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Analysis of the Contribution of Vertical Façade Photovoltaic Applications to Rooftop PV Generation in Istanbul Using PVGIS-Based Simulation

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Abstract

In Istanbul, where urban development is characterized by high-density vertical growth, a significant portion of the existing building stock is not well suited for rooftop solar photovoltaic (PV) installations due to limited roof area, architectural constraints, and structural limitations. In contrast, building façades represent a largely untapped resource for urban renewable energy generation, especially as the cost of PV technologies has declined substantially in recent years. This study aims to quantitatively assess the potential contribution of vertical façade-integrated PV systems to overall on-site energy production in the context of Istanbul, where tall and aging buildings dominate the urban landscape and usable rooftop surfaces are scarce. Using PVGIS-SARAH3 irradiance data, a three-year simulation (2021–2023) was conducted for the coordinates of Yıldız Technical University's Davutpaşa Campus. Two configurations were analyzed: (i) a 1 kW rooftop PV system oriented horizontally at 0° tilt, and (ii) a 1 kW vertical PV system mounted at 90° tilt facing the South–Southwest direction (azimuth: 45°). A system loss factor of 14% was applied to both configurations, and hourly irradiance-derived power values were used to calculate daily, monthly, and annual energy production. The results show that vertical PV systems can achieve remarkably high annual performance under Istanbul's climatic conditions, reaching 70.8% of the total annual production of the horizontal system. Over the three-year period, the Horizontal Rooftop PV (0°) installation produced 3572.2 kWh, while the vertical façade system produced 2530.4 kWh. Notably, during winter months when solar altitude is lower, the vertical system occasionally outperformed the Horizontal Rooftop PV (0°) configuration. These findings indicate that vertical PV installations can play a significant complementary role to rooftop PV, particularly during autumn and winter, thereby contributing to a more balanced annual production profile. Given Istanbul's limited roof availability and high-rise urban fabric, these results provide strong technical motivation for incorporating façade-integrated PV into building energy strategies. In real applications, the ratio of rooftop to façade PV capacity will vary from building to building; thus, system design and investment decisions should be optimized according to architectural, orientational, and operational conditions. Future research may include long-term experimental measurements at similar coordinates to validate simulation outcomes and extended simulations involving multi-aspect façade orientations. Such investigations would enable the development of a practical dataset for comparing real-world deviations from modeled performance.

Keywords: BIPV; Vertical PV; Façade Photovoltaics; PVGIS; Micro-grid.

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1. INTRODUCTION

Achieving urban decarbonization targets requires expanding renewable electricity generation within cities while minimizing additional stress on transmission and distribution networks. Photovoltaic (PV) systems are a mature and scalable technology; however, in dense metropolitan areas, rooftop-only PV deployment faces practical limitations such as insufficient roof area, unfavorable geometry, shading from neighboring buildings, and structural constraints of existing building stock [1]. These challenges are particularly pronounced in vertically growing cities with a large proportion of older buildings. For the net zero scenario, increasing urban PV contribution is inevitable and necessary [9].

Building-integrated photovoltaics (BIPV) have been proposed to overcome surface limitations by embedding PV modules directly into building envelopes, including façades [2]. Several studies emphasize that façade-integrated PV systems can unlock substantial additional surface area for solar energy harvesting without requiring new land use [1], [3]. In addition to electricity generation, façade PV may contribute to architectural integration, thermal performance, and shading benefits, thereby influencing overall building energy performance [4].

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In the Turkish context, national assessments such as the Solar Energy Potential Atlas (GEPA) indicate that cities like Istanbul possess significant solar resources [8]. Nevertheless, translating this potential into urban-scale PV deployment remains challenging when rooftop suitability is limited. Consequently, evaluating Vertical Façade PV (90°/45°) as a complementary solution—rather than a substitute—for rooftop PV is essential for realistic urban energy planning.

This paper presents a location-specific, data-driven comparison of Horizontal Rooftop PV (0°) and Vertical Façade PV (90°/45°) systems using PVGIS hourly time-series data for the Yıldız Technical University (YTU) campus in Istanbul over the period 2021–2023. The study aims to quantify the annual and seasonal contribution of façade PV and discuss its implications for micro-/nano-grid concepts and future urban energy systems.

