy, Jena, and Sharma 2018)

The majority of the literature focused studied radiation nonuniformity on the module surface, PV panel array reconfiguration, new circuit connections, etc. in the scale of PV panels. However, for the BIPV façade system, the radiation nonuniformity happens on the scale of PV cells. Therefore, the methods proposed in previous studies are not applicable for BIPV façade systems. While tools and technologies such as microinverter, MPPT, and bypass diode have specific requirements, BIPV power output does not meet such requirements and therefore, the feasible solution to maximize energy yields and minimize PV power curtailments in BIPV systems is a suitable wiring circuit. In the methodology section, the analysis recipe and how each software or tool has been used to get the final results are elaborated.

METHODOLOGY

To estimate power production and recommend circuit connections of a BIPV system, this research utilized tools and software including Rhinoceros (Robert McNeel 2022), Grasshopper (Scott Davidson 2022), and other plugins such as Ladybug (Chris Machey 2022), ClimateStudio (Solemma 2022), PVLightHouse website (Keith McIntosh 2022), Python programing language and Excel (figure 9). An in-depth explanation of the input and output of each software and tool follows.

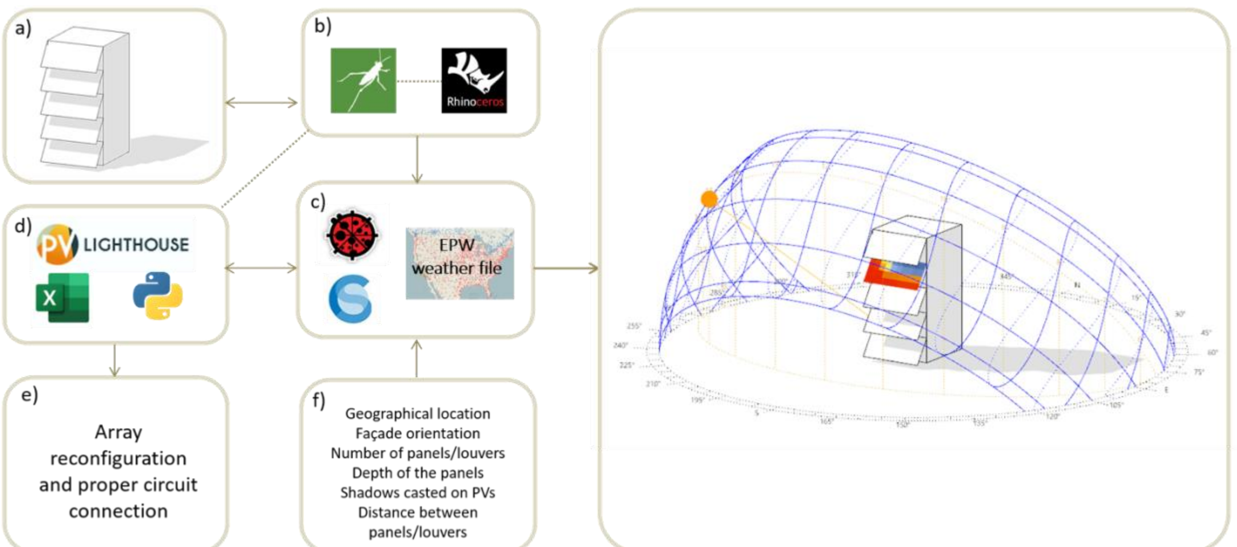


Figure 9: Workflow graphics: a) simplified building geometry with PV panels installed on the south façade, b) 3D modeling software, c) Shadows and solar analysis, d) I and V of the circuit connections calculations, e) array reconfiguration and proper circuit con

GEOMETRY

In order to reduce the time of running the shadow and solar analysis simulations, a box configuration is considered as a building (figure 10). It is widely accepted that solar panels should install horizontally on the south orienting façade, with a tilting angle equal to the latitude of a site location. (Kaji Esfahani et al. 2021) Thus, the solar panels also perform as shading louvers while generating electricity during sun hours of the day and year.

To make sure that the wiring circuit of the array reconfiguration, for both cells within each panel and the entire array, will lead to maximum power output, the system design and combination of components should be optimized.

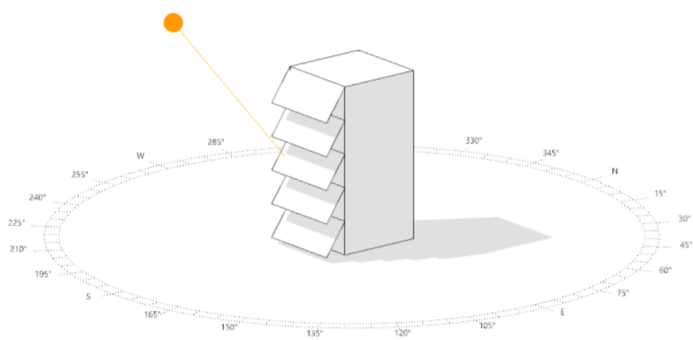


Figure 10:Simplified building geometry and PV panels installed on the south façade.

BIPV system's power output is influenced by the design constraints listed below:

- Façade orientation
- Tilt angle
- Total PV surface area (system size)
- Distance between the PV panels or louvers
- Local weather condition
- Analysis period

The daily average of global horizontal irradiance (GHI), and diffused normal irradiance (DNI) are varied in different locations over the globe. Based on the U.S. annual solar DNI, southwest regions of the U.S. have the highest DNI. (Sengupta et al. 2018) In this research, the geographical location is considered to be the city of Charlotte in the state of North Carolina, U.S.

