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Multi-Objective Performance Analysis of Façade-Integrated Photovoltaic Shading Devices under the İzmir Climate

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Abstract. Photovoltaic shading devices are important design features that can achieve both solar control and energy generation on building facades. These devices should be evaluated not only in terms of energy generation but also considering the building's total energy consumption and lighting demand. Especially in the early design phase, comparing different photovoltaic shading configurations with multiple performance targets contributes to a more balanced and performance-oriented facade design. This study aims to evaluate the energy generation, total energy consumption, and lighting performance of facade-integrated photovoltaic shading devices in the climate of Izmir. The study considered three window-to-façade width ratios, 19 PV tilt angles, and eight building orientations, resulting in a total of 456 scenarios generated through parametric façade modelling. The scenarios were analyzed using the EnergyPlus simulation tool, and annual performance outputs were evaluated comparatively. The multi-objective performance assessment was conducted using Pareto-dominance analysis to identify non-dominated alternatives among the 456 simulated scenarios. Annual PV electricity generation was defined as the objective to be maximized, whereas annual total electricity consumption was defined as the objective to be minimized. Parallel coordinate plots were subsequently used to examine the relationships among performance indicators and to interpret the Pareto-optimal solutions in terms of building orientation, window-to-façade width ratio, and PV tilt angle. The findings indicate that, under İzmir's climatic conditions, no single photovoltaic shading configuration performs best across all objectives. However, specific combinations of building orientation, window-to-façade width ratio, and PV tilt angle provide a more balanced energy performance. The Pareto-optimal alternatives reveal a clear trade-off between annual PV electricity generation and total electricity consumption. These results demonstrate that photovoltaic shading devices should be evaluated not only in terms of maximizing electricity generation, but also in relation to their effects on overall building electricity consumption. Overall, the study demonstrates that Pareto-based approaches provide a useful conceptual framework for identifying balanced façade scenarios when evaluating façade-integrated photovoltaic shading devices through multi-objective performance analysis during the early design phase.

Keywords: PV shading device; multi objective performance; building energy simulation; façade design; parametric modeling

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INTRODUCTION

Reducing energy consumption in buildings and using renewable energy sources are among the key objectives in developing low-carbon building and near-zero energy building (NSEB) approaches [1, 2]. The building envelope plays a significant role in achieving these key objectives by regulating thermal transfer between the interior and

exterior environments as well as generating energy. In this context, roof [3, 4] and facade [5, 6] applications of photovoltaic (PV) systems, which have a high energy generation potential, are becoming widespread. Facade applications of PV systems enable the increase of energy generation surfaces in buildings with limited roof surfaces and the integration of renewable energy technologies into architectural design.

PV shading elements applied to the facade can both control the amount of daylight entering the interior and simultaneously generate energy [7]. These systems also affect the building's heating, cooling, and lighting energy loads by controlling the daylight reaching the window surface. The energy performance of these systems, which affect the building's energy loads, varies depending on parameters such as the PV cell technology used, panel tilt, orientation, and the width of the applied window, as well as the active PV surface area [8, 9].

Studies in the literature address the effects of PV systems on energy generation, shading performance, or building energy consumption through different parameters [10-12]. However, studies that evaluate the holistic effects of different parameters within a broad parametric design space, clearly reveal the balance between building energy consumption and PV generation, and suggest the most balanced configurations accordingly are more limited in the literature. Evaluation based on a single performance indicator can prevent the evaluation of alternatives that perform better among different objectives. In this regard, the Pareto-based multi-objective evaluation method [12] provides an effective approach for identifying non-dominant design options by revealing the effect of an improvement in one performance on another performance objective, thus enabling the evaluation of alternatives.

This study aims to comprehensively evaluate the energy performance of PV shading elements applied to building facades in Izmir, a city with a hot Mediterranean climate, based on parameters such as window-to-facade width ratio, orientation, and PV tilt angle. Accordingly, a total of 456 design scenarios were examined, considering three window-to-facade width ratios, 19 PV tilts, and eight orientations. Pareto-optimal solutions were determined to minimize total energy consumption and maximize PV energy generation, and design configurations corresponding to minimum energy consumption, balanced performance, and maximum PV generation were presented.

METHODOLOGY

This study analyses the impact of PV shading elements applied to building facades on building energy performance in the İzmir climate through four stages. In the first stage, parametric model scenarios were defined based on design parameters such as window width ratio, PV tilt angle, and different building orientations. In the second stage, the energy performance of these scenarios was calculated through simulations. In the third stage, the effects of the defined design parameters on energy consumption and energy generation were compared. Finally, the objectives of minimizing total energy consumption and maximizing energy generation were considered together, and optimal designs were determined using Pareto charts. The study methodology is presented in Figure 1.

