Chapter 13
Computational BIPV Design: An Energy Optimization Tool for Solar Façades

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Abstract In contemporary buildings, façades are generally the largest borders between the inside and the outside which determine the proportion of energy consumption of the buildings. With today's technology, they could also offer the opportunity of producing energy by adding photovoltaics into their systems, to cover a portion of the building's need for electricity and reduce its dependency on fossil fuels, especially where there is a high amount of global horizontal irradiation (GHI) and a high potential for generating electricity from photovoltaics. In the new concepts, building-integrated photovoltaics (BIPV) is even being used in the transparent sections of the façades which should be a cautious decision as they can highly affect the total energy demand of the building due to the change in the proportion of daylight and heat that can pass through. Thus, they should all be taken into consideration during the first stages of design to get the best result possible. While there have been some studies on this subject, we are still facing a shortage of tools and methods for BIPV design in the preliminary design phases.

This research aimed to provide a design tool for BIPV systems by making use of the integration of energy simulation programs with visual programming tools to spot the best façade solutions for any specific project. The optimization of these solar façades by this tool is discussed and compared to the nonoptimized alternatives. To put it briefly, the tests were done on a common vertical two-section façade with windows to provide natural light and solar heat to a certain amount that would be beneficial energy-wise, with crystalline silicon-based photovoltaics in the remaining parts of the façades.

The simulation results illustrated how a great quantity of inputs could affect the performance to a great extent. For instance, glazing material was put on a test and the results with four different alternatives in the south façade of Cairo (Egypt) showed that a wrong decision on glazing material alone could result in an increase of 28% in lower window-to-wall ratios (WWRs) and 51% in higher WWRs in the energy

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consumption of an office room. Therefore, by choosing the optimal solution for each input, we could reduce the energy use of a building extensively which highlights the need for tools to come to the aid of the decision makers to find the best options and avoid choosing the inferior alternatives during the first stages of design.

13.1 Introduction

Throughout history, architects have always aimed to define some methods which were gained from their experience to achieve designs that lead to higher-performance buildings, but today with the emergence of energy simulation programs which can simulate the performance of buildings in terms of heating and cooling electricity consumption within 3% of mean absolute error [1] and with the high degree of complexity in projects, practicing rules of thumb would be a failure in catching up with the developments in the field.

There have been previous studies on using simulation tools for the optimization of solar façades with different methods. This was done by providing a tool to optimize the geometry of the building to achieve maximum insolation [2] and focusing on maximizing the amount of energy production rather than minimizing the net energy need or by trying to optimize energy production by finding the façade parts that have the highest insolation for BIPV positioning [3]. There have also been some studies on the PV area ratio on glazing to provide light and energy production at the same time and reach the lowest net energy consumption [4, 5]. In this research, minimizing also the dependency on fossil fuels was considered as the goal rather than maximizing the production of renewable energy; thus, the solutions which had the lowest net energy need were considered optimum.

In producing an optimizing tool for solar façade design, the first task would be to find the variables that could change a façade's performance for better or worse. One of the main effective parameters in changing the amount of energy loads of buildings is the size of windows. Nowadays, façades with vast glazing are more common to make the best use of daylight, which could result in higher loads due to the lower capabilities of glass to act as a heat insulator in comparison with walls in general. Therefore, they should have high-performance materials or preferably a reasonable size to provide the required daylight level while keeping the amount of heat transfer at its best rate.

There are other variables that could change the amount of solar gain and as a result the optimum window-to-wall ratio (WWR). An adjustment in the material properties of the walls or the windows themselves such as solar heat gain coefficient (SHGC) or U-value or whether the windows have external blinds or not could change the amount of energy loads and the ideal WWR to a great extent. Other factors like geographical location, orientation, the required light level inside of the building, etc., would also affect the optimum window-to-wall ratio for façades. In designing these solar façades where building-integrated photovoltaics (BIPV) are a part of their system, the amount of energy that photovoltaics produce would also be added as a factor that plays a role in determining the optimized WWR.