While the effects of PV orientation and tilt angle are well-documented in the literature, this study provides a specific, data-driven contribution tailored to the high-density and vertically growing urban fabric of Istanbul. By utilizing the latest PVGIS-SARAH3 database for a continuous three-year period (2021–2023), this research quantitatively demonstrates the seasonal complementarity of Vertical Façade PV (90°/45°) systems, particularly highlighting their enhanced performance during winter months. This approach addresses a critical gap in urban energy planning for aging metropolitan areas where rooftop availability is severely constrained, offering a realistic assessment of multi-surface solar harvesting.

2. RELATED WORK

Extensive research has investigated BIPV as an integrated component of building envelopes. Hamidi and Asfour provide a comprehensive review of design strategies for BIPV in high-rise buildings, highlighting the importance of early-stage architectural integration and the influence of orientation, module type, and façade geometry on energy yield [2]. Their findings underline that façade surfaces represent a critical opportunity for increasing PV capacity in dense urban environments.

From an energy optimization perspective, prior research on building-integrated PV systems emphasizes that irradiation potential varies significantly across building surfaces, making multi-surface assessment essential for effective system design [3]. This reinforces the need to evaluate façade PV independently rather than extrapolating rooftop performance assumptions.

Beyond pure energy generation, façade-integrated PV can act as an active building element. Göksu and Zorer Gedik analyze the use of CIS-based BIPV as a shading device and demonstrate that such systems can reduce building life-cycle energy consumption by combining electricity generation with solar shading effects [4]. These results suggest that façade PV may provide compounded benefits at the building scale.

At the system level, distributed generation is increasingly associated with microgrid and nano-grid concepts aimed at enhancing local energy resilience and sustainability. Reviews on microgrids highlight their role in integrating distributed renewable sources and reducing dependency on centralized infrastructure [6]. In this context, increasing the fraction of locally generated energy through façade PV aligns with broader energy transition strategies [10].

Furthermore, long-term visions of urban energy systems increasingly consider storage and flexible demand, including vehicle-to-grid (V2G) concepts. Kempton and Tomić establish the fundamentals of V2G, illustrating how distributed storage can support local energy balancing and grid services [6]. Although storage and V2G are not modeled in the present study, façade PV may enhance their effectiveness by extending generation across different times of the day [5],[6],[10].

3. METHODOLOGY

3.1 Study Area and Data Source

The case study focuses on the Yıldız Technical University (YTU) Electrical and Electronics Faculty area in Istanbul (approximately 41.029°N, 28.891°E). Hourly PV production data for the period 2021–2023 were obtained from the Photovoltaic Geographical Information System (PVGIS) developed by the European Commission Joint Research Centre [7]. PVGIS is widely used for estimating PV system performance and has been employed in numerous recent academic studies [3].

3.2 PV System Scenarios

Two PV installation scenarios were defined:

- Scenario H (Horizontal Rooftop PV (0°)):

Tilt (slope) = 0°, azimuth = 0°. For a horizontal surface, azimuth does not affect irradiation and is specified only to satisfy PVGIS input requirements.

- Scenario V (Vertical Façade PV (90°/45°)):

Tilt (slope) = 90°, azimuth = 45° (PVGIS coordinate system convention), representing a south–southwest-facing façade, selected to capture afternoon and evening solar exposure.

Both scenarios assume:

- Nominal capacity: 1 kWp
- PV technology: crystalline silicon
- System losses: 14%

For the simulations, the PVGIS-SARAH3 solar radiation database was utilized to ensure the highest accuracy for the 2021–2023 period. Both scenarios assume building-integrated or tightly mounted configurations, which inherently influences the thermal dissipation parameters in the model. A standard ground albedo coefficient was maintained for urban settings, and system losses were uniformly set to 14% to account for inverter efficiency, temperature effects, angular reflectance, and DC/AC cable losses.

Normalizing both configurations to equal installed capacity allows direct comparison of orientation effects independent of absolute system size.

3.3 Data Processing

Hourly PVGIS outputs were processed using MATLAB to compute:

- Daily energy production (kWh/day),
- Monthly totals (kWh/month),
- Annual totals (kWh/year),
- And cumulative production for 2021–2023.

The ratio of vertical-to-horizontal energy production (V/H) was calculated on monthly and multi-year bases to assess seasonal complementarity.