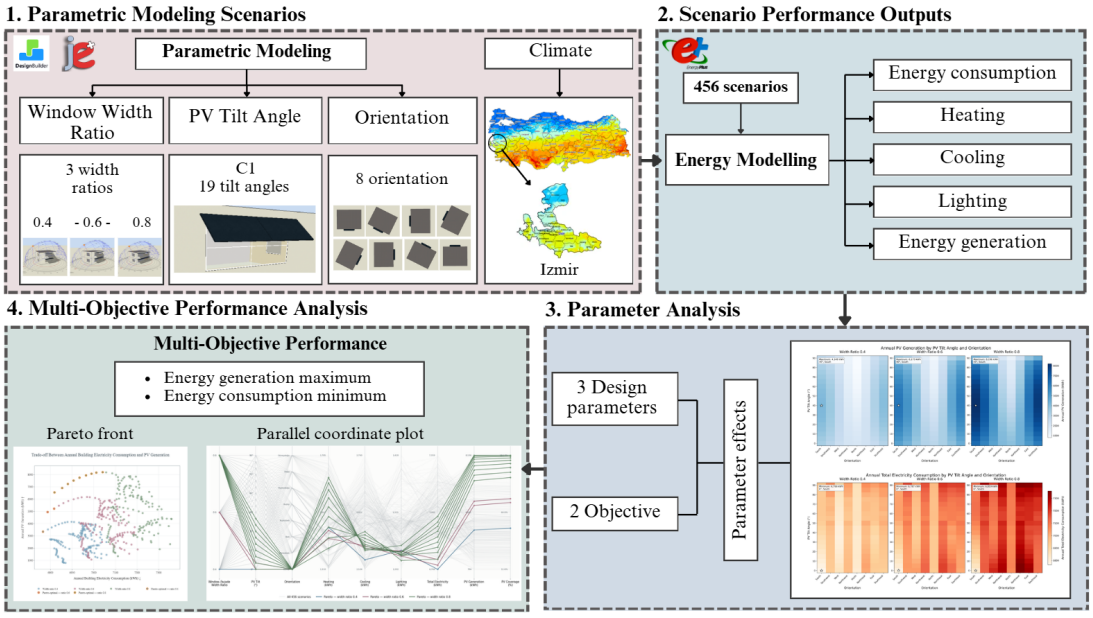


FIGURE 1. Methodological workflow of the parametric simulation and multi-objective performance analysis

Case Study Building Description

Within the scope of the study, a two-story residential building was designed in Izmir, located in the Mediterranean Region. The building has a base area of 80 m² and a total area of 160 m². The building facade width is 10 m x 8 m, and the floor height is 3 m. The energy modeling of the residential building was carried out using DesignBuilder Version 6.0 simulation [13], and the EnergyPlus 8.9 simulation tool [14] was used for energy calculations of all scenarios. The 2009-2023 Typical Meteorological Year (TMY) weather data file for Izmir was used for climate data.

The building envelope materials defined for the residential building were kept the same in all scenarios. The building envelope components (exterior wall, floor slab, roof, window) meet the U value required by Turkey's thermal insulation standard TS 825 for the 2nd degree day zone where Izmir is located [15]. An electric heat pump was defined for the building's heating and cooling needs via HVAC system settings. Domestic hot water and mechanical ventilation were not included in the energy calculations. Building envelope applications, internal loads (lighting, equipment, users) and HVAC system were kept constant in all scenarios, and only the effects of the facade design parameters of the scenarios were evaluated. All the energy needs of the building are met by electrical energy. Basic data for the building envelope are presented in Table 1.

TABLE 1. The basic building data for all scenarios.