Table 13.1 Required input

Geometry		Material properties (wall)	Material properties (glazing)
Length	Function	U-value	U-value
Width	Lighting set point	PV-to-wall ratio	SHGC (solar heat gain coefficient)
Height	Shading scenario	PV efficiency	VT (visible transmittance)
Orientation		PV temperature coefficient	PV efficiency
Location			PV temperature coefficient

13.2 Methodology

It was decided to study the effectiveness of the variables on the optimal solar façade solution by testing them on different WWRs to monitor the changes. Consequently, the enumerative method was used for the tests. The principle of this method is simple. Within a finite search space, or a discretized infinite search space, the algorithm assesses the fitness function at every point in the space, one at a time [6]. In this way, a better understanding of the impact of the variables could be reached.

13.2.1 Inputs

A list of all effective parameters on the ideal façade solution was gathered as changing variables for the simulations. A detailed list of the provided inputs is demonstrated in Table 13.1.

Function By choosing the function input, visual properties of the surfaces, equipment and lighting power density, or thermal loads conditions like ventilation and occupancy schedules would be set automatically by predefined values based on the given function.

Lighting set point This input sets the needed amount of light. When there is a lower light level than the set point input, it means there is a shortage of daylight, and the artificial lighting system will fill the gap with its automatic dimming controls.

Shading scenario By selecting true for the shading scenario, an optimized horizontal blind system would be calculated for the windows (based on the other inputs selected) at the starting point of the calculations, and it would be considered in the evaluations.

Each input could take more than one value that would be tested in the later rounds of the calculations. For instance, in the second round, all the second inputs would be taken into account altogether, and for the third round, the third inputs and so on. Where there is no value for the second test for an input, the tool will automatically use the same last value for the new round. The existence of any multiple values for one input would result in multiple calculations.

13.2.2 Predetermined Inputs for the Evaluations

In the calculations of this article, there are some fixed and some changing values as inputs and not all inputs would be tested and considered as variable. Three different cities with different climates in the Mediterranean region were selected as locations for a typical office room with an area of 35 m^2 and geometry inputs of 7 m width, 5 m depth, and 4 m clear height, which was the case study for all the evaluations (Fig. 13.1).

This single office is included in an entire building; thus, only one wall would be fully exposed to the outdoor space (Fig. 13.2). This external wall consists of a single window placed at its center, as the energy load of the office would be at its lowest when the windows are located in middle height [7]. The WWR test range is from 1% to 100%.