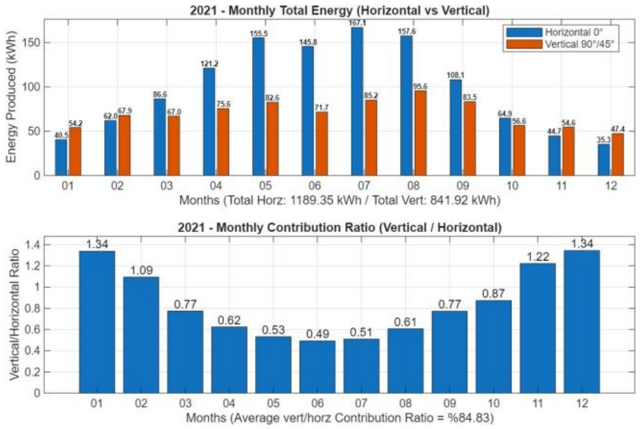

Figure 1. 2021 - Monthly simulation results.

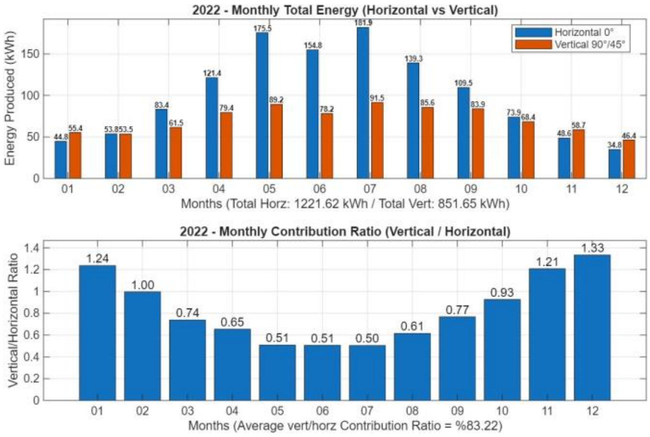

Figure 2. 2022 - Monthly simulation results.

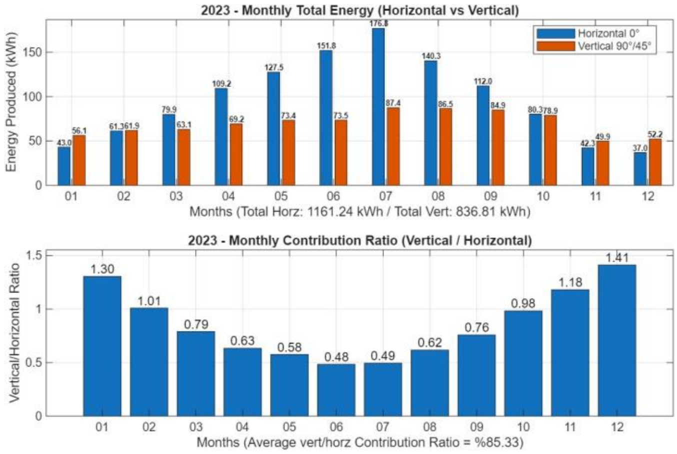

Figure 3. 2023 - Monthly simulation results.

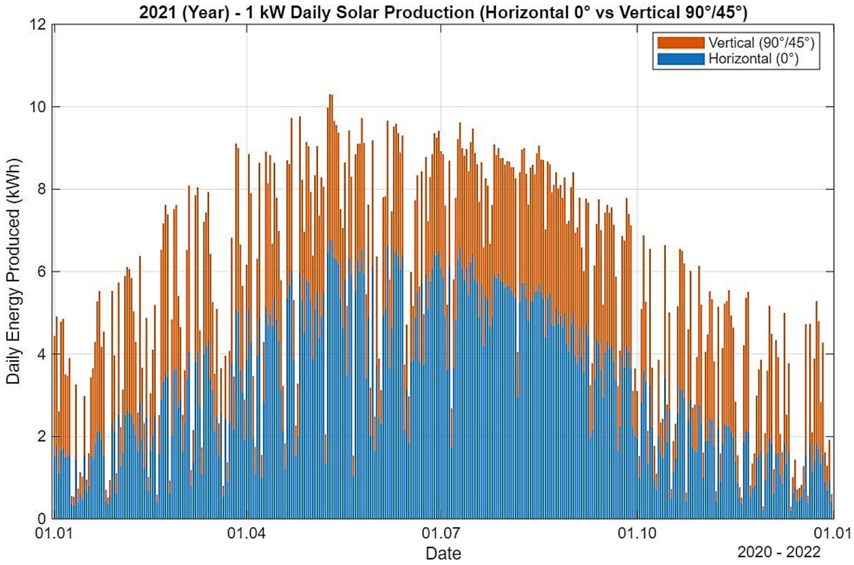

Figure 4. 2021 – Daily simulation results.