	Parameter	Description
Building	Type of use	Residential
	Floors / area	2 floor / 160 m^2
	Floor height / façade width	3.0 m / 10 m
Climate	Climate data	İzmir 2009-2023 TMY EPW
Thermal control	Heating	22°C; setback: 20°C
	Cooling	24°C; setback: 26°C
HVAC	System	Packaged Terminal Heat Pump (PTHP)
	Operation time	24 h/day, 7 days/week
External wall	Basic layers	Cement plaster + 70 mm rock wool insulation + 200 mm aerated concrete block + gypsum plaster
	U Value	0.248 W/m²K
Roof	Basic layers	Asphalt layer + 110 mm rock wool insulation + 150 mm reinforced concrete slab
	U Value	0.290 W/m²K
Ground floor	Basic layers	Screed + 150 mm concrete slab + 80 mm XPS insulation + 100 mm dense concrete
	U Value	0.339 W/m²K
Window	Basic layers	Low-E double glazing with a 16 mm air gap
	U Value	1.746 W/m²K

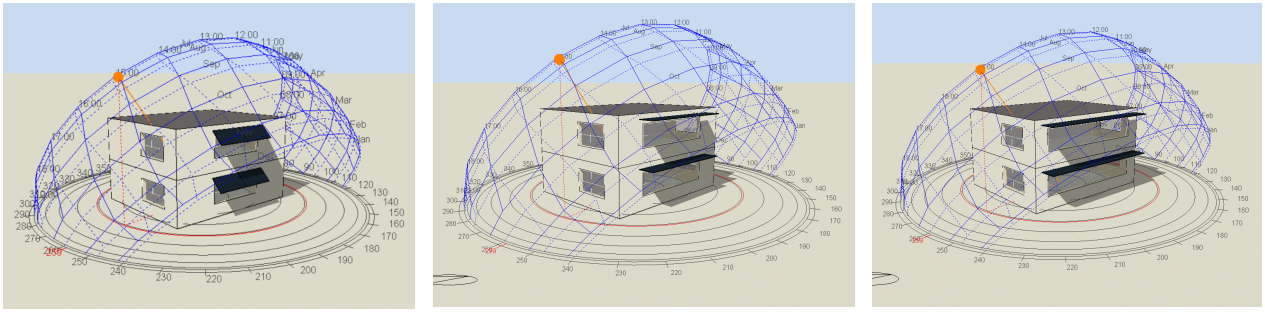
Parametric Scenarios and Performance Outputs

A sloping facade concept has been implemented as a PV shading system in the residential building. The PV systems are positioned as shading elements 30 cm above the window openings. The panel dimensions of the PV systems are 2.278 m x 1.134 m, and they consist of monocrystalline silicon cells. The module power of the PV systems used is 580 W. The efficiency of the PV modules is 22.5%.

In the parametric model, three different ratios of 0.4, 0.6, and 0.8 were selected for the impact evaluation of the window-to-facade width ratio parameter. These ratios correspond to window widths of 4, 6, and 8 m, respectively. In relation to these window width ratios, two, three, and four PV panels were integrated proportionally above the windows on a single facade with a width of 10 m. The total widths of the PV modules according to the facade openings are 4.556, 6.834, and 9.112 m, and in all three configurations, the PV shading elements proportionally match the window openings (Figure 2).

For the PV tilt angle parameter, 19 different alternatives were created, varying in 5° increments between 0° and 90°. For the building orientation parameter, eight directions were determined: south, southwest, west, northwest,

north, northeast, east, and southeast. Accordingly, a total of 456 scenarios were created based on three window facade width ratios, 19 PV tilt angles, and eight orientations. All scenarios were parametrically implemented by transferring the basic model data generated from the DesignBuilder simulation to the jEPlus program and performing calculations in the background using the EnergyPlus tool (Table 2).



(a) (b) (c)

FIGURE 2. Window to width ratio of a residential building (a) 0.4 ratio, (b) 0.6 ratio, (c) 0.8 ratio

The main outputs of the created scenarios, including heating, cooling, lighting, total annual electricity consumption, and energy generation, were calculated using the EnergyPlus simulation tool. In addition to the calculated main outputs, the PV energy coverage ratio was evaluated based on the ratio of energy generation to total annual energy consumption.

Simulation results were compared in terms of window-to-facade width ratio, PV tilt angle, and orientation parameter variables. Graphs such as heat maps and parallel coordinate plots were used to evaluate parameter effects. The aim of the multi-objective evaluation was to minimize building energy consumption and maximize energy generation. If the design scenario is not suppressed by another scenario that simultaneously provides lower energy consumption and higher energy generation, that scenario is considered the Pareto-optimal solution. Balanced solutions in the Pareto front set were determined as the scenario with the lowest Euclidean distance from the ideal point in terms of two normalized objective functions.