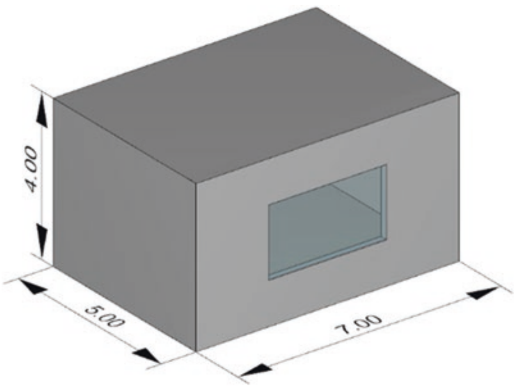


Fig. 13.1 Geometry of the case study

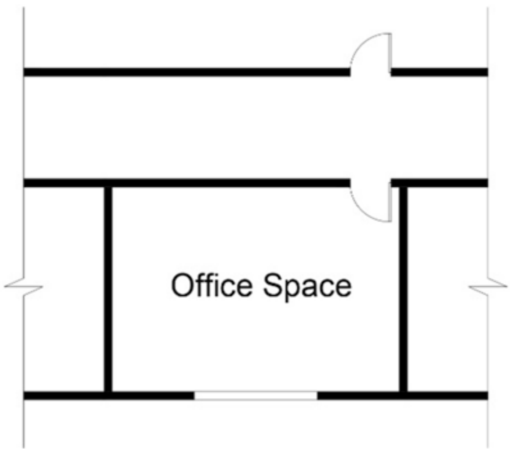


Fig. 13.2 Context's scenario

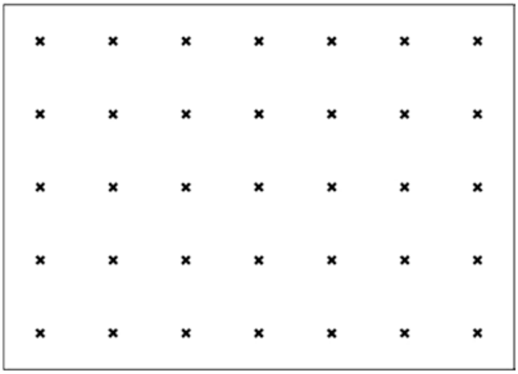


Fig. 13.3 Arrangement of daylight sensors

For the artificial lighting, a set point of 500 Lux, which is the minimum level for comfort in offices according to EN 1246-1 [8], was given as input to the auto-dimming system. The reference plane of the daylight simulations was placed at a working plane of 0.8 m height with a sensor dedicated to each square meter which would be a default action in the provided tool. In Fig. 13.3, the arrangement of these sensors in this office space is demonstrated.

13.2.3 Evaluation Tools

All the simulations are carried out in Grasshopper, Ladybug, and Honeybee which are all Rhinoceros 3D plug-ins, and they are all used to interface EnergyPlus [9] and Radiance [10] for the annual energy and illuminance computations. EnergyPlus is a free and open-source building energy simulation program. Its development is funded by the US Department of Energy that is open source. Radiance is also an open-source program, which is the most generally useful software package for architectural lighting simulation [11]. Even though Radiance is not a common tool for architects due to the lack of a graphic user interface, and as it needs an accurate model for simulation purposes, Grasshopper which is a visual programming tool was used as the modeling software.

13.3 Results and Discussions

13.3.1 Adding Photovoltaics to the Wall's System

For the first evaluation, the effectiveness of different WWRs on energy consumption of the office with a simple wall with no photovoltaics was compared with a BIPV wall system. In the second wall system, where BIPV was used, the whole area of the façade had photovoltaics added to its system except for the transparent section; thus,

Table 13.2 Inputs considered for the first test

Geometry	Material properties (wall)	Material properties (glazing)
Orientation: South	U-value: 0.34	U-value: 2.56
Location: Cairo	PV efficiency: None, 14%	SHGC: 70
Shading scenario: True, true	PV temperature coefficient: None, 0.45	VT: 80

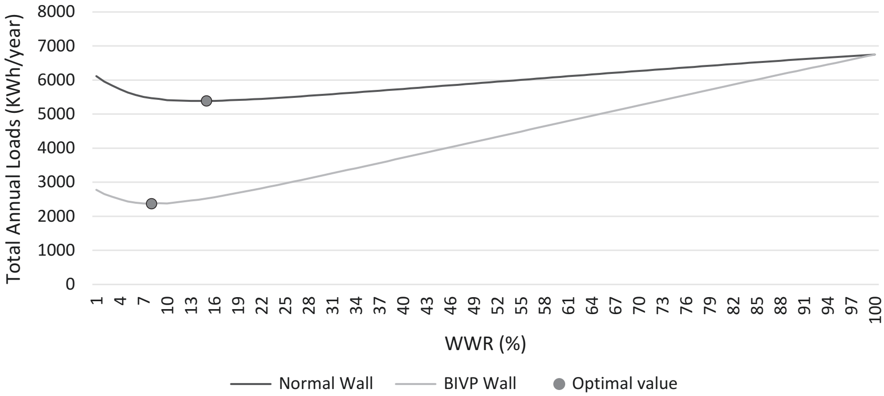


Fig. 13.4 Energy consumption based on window-to-wall ratio (WWR) for different wall materials. (Location: Cairo, Egypt; Orientation: South)

the PV-to-wall ratio was equal to one minus the WWR value. The other inputs that were used for this simulation are illustrated in Table 13.2.