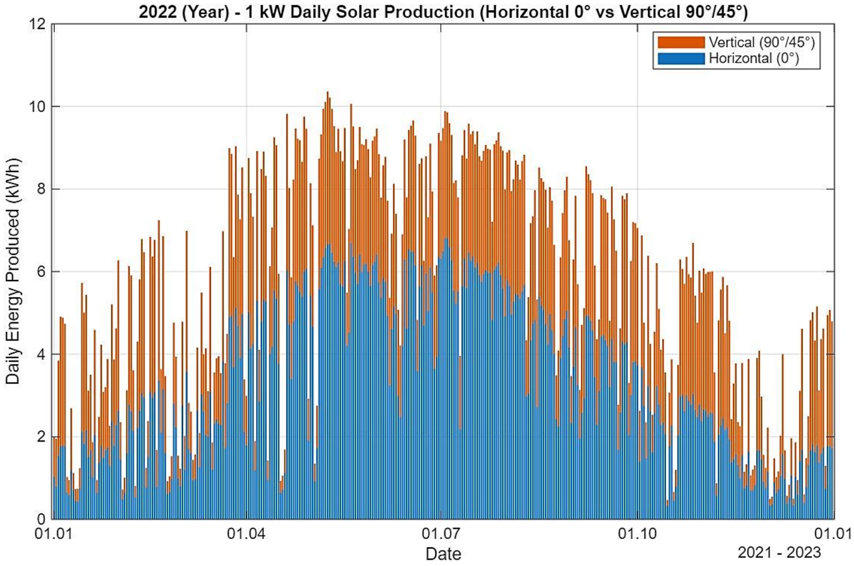

Figure 5. 2022 – Daily simulation results.

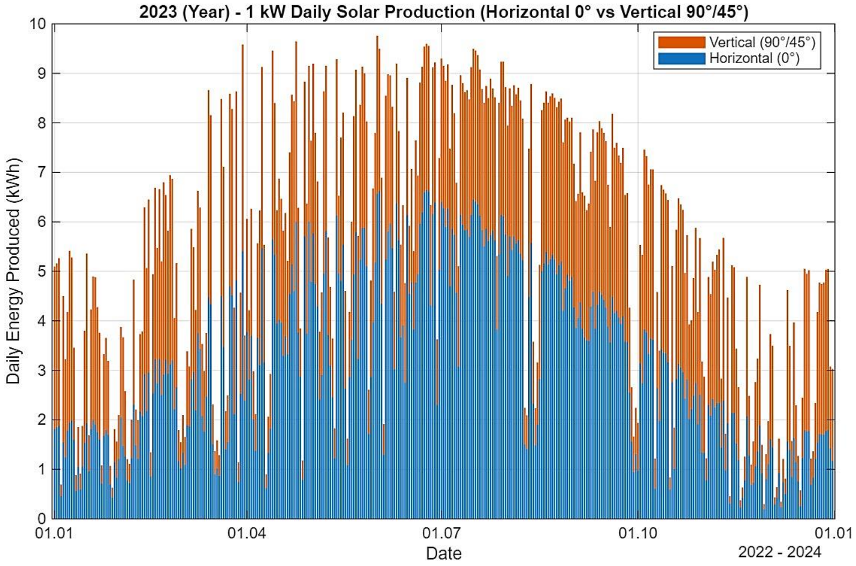

Figure 6. 2023 – Daily simulation results.

4. RESULTS

4.1 Yearly and Cumulative Energy Production

To provide a clear and quantitative comparison, Table 1 presents the annual energy production of both configurations for each year between 2021 and 2023, while Table 2 summarizes the cumulative three-year performance. This approach allows the reader to assess both year-to-year variability and overall contribution without requiring additional data aggregation.