TABLE 2. Parametric model definition of PV configurations for tree window to facade width ratios

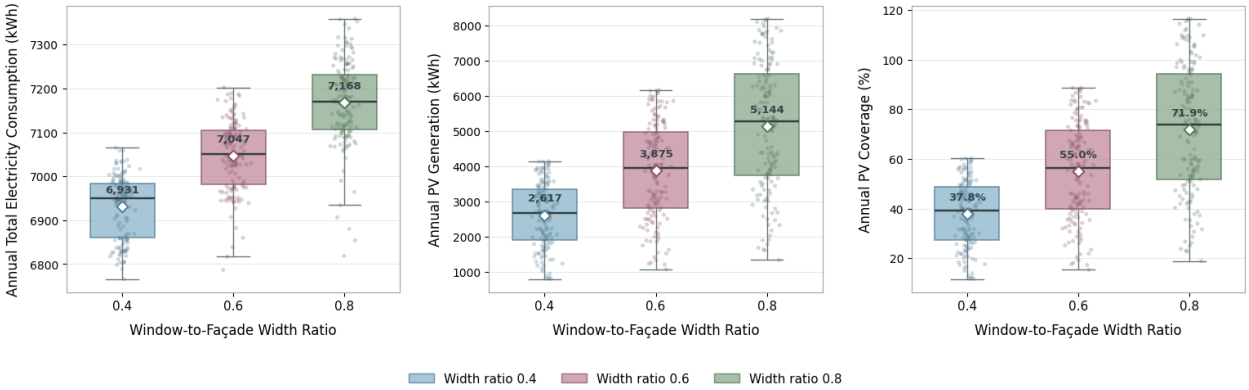
Window width ratio	PV modules	Total PV area	PV tilt angles	Orientations	Total scenarios
0.4	4	10.333 m²	0°–90°, 5° intervals	8	152
0.6	6	15.498 m²	0°–90°, 5° intervals	8	152
0.8	8	20.666 m²	0°–90°, 5° intervals	8	152
Total	-	-	19 tilt angles	8	456

RESULTS AND DISCUSSION

The results of the 456 parametric scenarios simulated in the study show that total annual electricity consumption varies between 6,765.5–7,359 kWh, annual PV energy generation between 793.8–8,196.5 kWh, and annual PV coverage between 11.6% and 116.4%. These wide performance ranges indicate that window-to-facade width ratio, PV tilt angle, and orientation play a significant role, particularly in PV energy generation. They also show that the impact on building electricity consumption is more limited, but creates differing effects among consumption components. The lowest total electricity consumption was achieved with a width ratio of 0.4, a PV tilt of 0°, and a south orientation, while the highest PV energy generation occurred with a width ratio of 0.8, a PV tilt of 40°, and a south orientation. The results reveal that the scenario minimizing energy consumption is not the same as the scenario maximizing PV generation, and that the design decision depends on balancing the two performance objectives.

Figure 3 shows the effects of window-to-facade width ratios on total electricity consumption, PV energy generation, and annual PV coverage rate. The average total electricity consumption was calculated as 6,930.8 kWh at a ratio of 0.4, 7,047.4 kWh at a ratio of 0.6, and 7,168.4 kWh at a ratio of 0.8. For the same ratios, the average PV

energy generation was determined as 2,616.9, 3,874.9, and 5,143.6 kWh, respectively; and the PV coverage rate was determined as 37.8%, 55.0%, and 71.9%.



(a) (b) (c)

FIGURE 3. Performance comparison across window to façade width ratios (a) total electricity consumption, (b) PV generation, (c) PV coverage