The results in Fig. 13.4 show how the ideal WWR value changes by adding photovoltaics to the façade system. While the best WWR for a normal façade with the mentioned properties was 15%, this ideal ratio stepped down to 8% after adding the photovoltaics. This change is due to an added factor which is the energy production by the photovoltaics. The higher they produce energy, the lower the optimal WWR becomes.

13.3.2 Adding Photovoltaics to the Glazing's System

After photovoltaics was added to the wall's system in the first simulation, the effectiveness of different materials for glazing on the total energy consumption and the ideal WWR was put to the test. Three photovoltaic glazing types with different properties were chosen for a better investigation, as adding photovoltaics to the transparent part of the façade would be more complex in comparison with adding them to the opaque parts. The properties of these glazing materials are demonstrated

Table 13.3 Inputs considered for the glazing in the second test

Properties	Normal glass with optimized blinds	BIPV 1	BIPV 2	BIPV 3
U-value (W/m^{2}K)	2.56	1.2	1.2	1.2
SHGC (%)	70	30	20	10
VT (%)	80	50	30	10
PV efficiency (%)	–	2.8	3.4	4
PV temperature coefficient (%/°C)	–	−0.13	−0.13	−0.13

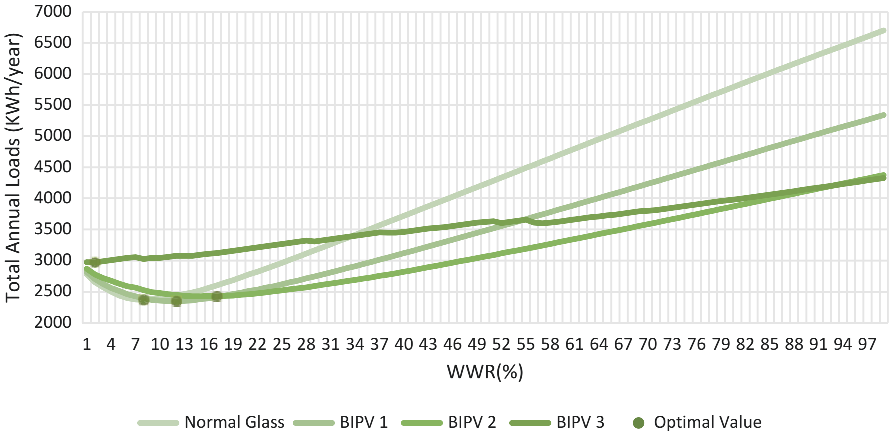


Fig. 13.5 Energy consumption based on window-to-wall ratio (WWR) for different glazing materials. (Location: Cairo, Egypt; Orientation: South)

in Table 13.3 as inputs along with the others. Other inputs remained the same as the previous test for the BIPV wall.

The results in Fig. 13.5 show how the optimal value of WWR changes for each material, from 8%, which belongs to the previous test results with only the wall as a source of energy production, to 12% for the first BIPV alternative, 17% for the second BIPV, and 2% for the third. The results illustrate how a wrong choice for the glazing material could result in a higher energy load. For instance, by choosing BIPV 3 instead of the normal window at a WWR of 8%, 655.64 kWh would be added to the annual energy consumption of the office which would be a 28% increase.

The graph also shows how each material has its own best WWR range which would be beneficial while it would be a wrong pick for other situations. For example, choosing the same BIPV 3 instead of normal glass in a WWR of 93% where BIPV 3 would be the best choice, energy consumption of the office drops from 6407.36 kWh per year to 4210.96 kWh, which would be a decrease of 34%. Figure 13.6 shows the most beneficial glazing material for different window-to-wall ratios.

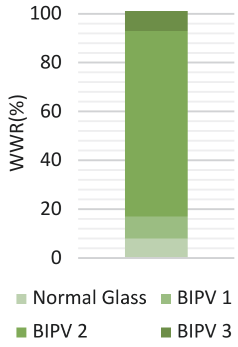


Fig. 13.6 Best glazing material based on energy consumption for different WWRs. (Location: Cairo, Egypt; Orientation: South)

For the first 8%, normal glass with blinds would be the best solution, from 9% to 17% BIPV1, from 18% to 92% BIPV2, and from 93% to a whole glass façade; BIPV3 had the best results in comparison to other materials provided as inputs in this test.