In order to have an accurate comparison, different permutations of the components including depth of the panels, number of rows, and the distance between them have been generated while keeping the total area of the PV panels consistent. Afterward, using the EPW weather file (Chris Machey 2022), Ladybug, and ClimateStudio, the hourly radiation on the PV panels' surface, at the summer and winter solstices, as well as the spring and fall equinoxes were simulated. Based on the results, the optimum combination of the components in all four analysis periods occurred when the building model had 5 rows of PV panel louvers, with a depth of 0.7 m (figure 11). Setting the grid size of the LB IncidentRadiation component equal to 0.15 m, it visualizes the solar irradiance analysis grid exactly equal to the size of each PV cell within the solar panel. Therefore, one PV panel consists of 40 cells (figure 12). Since each square in the analysis grid is representing one PV cell, they are interchangeable. In this research, to keep the terminology consistent and simple, the PV cell will be used.

The in-depth shadow analysis in four critical times of the year including summer and winter solstices as well as spring and fall equinoxes illustrated that although the solar intensity is constantly changing, the patterns are not significantly varying. Table 4 visualizes clear trend of solar intensity receiving on each PV cell. According to the study done by Zomer and Rüther although shadows on the PV surface are constantly changing during the course of a year and a day, the yearly analysis period gives an acceptable result with a negligible error compared to the more refined analysis period. (Zomer and Rüther 2017) Therefore, in this research the yearly analysis period has been considered for shadows and solar analysis. The numerical output results of the Ladybug component show the cumulative irradiance each solar cell received from the sky matrix, during the analysis period, in kWh/m2. Thus, the yearly solar analysis indicates how much solar irradiance each cell receives in one year.

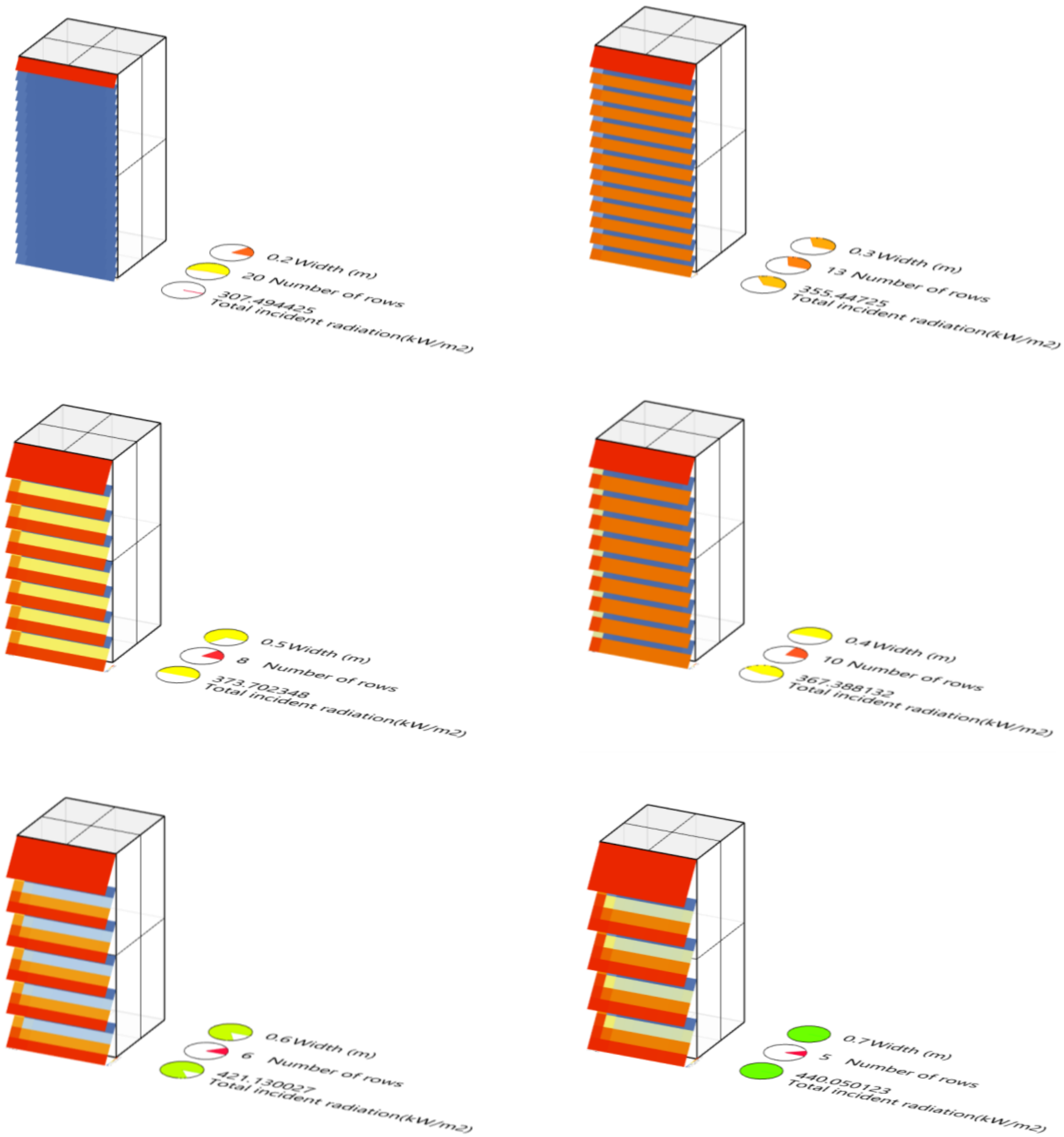


Figure 11:Simulation results of hourly radiation on the PV surface at summer soloistic (July 21st) while total PV surface area was consistent.