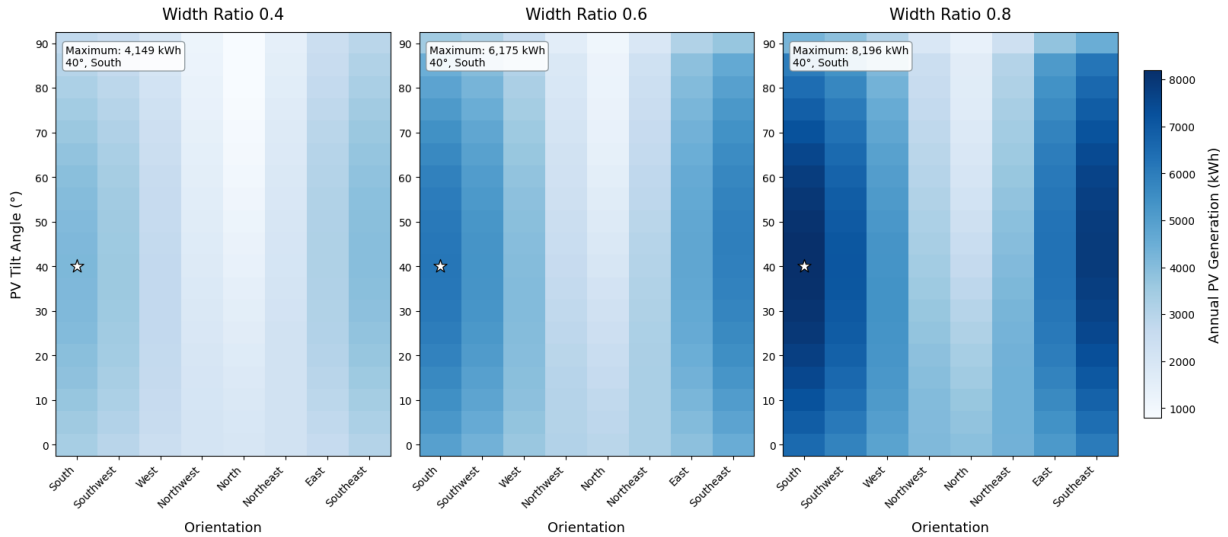
Increasing the window-to-facade width ratio from 0.4 to 0.8 resulted in only a 3.43% increase in average total electricity consumption, while increasing PV generation by 96.55%. Analysis of energy consumption components revealed that this increase in the window-to-facade width ratio led to a 6.13% increase in heating consumption and a 7.15% increase in cooling consumption, while lighting consumption decreased by 1.77% due to daylight-dependent lighting control. Therefore, although wider window and PV configurations increased heating and cooling loads, they significantly increased energy generation capacity thanks to the larger PV surface area. Furthermore, it was observed that the increase in average PV energy generation was due not only to the window ratio but also to the increase in total PV area from 10.33 m² to 20.67 m². Based on the three window widths, energy generation per area was calculated to be approximately 253.3 kWh/m² for a ratio of 0.4, approximately 250.0 kWh/m² for a ratio of 0.6, and approximately 248.9 kWh/m² for a ratio of 0.8. Accordingly, the fact that the average energy generation per PV area is close to each other across the three ratios indicates that the overall increase in energy generation is largely related to the increase in the installed PV surface area.

Effect of PV Tilt Angle and Orientation

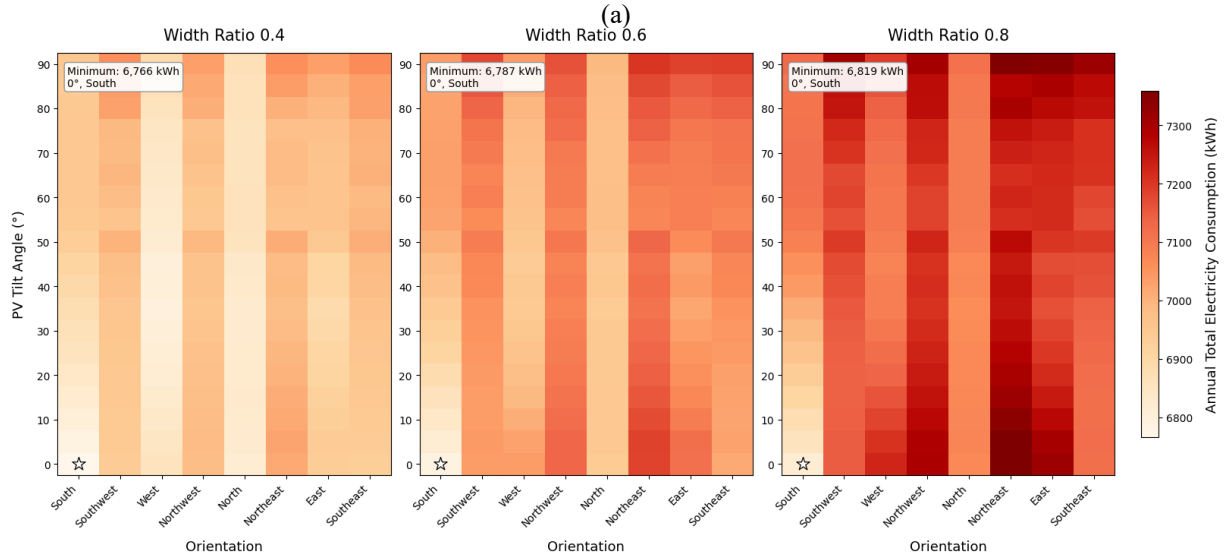
The combined effects of PV tilt angle and orientation on energy generation and total energy consumption are presented in Figure 4 via heat maps. Maximum PV generation was achieved in the south direction and at a 40° PV tilt for all three window-facade width ratios. Maximum annual energy generation values were calculated as 4,149.0, 6,174.5, and 8,196.5 kWh for ratios of 0.4, 0.6, and 0.8, respectively. Comparing the orientation averages, the south direction yielded the highest average energy generation with 5,513.0 kWh, while the north direction yielded the lowest with 1,937.7 kWh. Furthermore, the average energy generation of 5,329.5 kWh obtained in the southeast direction showed an energy performance close to that of the south direction. These results highlight the decisive effect of orientation on PV generation potential.