Table 1. Annual PV Energy Production (1 kWp, Istanbul, PVGIS, 14% losses)

Year	Horizontal Rooftop PV (0°) [kWh]	Vertical Façade PV (90°/45°) [kWh]	Vertical/ Horizontal [%]	Mean	Min-Max	Std. Dev. (SD)
2021	1189	842	70.81	1190.73	1161.24 – 1221.62	30.25
2022	1221	851	69.69	843.46	836.81 – 851.65	7.73
2023	1161	837	72.09	70.86	69.69 – 72.09	1.2

Table 2. Total PV Energy Production (2021-2023, 1 kWp, Istanbul, PVGIS, 14% losses)

Configuration	Total Energy [kWh]	Relative Contribution [%]
Horizontal Rooftop PV (0°)	3571	100.00
Vertical Façade PV (90°/45°)	2530	70.84

4.2 Interpretation of Yearly Results

As shown in Table 1, the Vertical Façade PV (90°/45°) system consistently produces approximately 70–72% of the annual energy yield of the Horizontal Rooftop PV (0°) system across all three years. This consistency indicates that the performance gap between Horizontal Rooftop PV (0°) and Vertical Façade PV (90°/45°) configurations is structurally driven by orientation rather than anomalous climatic conditions in a specific year.

Table 2 confirms that, when aggregated over a multi-year period, Vertical Façade PV (90°/45°) systems can deliver a substantial fraction of rooftop PV energy output for the same installed capacity. This finding is particularly relevant for dense urban environments where rooftop PV capacity is limited, and façade surfaces remain underutilized.

4.3 Seasonal and Monthly Behavior

Daily and monthly analyses reveal distinct seasonal patterns (see Figures 1–3 for monthly ratios and Figures 4–6 for daily production profiles). Horizontal Rooftop PV (0°) dominates during summer months when solar altitude is high, whereas Vertical

Façade PV (90°/45°) exhibits relatively stronger performance during winter months with lower solar angles. Monthly V/H ratios exceed unity in several winter periods, highlighting the complementary nature of façade PV to rooftop systems.

5. DISCUSSION

The results confirm that façade-integrated PV systems, while producing less annual energy per kWp than horizontal rooftop systems, can significantly contribute to urban PV deployment by utilizing otherwise unused vertical surfaces. This finding is consistent with prior studies emphasizing the importance of multi-surface PV integration in dense urban environments [1-3]. As emphasized by Smith et al. [10], thin-film configurations offer significant potential for façade integration where conventional crystalline modules may face limitations.

In cities like Istanbul, where rooftop suitability is often constrained, façade PV offers a practical pathway to increase local renewable generation without additional land use. Moreover, the observed seasonal complementarity suggests that façade PV can help mitigate winter generation deficits commonly associated with rooftop PV systems.

From a systems perspective, increasing local generation capacity supports microgrid concepts and reduces stress on upstream distribution infrastructure [5-7]. When combined with future storage or V2G solutions, façade PV could further enhance self-consumption and extend the usefulness of solar energy into evening demand periods [5-7].

6. LIMITATIONS AND FUTURE WORK

A primary limitation of this study is its reliance on unshaded PVGIS simulation data, which inherently neglects environmental shading from neighbouring buildings, local soiling, and façade-specific thermal effects. As explicitly noted, shading from neighbouring buildings was neglected in the simulations. In a dense urban context like Istanbul, this assumption significantly limits the generalizability of the absolute yield estimates, as production losses will be substantially higher for lower floors compared to upper floors. Therefore, the results represent ideal, unshaded conditions, and real-world system designs would require site-specific adjustments and multi-aspect façade orientation planning.

Additionally, equal-capacity normalization does not reflect real-world constraints on installable rooftop versus façade PV capacity. Future work should include physical test-bed installations at identical coordinates to compare measured and simulated data, enabling identification of systematic deviations. Further simulations incorporating multi-façade configurations (e.g., east–northeast and south–southwest) and storage/V2X integration are also recommended.

7. CONCLUSION

This study evaluated Horizontal Rooftop PV (0°) and Vertical Façade PV (90°/45°) systems using PVGIS hourly time-series data for a specific location in Istanbul over 2021–2023. The Vertical Façade PV (90°/45°) configuration achieved approximately 70.8% of the energy yield of the horizontal system for equal installed capacity, while demonstrating strong seasonal complementarity. These results indicate that façade-integrated PV systems can play a meaningful role in expanding urban solar capacity and supporting localized energy systems in dense metropolitan environments.

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Declaration of Competing Interest

There are no known competing financial interests or personal relationships that could have appeared to influence this paper.

Authors' Contributions

No	Full Name	ORCID ID	Author’s Contribution
1	Ahmet Süslü	0009-0004-3274-882X	1,2,3,4
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing			

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