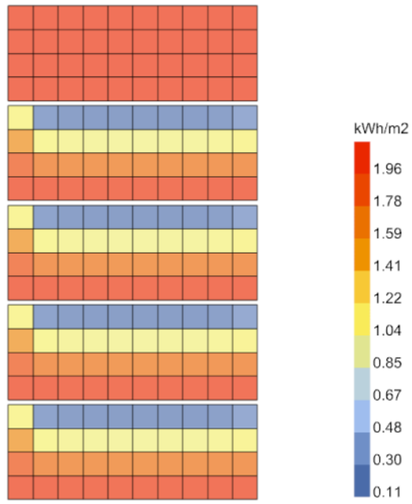


Figure 12:Analysis grid size has been set to 0.15 m which is equal to the actual size of the PV cells in manufacturing PV panels

GETTING I_{mp} AND V_{mp}

The Grasshopper does not report the results based on watt per square meter, which is irradiance. It does, however, visualize the insolation intensity with colors on the PV panels surface, each color associated with a range based on kWh/m^2. Figure 13 is demonstrating how the legend parameters can be interpreted into circuit light collected current (JL) (mA/cm^2) and then V_{mp}. By assigning the I_{mp} to the color red in the legend which is the highest intensity, V_{mp} and other variable outputs of the circuit were extracted from the PVLightHouse website (Table 2). (PVLightHouse, 2022) Afterward, by having I_{mp} and V_{mp} associated with each color, the power output (P) of different circuit connections can be calculated simply using the formula below.

For parallel connection,

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

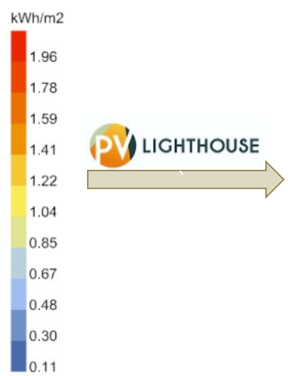
and for serries connection,

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

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

To reduce the possible errors of the human eye regarding detecting a shade of color, in the visualized solar analysis by grasshopper, a python code has been developed (figure 14). By inputting two numbers as a minimum and maximum radiation, the python code highlights the cells that are receiving that specified range of radiation. This extra step validates the accuracy of reading the numbers from PVLightHouse data from their associated colors.

legend values	normalized
dark red	1
red	0.9
dark orange	0.8
orange	0.7
dark yellow	0.6
yellow	0.5
green	0.4
light blue	0.3
blue	0.2
dark bule	0.1



PV LIGHTHOUSE

JL (mA/cm²)	Vmp (V)
10	0.5058956
9	0.504295182
8	0.50250236
7	0.500084755
6	0.497371326
5	0.493752505
4	0.489156328
3	0.482979975
2	0.473605805
1	0.456457941

Figure 13: Interpreting legend parameters into JL and V_{mp}.

Table 2: Circuit information from PVLightHouse website.

Vmp (V)	Jmp (mA/cm2)	Voc (V)	Jsc (A/cm2)	Pmp (W/cm2)	FF	Eff (%)	m at mp	m at oc	Temperature (°C)	Intensity (W/cm²)	JL (mA/cm²)
0.50589531	0.009459133	0.595109784	0.0099988	0.00478532	0.804205436	4.7853237	1.1165005	1.47062343	26.85	0.1	10
0.50429518	0.008508752	0.592369595	0.00899892	0.00429093	0.804947439	4.290928	1.12460062	1.42363829	26.85	0.1	9
0.50250236	0.007556367	0.589304248	0.00799904	0.00379711	0.80551512	3.7971064	1.13475125	1.37780866	26.85	0.1	8
0.50008475	0.006607017	0.58582607	0.00699916	0.00330407	0.805813292	3.304068	1.14914908	1.33198432	26.85	0.1	7
0.49737133	0.005654712	0.581806328	0.00599928	0.00281248	0.80577474	2.8124826	1.16771994	1.2864335	26.85	0.1	6
0.49375251	0.004704923	0.577044767	0.0049994	0.00232307	0.80525693	2.3230731	1.19550075	1.24131233	26.85	0.1	5
0.48915633	0.003754268	0.571204321	0.00399952	0.00183643	0.803847271	1.8364268	1.23681314	1.19697001	26.85	0.1	4
0.48297997	0.00280344	0.563648662	0.00299964	0.00135401	0.800834575	1.3540105	1.30479827	1.15383854	26.85	0.1	3
0.4736058	0.00185391	0.552932132	0.00199976	0.00087803	0.79406493	0.8780251	1.44092405	1.11609129	26.85	0.1	2
0.45645794	0.000905655	0.534318091	0.00099988	0.00041339	0.773777311	0.4133925	1.83494855	1.09477353	26.85	0.1	1