In terms of total electricity consumption, the absolute minimum for all three orientation ratios occurred in the south direction and at a 0° PV tilt. The minimum values were calculated as 6,765.5, 6,786.9, and 6,818.7 kWh for ratios of 0.4, 0.6, and 0.8, respectively. However, the fact that the average total energy consumption values vary over a more limited range than PV generation indicates that the main effect of orientation is on electricity generation. Since heating, cooling, and lighting loads vary in different directions depending on orientation, the total energy consumption is the result of the balance between these components.

When all orientations are considered together, the average PV output peaks around 30°, while the absolute maximum energy output is achieved at a 40° tilt towards the south. This difference indicates that the optimum PV tilt is not a fixed value independent of orientation, but rather a significant interaction between orientation and PV tilt parameters.



(a)



(b)

FIGURE 4. Effects of PV tilt angle and building orientation on (a) annual PV electricity generation and (b) annual total electricity consumption for different window-to-façade width ratios

Determining Pareto Optimal Solutions and Performance Assessment

In this study, by evaluating the objectives of minimizing total electricity consumption and maximizing PV energy generation across all scenarios, 12 scenarios were determined to be Pareto-optimal out of 456 scenarios. The Pareto chart in Figure 5 presents the distribution of all scenarios in terms of annual total electricity consumption and annual PV energy generation. In the graph, all scenarios are grouped and color-coded according to the window-to-facade width ratio. Accordingly, scenarios with a ratio of 0.4 are represented in blue, those with a ratio of 0.6 in pink, and those with a ratio of 0.8 in green. Pareto-optimal solutions are highlighted in orange. The graph shows that as the window-to-facade width ratio increases, the scenarios generally shift to a higher PV energy generation region, but this also results in a certain increase in total electricity consumption. This reveals a clear design trade-off between building energy consumption and PV energy generation.

Three representative solutions are also marked within the Pareto cluster: minimum energy consumption, trade-off solution, and maximum PV energy generation. Minimum energy consumption was obtained in the scenario with a window-to-facade width ratio of 0.4, a PV tilt of 0°, and a south orientation. In the minimum energy consumption solution, the total annual electricity consumption was calculated as 6,765.5 kWh, the annual PV generation as

3,345.3 kWh, and the PV coverage rate as 49.4%. In the trade-off solution, the scenario closest to the ideal point was determined according to two normalized objective functions. In this solution, the total energy consumption is 6,818.7 kWh, the PV energy generation is 6,547.4 kWh, and the PV coverage rate is 96.0%. Maximum PV generation was obtained in the scenario with a ratio of 0.8, a PV tilt of 40°, and a south orientation. In the maximum PV energy generation solution, total electricity consumption was calculated as 7,041.2 kWh, PV generation as 8,196.5 kWh, and the PV coverage rate as 116.4%. Compared to the minimum energy consumption solution, in the balanced solution, total energy consumption increased by only approximately 0.8%, while PV generation increased by approximately 95.7%. Compared to the balanced solution, in the maximum PV energy generation solution, total energy consumption increased by approximately 3.3%, while PV energy generation increased by approximately 25.2%.

The values for the multivariate performance characteristics of Pareto-optimal solutions are presented in the parallel coordinate graph in Figure 6. In this graph, the gray lines represent the non-Pareto optimal scenarios of the 456 scenarios, while the coloured lines represent the Pareto-optimal solutions. The graph clearly shows the common parameter values of the Pareto solutions. In the context of building orientation, all Pareto-optimal solutions are clustered towards the south. For the PV tilt angle variable, Pareto solutions are concentrated in PV tilts between 0° and 40°. While a solution with a window-to-facade width ratio of 0.4 is included within the context of low energy consumption, solutions providing higher PV energy generation and PV coverage ratio are predominantly clustered at a window-to-facade width ratio of 0.8. This distribution shows that the south orientation is dominant in terms of multi-objective performance, and that larger window-to-facade width ratios particularly strengthen the PV energy generation potential.