It can be seen in Figs. 13.5 and 13.6 that highest range of WWR for being the best material belongs to the second alternative of BIPVs, while the optimized value belongs to the first (at 12% with a total energy load of 2345 kWh).

It is worth mentioning that the energy-wise optimal value would not always be the proper solution. By having access to this valuable data, decision makers could decide what would be the optimal value according to their own requirements. For instance, the optimal value of WWR for normal glass is 8% with a total energy load of 2368.5 kWh. Generally, the preference would be bigger windows and more natural light inside. The decision maker could expand the WWR without sacrificing net energy consumption. By choosing the BIPV1 for instance, the WWR could rise to 14% with a total energy load of 2361 kWh which is even less than the consumption of normal glass at 8%, while the amount of lighting energy would have a decrease of 26% due to having a higher amount of daylight (Table 13.4).

13.3.3 Orientation

For the third test, the same previously used materials for the wall and glazing were put to the test with different orientations of the façade. The given inputs to the tool were the same as the former simulation; only the other three orientations were added to the orientation input.

Figure 13.7 shows how the proper material for each WWR varies in different orientations which is due to the change of the amount of direct solar radiation on the façade, which reduces the effectiveness of photovoltaics on WWR optimal value and the amount of heat gain from the transparent part of the façade which would make higher WWRs and more transparent materials suitable to a greater extent as

Table 13.4 Comparison of two different alternatives for glazing

Material	Cooling consumption	Heating consumption	Lighting consumption	PV production	Total
Normal glass with blinds WWR = 8%	4573.24	712.87	362.64	3098.54	2368.53
BIPV 1 WWR = 14%	4578.31	694.61	267.23	2997.13	2361.34

Location: Cairo, Egypt; Orientation: South

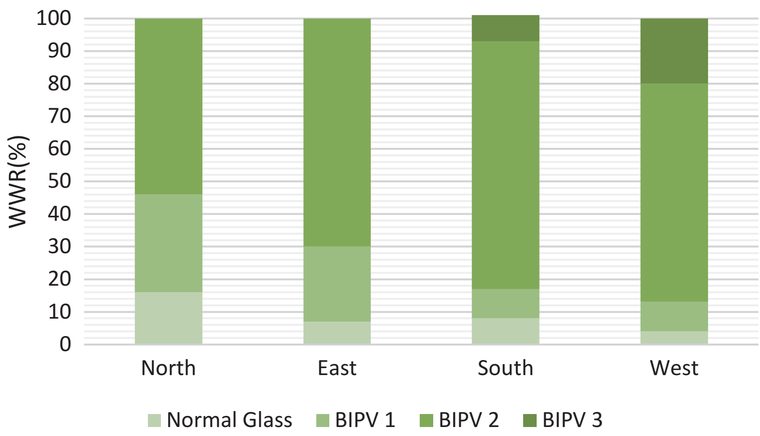


Fig. 13.7 Best glazing material based on energy consumption for different WWRs. (Location: Cairo, Egypt)

they would lead to a lower energy need for artificial lighting. Figure 13.8 clarifies the fluctuation of different sections of energy in different orientations while it also illustrates how the energy consumption of the same office cell could change up to 44% which would be 1913 kWh per year only by a change in the cardinal direction in which it is oriented.

13.3.4 Geographical Location

For the last test, the same simulations were done for all the selected location inputs. The cities of Palermo and Marseille were also added to Cairo to study the location input's impact on the façade solution. BIPV 1 was selected as it had the highest capability of reducing the energy loads in the previous tests.