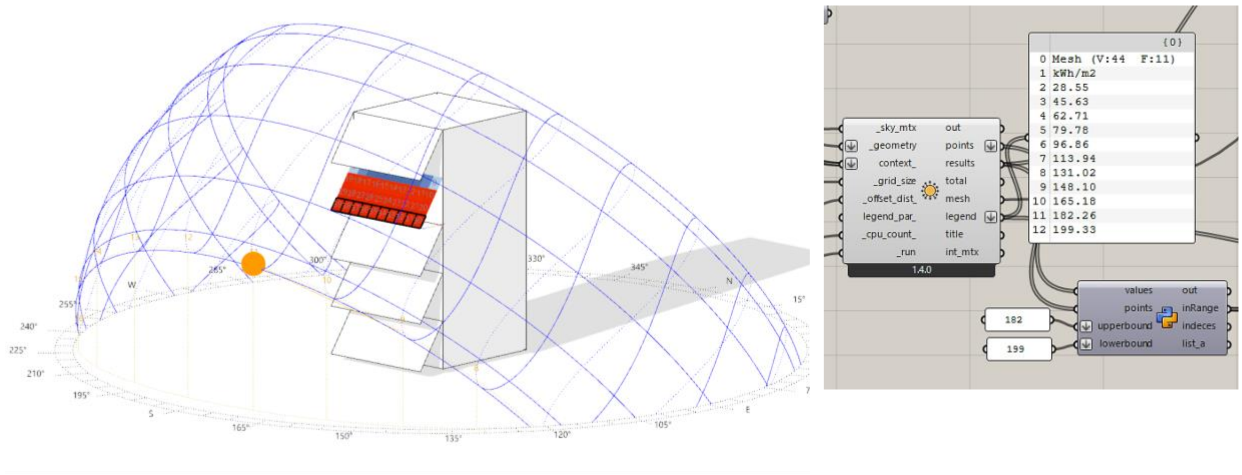


Figure 14: Using python programing language to reduce the possible human eye errors in reading color map

Table 3:Shadow and sun analysis.

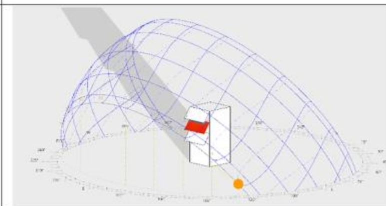
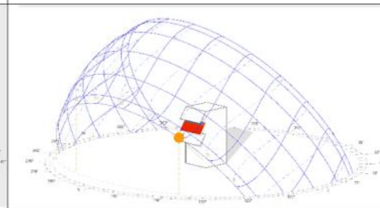
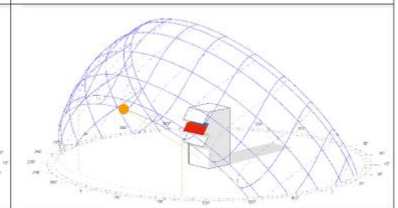
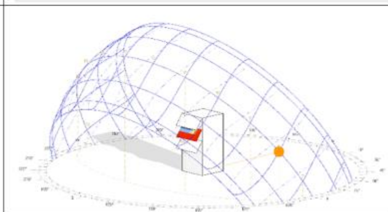
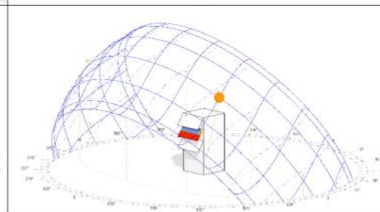
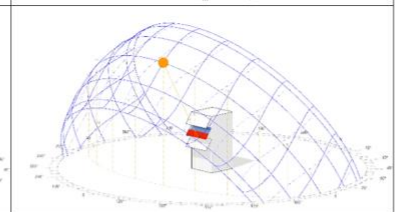
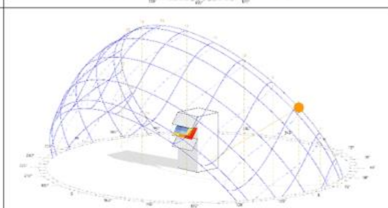
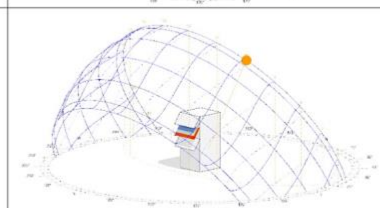
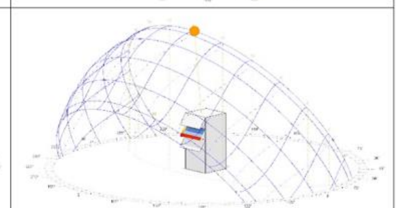
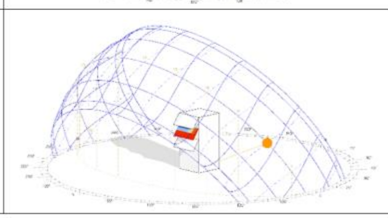
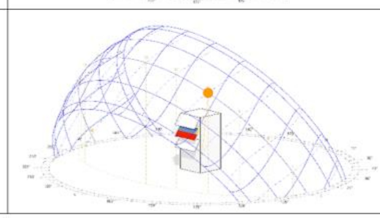
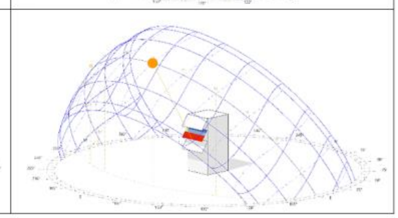
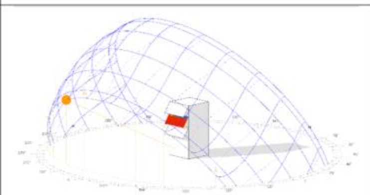
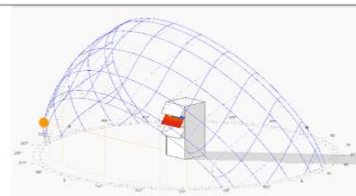
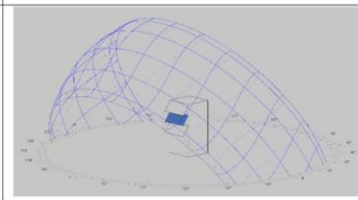
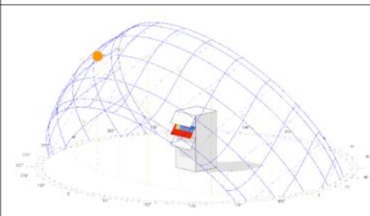
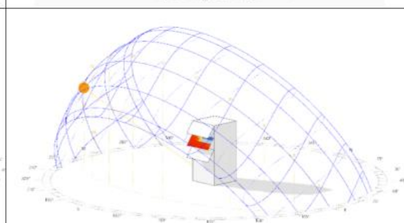
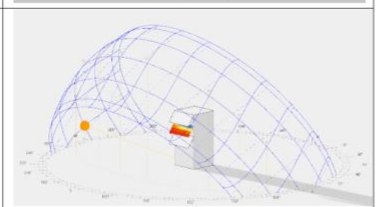
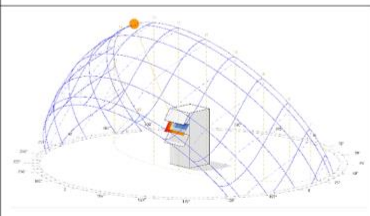
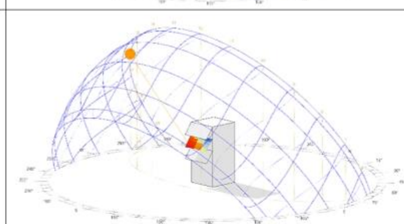
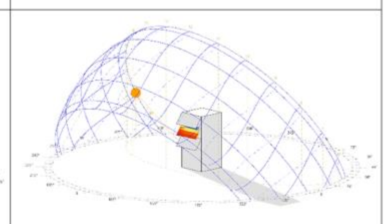
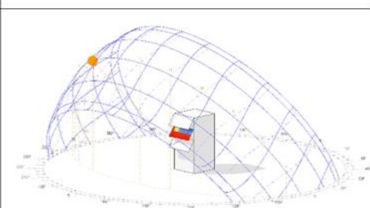
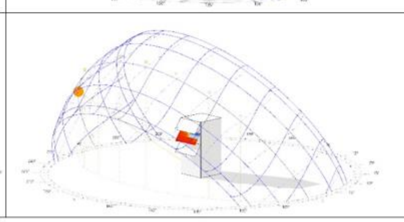
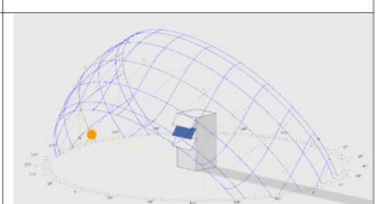
Month / Time	8 am	10 am	12 pm
December 21st			
March 21st			
July 21st			
September 21st			