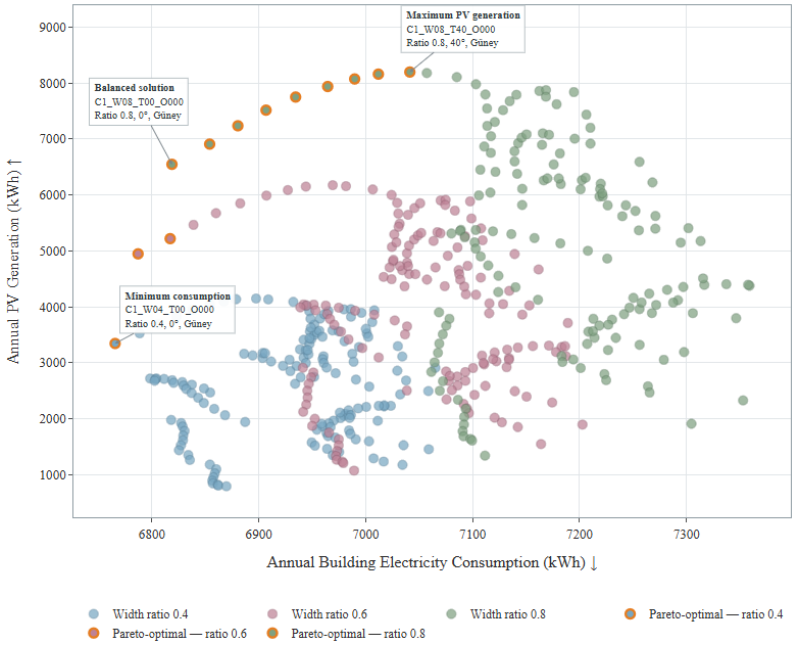


FIGURE 5. Trade-off between annual total electricity consumption and annual PV energy generation, highlighting Pareto-optimal and representative solutions

The generated parallel coordinate graph also shows how the energy components differ along the Pareto solutions. As we move from a low energy consumption solution to a high PV energy generation solution, there is an increase in heating consumption, while cooling consumption shows a limited decrease. Lighting consumption, however, varies within a relatively narrower range. For example, a 0.8 increase in PV tilt from 0° to 40° increases PV energy generation from 6,547.4 kWh to 8,196.5 kWh, while total electricity consumption increases from 6,818.7 kWh to 7,041.2 kWh. This reveals that the increase in PV energy generation does not occur in the same direction in the energy sub-components. In terms of energy consumption components, increasing the window-to-facade ratio from 0° to 40° with a PV tilt of 0.8 results in an increase of approximately 300 kWh in heating load, while reducing cooling load by 100 kWh and increasing lighting load by 40 kWh. This also demonstrates that Pareto solutions

should be evaluated not only in terms of total energy consumption and generation, but also in terms of heating, cooling, and lighting components.