Figure 13.9 visualizes how the ideal amount of WWR varies by the change of geographical location. Marseille has the highest recommended sizes for windows, and from Fig. 13.10, it could be seen that it also has the uppermost energy consumption among the selected cities due to its heating-dominated climate. Cairo

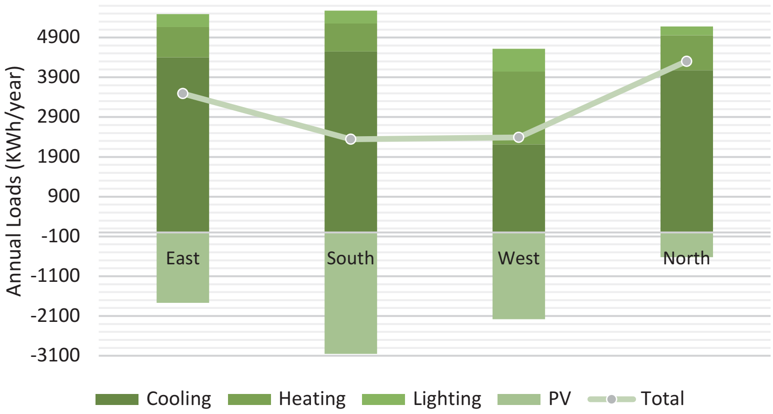


Fig. 13.8 Different sections of the total load at the optimized solutions for each orientation (East = 19% − South = 12% − West = 12% − North = 30%) in Cairo, Egypt

Fig. 13.9 The optimal WWRs

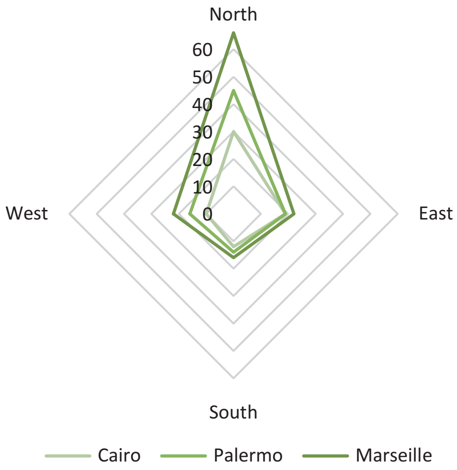
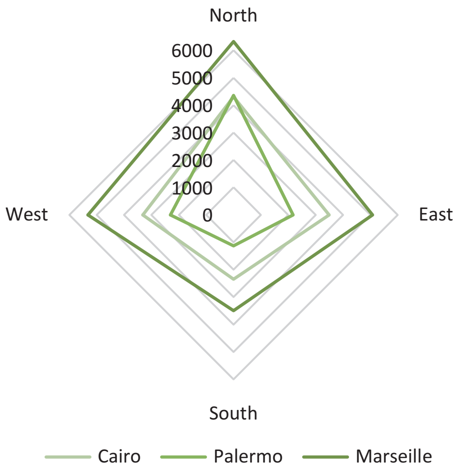


Fig. 13.10 The total energy loads at the optimal WWRs



on the other hand is the most cooling-dominated climate which resulted in lower WWRs as optimum. The changes were small in east and south orientations, and the best result would be derived from almost the same WWRs as in Palermo. In general, west and north orientations had the most contrast between the three locations, while east and south had the least.

13.4 Conclusion

The test results demonstrated how a change in each of the material properties, like the efficiency of the photovoltaics, visible transmittance (VT), and solar heat gain coefficient (SHGC) of windows, window-to-wall ratio, the orientation of the façade, and the location of the building could result in a completely different ideal solution. They clarified that not only BIPV glazing materials would not be beneficial at all times, but also they could considerably increase the total energy consumption in some cases. This underlines the decision makers' need for a precise set of data from computational simulations to allow them to choose the best active and passive design options and avoid making energy-wise costly mistakes. It also helps them to make their decisions based on their own predefined requirements; if they need to meet some *regulations* for *daylighting or a demand for having larger windows to comply with visual needs of the occupants, the proper solution would be different. It is also worth mentioning that* the illustrated results are based on the specifications of today's existing building materials on the market. With the developments on material properties every day like the efficiency of BIPV or U-value of glazing or walls, the ideal solution would be different through the time due to these ever-changing values. By taking into consideration the valuable data from computational simulations, designers could catch up with these developments and have the highest performance designs possible with the latest materials.

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