Table 4:Shadow and sun analysis.

Month / Time	2 pm	4 pm	6 pm
December 21st			
March 21st			
July 21st			
September 21st			

GROUPING PV CELLS BASED ON RADIATION UNIFORMITY

To better understand the uniformity patterns of sun expositor, shadow patterns, and irradiance levels on each PV cell, the data visualization of hourly radiation of one shaded panel has been generated. Figure 15 illustrates the solar radiation on all of the 40 cells of the PV panel on December 21st. In order to identify PV cells with similar radiation level, hourly radiation on horizontal and vertical strings of PV cells was visualized. Figure 16 shows more uniformity in horizontal strings of PV cells, compared to the vertical strings of PV cells which have a noticeable difference.

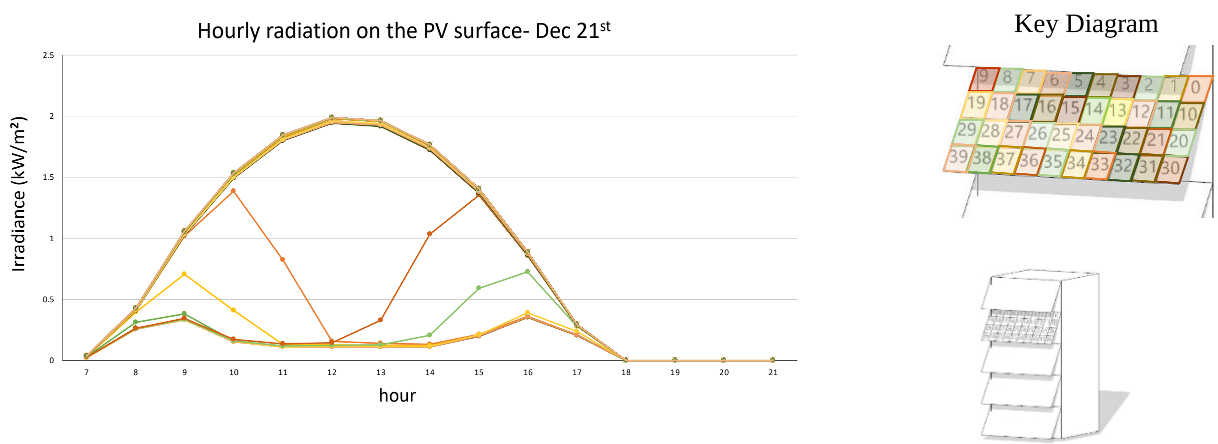
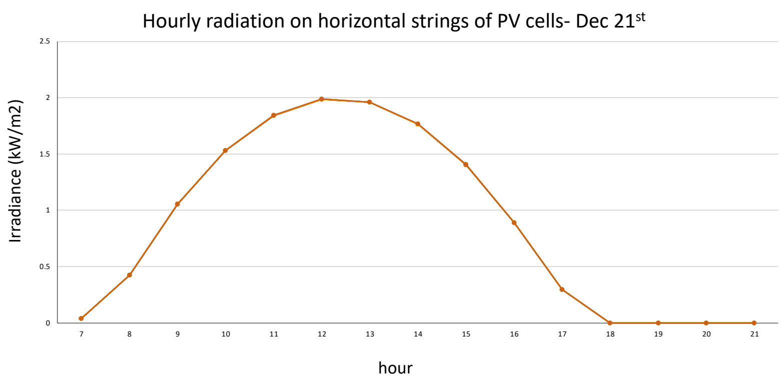
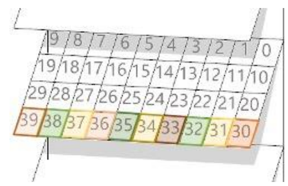
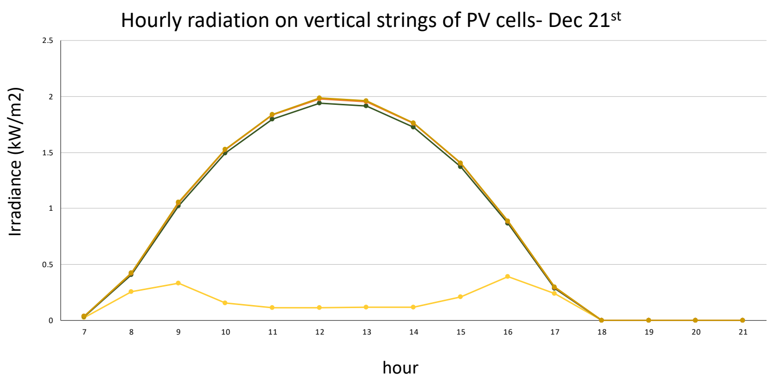