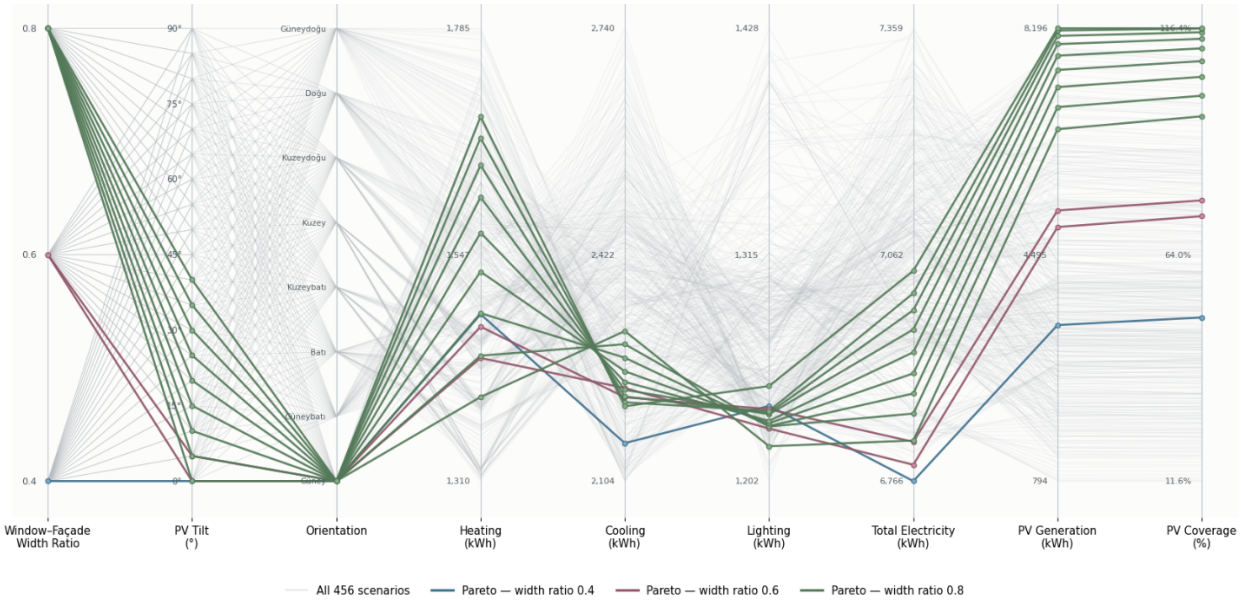


FIGURE 6. Parallel coordinates of all scenarios and pareto-optimal solutions

When all the findings are considered together, it is seen that the three design parameters examined have different effects on building energy consumption and PV energy generation. The window-to-facade width ratio determines the installed PV area and, consequently, the total energy generation capacity; while orientation and tilt angle control the distribution of solar radiation reaching the PV surface. Total building electricity consumption, on the other hand, varied within a more limited range compared to PV energy generation due to the partial balancing of heating, cooling, and lighting loads. Accordingly, it is not possible to say that a scenario advantageous in terms of energy generation directly constitutes the best solution in terms of energy consumption.

The findings indicate that when the design priority for preferred PV shading scenarios is solely to reduce electricity consumption, a window-to-facade width ratio of 0.4, a PV tilt of 0°, and a south orientation stand out. When the goal is to maximize PV energy generation, a window-to-facade width ratio of 0.8, a tilt of 40°, and a south orientation constitute the most suitable option. In contrast, the balanced solution consisting of a 0.8 ratio, a tilt of 0°, and a south orientation consumes only 0.8% more electricity than the minimum energy consumption scenario while increasing PV energy generation by 95.7%. In this context, this scenario configuration offers the strongest balance between building energy demand and renewable energy generation. Instead of proposing a single general optimum scenario configuration, the results reveal the most balanced solution regions for different design scenario priorities.

CONCLUSION

This study evaluates the energy performance of inclined PV shading elements applied to building facades under İzmir's climatic conditions, considering variables such as window-to-facade width ratio, PV tilt angle, and building orientation. 456 different design scenarios were created by combining three different window-to-facade width ratios, 19 PV tilt angles, and eight orientations. These scenarios were evaluated in terms of total annual electricity consumption, PV electricity generation, and annual PV coverage rate. Subsequently, Pareto-optimal design solutions were determined by considering both the objectives of minimizing total electricity consumption and maximizing PV generation in the design configurations.

The results showed that increasing the window-to-facade width ratio from 0.4 to 0.8 increased the average total electricity consumption by only about 3.4%, while the average PV generation increased by approximately 96.6%. Orientation and tilt angle had a particularly significant effect on PV energy generation. Maximum energy generation was achieved in the south direction and at a 40° PV tilt for all three width ratios. The lowest total electricity

consumption occurred again in the south direction, but at a 0° PV tilt. This reveals that the configuration that maximizes PV generation is not the same as the configuration that minimizes building energy consumption.

Pareto analysis revealed a total of 12 optimal solutions. All of these solutions were found to be located in the south direction, within the 0°-40° PV tilt range. To reduce total energy consumption, a window-to-facade width ratio of 0.4 and a 0° tilt were preferred; while to increase PV energy generation, a ratio of 0.8 and a 40° tilt were favored.

However, the balanced solution consisting of a 0.8 ratio, 0° tilt, and south orientation increased PV generation by approximately 95.7% while generating only about a 0.8% increase in total electricity consumption compared to the minimum consumption scenario. Therefore, this configuration was considered to offer the strongest balance between annual building electricity demand and renewable electricity generation.

The findings indicate that facade-mounted PV shading elements should not be designed based on a single performance criterion, and that the appropriate design configuration depends on the installer's priority of reducing energy needs or increasing energy generation. The study is limited to a single residential typology, PV shading concept, and the climate of Izmir. Furthermore, PV energy generation and building energy consumption were compared based on total annual values. Accordingly, hourly energy calculations, storage, economic impact, carbon emissions, and user comfort were not included in the evaluation. It is recommended that future studies be expanded to include different climates, building types, and PV geometries, and that hourly energy consumption, life cycle cost, and environmental performance metrics be added to the multi-objective evaluation.

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