Figure 15: a) Hourly radiation that all of the PV cells received during the winter solstice (Dec 21st), b and c) Location of each cell a PV panel

Key Diagram







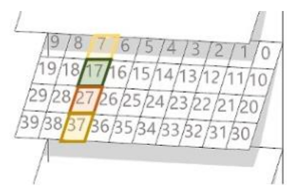


Figure 16:radiation levels in horizontal vs vertical strings of PV cells

CIRCUIT RECONFIGURATION SCENARIOS

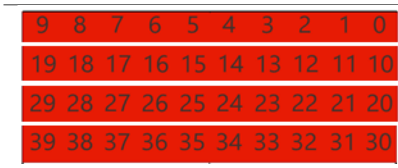
As mentioned in the previous sections of this study, the yearly analysis period has been considered. Each panel consists of 4 rows and each row has 10 cells, totally 40 cells for each PV panel. The power output of horizontal and vertical strings of the PV cells, in both series and parallel connection, were calculated, using table 2.

HORIZONTAL STRINGS

CLOSEST PANEL TO THE ROOFTOP

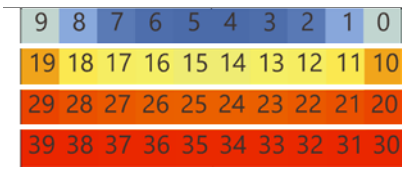
It is obvious that the top most PV panel of the array always receives the highest amount of solar radiation. Based on the calculation outcomes, there is not any difference in series or parallel connection and the amount of power production in both circuit connections are identical (Table 5).

Table 5: Power output calculation of the horizontal strings of PV cells within closest panel to the rooftop

Strings of PV cells	Calculations				
		Series		Parallel	
		I output	V output	I output	V output
		10	20.23	40	5.05
	Power (milliwatt/cm^2)	202.35		202.35	

Based on the calculated power output in each series and the parallel connection between the strings of PV cells in partially shaded panels, the parallel connection between strings of PV cells outperforms the series connection (Table 6).

Table 6: Power output calculation of the horizontal strings of PV cells within partially shaded panel

Strings of PV cells	**Calculations**				
		Series		Parallel	
		I output	V output	I output	V output
		1	19.77	25	4.71
	Power (milliwatt/cm^2)	19.77		117.93	

VERTICAL STRINGS

Same process for calculating power output of the strings of PV cells have been done but in this scenario strings of the PV cells have been considered to be located vertically on the PV panel surface.

CLOSEST PANEL TO THE ROOFTOP

Similar to the horizontal strings of the first panel from the top, there is not any difference in vertical strings of PV cells' power output. Calculations demonstrated in table 7.

Table 7: Power output calculation of the vertical strings of PV cells within closest panel to the rooftop

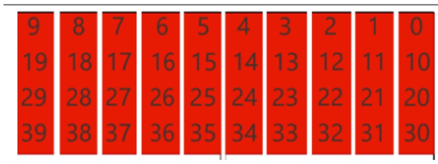
Strings of PV cells	**Calculations**				
		Series		Parallel	
		I output	V output	I output	V output
		10	20.23	100	2.02
	Power (milliwatt/cm^2)	202.35		202.35	

Table 8: Power output calculation of the vertical strings of PV cells within partially shaded panel

Strings of PV cells		Calculations			
		Series		Parallel	
		I output	V output	I output	V output
		1	18.81	22	1.50
	Power (milliwatt/cm^2)	18.81		33.16	

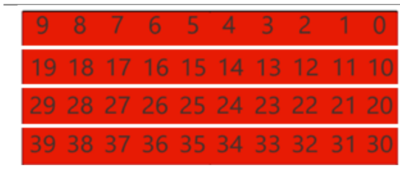
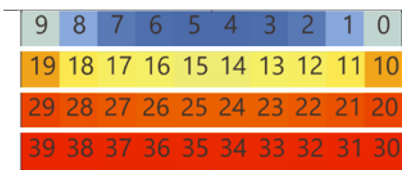
CONVERTING UNITS AND APPLYING PV EFFICIENCY

Since the current (I) unit was in milliamps, the calculated power was in milliwatts/cm^2. To make a correct comparison, all of the calculated power outputs were converted to W/m^2 and then multiplied by the area

(m^2) of the PV panel. Finally, to get the electricity output the outcomes are multiplied by PV efficiency of 18% (table 9 and 10).

Horizontal PV cell strings connected in parallel outperform the other circuit connections and vertical strings of PV cells. The power output of another analysis period which caused high nonuniformity radiation on the PV panel surface has been calculated to examine the performance of the system using reconfigured circuit connection. To do that, the analysis period has been set to July 21st, from sunrise to sunset (figure 17). According to the calculations in table 10 the parallel connection between vertical strings of PV cells has less power loss; however, the amount of current (I) is higher than the microinverter threshold and this circuit reconfiguration is not applicable for the BIPV systems. Therefore, the parallel connection between horizontal strings of PV cells is the optimum configuration for the most nonuniform radiation on the PV panel surface.

Table 9: Unit conversions and applying PV efficiency

Reconfiguration scenario	**Unit conversion and applying PV efficiency**			
	Power (milliwatt/cm^2)	Power (watt/m^2)	efficiency (%)	PPV (Watt)
	1	10	0.18	
	202.35	2023.58	364.24	382.45
	1	10	0.18	
	117.93	1179.32	212.27	222.89

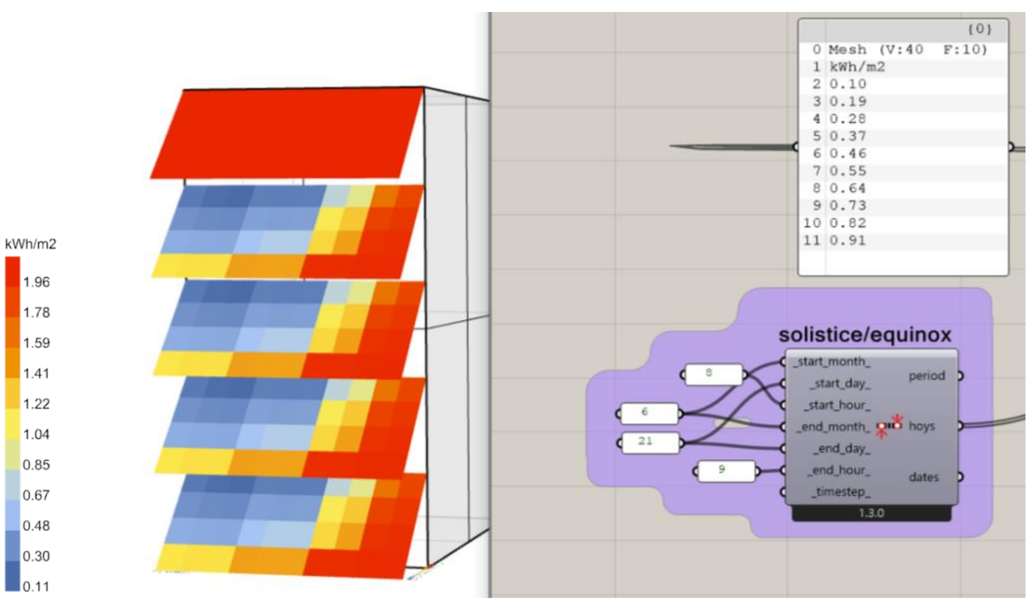


Figure 17: The most nonuniform solar radiation, analysis period was set to summer soloistic

Table 10: Comparing power production of the most nonuniform radiation on the PV panel surface in different scenarios – July 21st

PV cells string	**Reconfiguration scenario**					**Unit conversion and applying PV efficiency**			
		Series		Parallel		Power (milliwatt/	Power (watt /m²)	efficiency (%)	PPV (Watt)
		I output	V output	I output	V output				
		1	19.03	12	4.27				
	Power (milliwatt/cm²)	19.03		51.34		51.34	513.45		97.04
		Series		Parallel		Power (milliwatt/	Power (watt /m²)	efficiency (%)	PPV (Watt)
		I output	V output	I output	V output				
		1	19.52	35	1.91	1	10	0.18	
	Power (milliwatt/cm²)	19.52		66.86		66.86	668.64		126.37

CONCLUSION

The BIPV facade systems are often subject to partial shades from panels self-shading, buildings and surrounding objects. Since, in a BIPV façade system, the radiation nonuniformity happens on the scale of PV cells, traditional default circuit connections do not output maximum power for BIPV applications under partially shaded conditions even with the technologies such as microinverter, MPPT, and bypass diode due to incompatible applications for BIPV façade systems.

This study proposed a proper circuit connection and array reconfiguration of a BIPV façade system for more accurate power estimates and practical real-world applications, based on a robust analysis recipe for in-depth shadow analysis through evaluating radiation uniformity on PV panel surface from scale of the PV cells to an array of PV panels. Outcomes of the study demonstrate that the series connection between PV cells within the string that receive similar solar radiation is the proper way to wire strings of PV cells. Horizontal strings that have parallel connection output more power compared to vertical scenario or other connection types (figure 18). For the closest panels to the rooftop where there are no shadows casted from the PV panels itself, the radiation intensity is uniform on those panels' surface. Therefore, in all of the connection scenarios, those panels at the top have the same power output during the same analysis period (figure 19). Series connection between PV panels within an array outperforms other connection types (figure 20). The proposed system configuration will maximize power output of the BIPV systems by 10%.

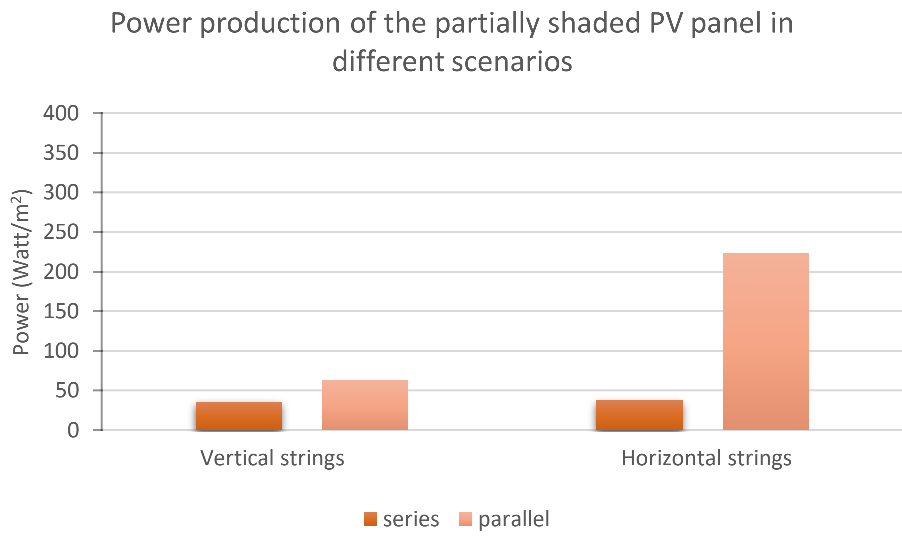


Figure 18: Comparing power production of the partially shaded PV panel in different scenario

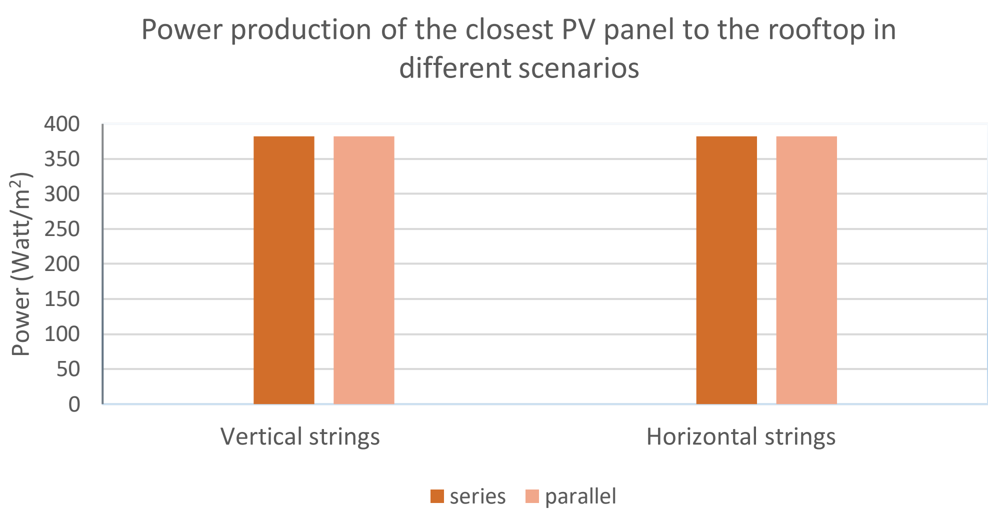


Figure 19: Comparing power production of the closest PV panel to the rooftop in different scenario

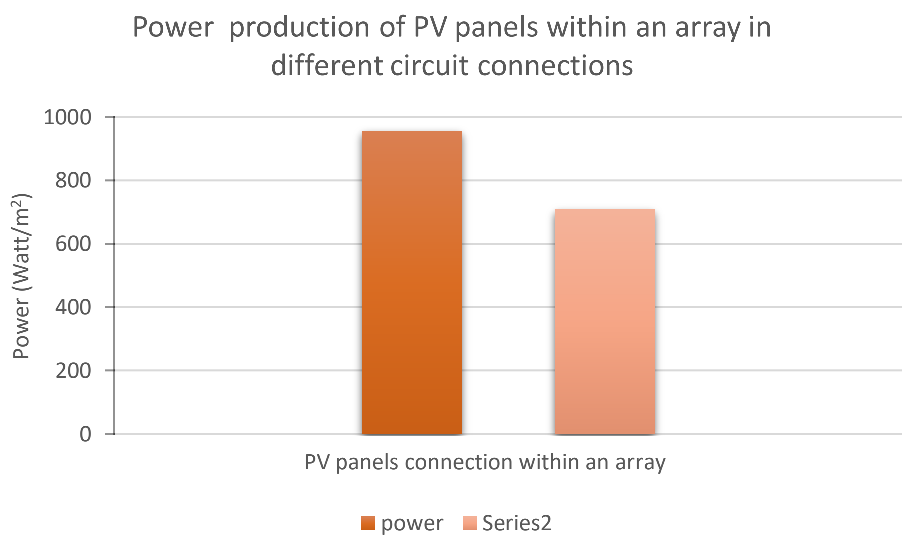


Figure 20: Comparing power production of the PV panels within an array in different scenarios

IMPACT AND CONTRIBUTION

The methodology of this study helps architects and designers to run in-depth shadow analysis and make inform decisions about addressing the BIPV façade design and power production reduction without investing extra budget to oversize the system. In addition to promoting net zero energy and carbon neutral buildings, the outcomes of this study enhance energy yields of BIPV façade systems in real-world applications, as they intend to perform during design process of the project.

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