A Comparative Case Study on Photovoltaic Rooftop and Window Systems for Primary School Buildings Using EnergyPlus

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Abstract: This study evaluates the performance of rooftop and window-based building-integrated photovoltaic (BIPV) systems on a Department of Energy prototype primary school building using EnergyPlus simulations. Energy generation, thermal effects, and economic feasibility of three scenarios (roof only, window only, and a combination of both) were analyzed. Results show that rooftop PV systems produce the highest annual output, while window PV provides additional gains through façade utilization and shading benefits. The combined configuration yields the most balanced performance, although cost and electricity rates strongly influence payback periods. These findings highlight the complementary role of rooftop and window PV systems in advancing energy efficiency and sustainability in educational buildings.

Keywords: BIPV, EnergyPlus, renewable energy, thermal performance, commercial buildings.

1. Introduction

Solar energy is a major solution for energy production due to its abundance, widespread availability, and versatility, especially in the building sector, which accounts for approximately 40% of global energy consumption [1]. Among renewable energy solutions, Building Integrated Photovoltaic (BIPV) systems offer the unique advantage of integrating photovoltaic modules directly into the building envelope, replacing traditional building components such as roofs, façades, and windows [2]. BIPV technology transforms a building from an energy consumer to an energy producer, supporting the achievement of net-zero energy goals while improving energy efficiency and aesthetics. These advantages make BIPV systems particularly attractive for commercial buildings in urban areas, where available space for solar deployment is often limited [3]. Rooftop BIPV systems harness direct solar radiation, while BIPV windows reduce cooling loads by mitigating solar heat gain and enabling daylighting [4], [5]. Prior studies have evaluated BIPV on individual envelope elements or within specific climates, but few quantify the combined role of rooftop and window-integrated PV on a K–12 prototype with a full building load profile and DOE reference geometry. This work contributes by: (1) comparing rooftop, window, and combined configurations on the DOE Primary School model in Climate Zone 3A using a transparent, replicable EnergyPlus workflow; (2) reporting normalized metrics (kWh/m²-floor and percent of annual load offset) alongside absolute generation; (3) examining thermal interactions relevant to classrooms; and (4) providing practice-oriented guidance for K–12 facilities. Together, these elements clarify when window PV complements rooftop PV in schools and how economics and façade conditions govern adoption.

2. Methodology

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The study utilizes OpenStudio and EnergyPlus to simulate the Department of Energy (DOE) Prototype Primary School model [6] as a baseline, selecting Climate Zone 3A (Warm-Humid, representative city: Birmingham, AL) for simulation. EnergyPlus v22.1 [7] was used for performance modeling, with PV modules characterized by manufacturer specifications for Qcells models, as Qcells currently operates the largest solar module factory of its kind in the United States. Three scenarios were simulated: (1) Rooftop PV only, (2) Window PV only, and (3) Combined Rooftop + Window PV. The Figure 1 and 2 show the baseline model and the PV installation scenarios.

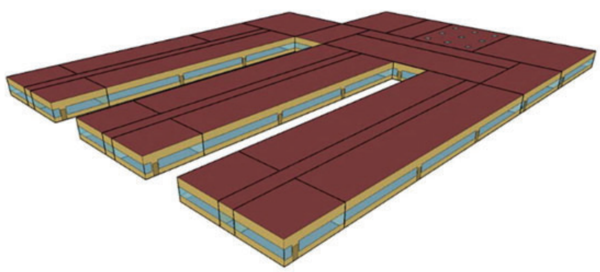

Figure 1: Baseline Model Primary School

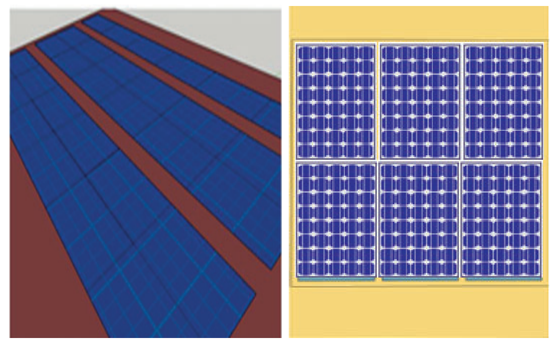

Figure 2: PV Rooftop and Window System

We selected Qcells "Q.TRON XL-G2 BFG" and "Q.PEAK DUO ML-G12S BFG" modules as representative, widely available North American products that provide a useful contrast in efficiency, module area, and temperature coefficients. This contrast tests sensitivity to array-packing and thermal derate effects that are relevant to school rooftops with finite area and to façade layouts. Manufacturer-reported parameters were used as inputs to EnergyPlus. PV modules were defined using manufacturer datasheets [8]:

- Q.TRON XL-G2 BFG: 645 W, 23.0% efficiency, 2.791 m²/module, −0.28%/°C temp. coefficient.
- Q.PEAK DUO ML-G12S BFG: 680 W, 21.9% efficiency, 3.106 m²/module, −0.24%/°C temp. coefficient.

Because there is currently no commercial semi-transparent PV window on the market, prototype PV window panels were used for the simulations. In EnergyPlus, the glazing was represented with *WindowMaterial:Glazing* and assembled into *Construction* objects for applicable façades. We explicitly set: (i) U-factor = 2.455 W/m^2-K, (ii) solar heat-gain coefficient SHGC =0.25, and (iii) visible transmittance Tvis = 0.25, targeting a moderate-transparency PV laminate appropriate for learning spaces. Shading control and daylighting were held constant across cases to isolate the PV effect on loads.

Annual electricity generation was calculated directly from EnergyPlus PV performance outputs. Economic analysis was conducted using simple payback period (SSP) based on installed system costs, electricity rates, and annual energy savings.

3. Results and Discussion

The baseline model is a typical one-story educational facility with a floor area of approximately 6,871 m² (74,000 ft²). The envelope follows ASHRAE Standard 90.1-2019 guidelines, with exterior walls, roof insulation, and window-to-wall ratios consistent with contemporary K–12 construction. The school employs packaged rooftop HVAC units for cooling and heating. The baseline model energy use is 1,021,410 kWh/yr.

Simulation results indicate that rooftop PV systems deliver the highest annual energy output. The Q.TRON rooftop configuration produced approximately 376,125 kWh/year, compared with 356,586 kWh/year for Q.PEAK. When window PV systems were added, the combined annual output increased to 397,968 kWh/year (Q.TRON) and 376,245 kWh/year (Q.PEAK), an additional ≈5–7% over rooftop-only systems. Table 1 reports the annual PV output for both panels.

Table 1. Normalized PV performance (floor-area basis and % load offset)

Configuration	Annual PV (kWh)	kWh/m²-floor	% of Annual Load Offset	Array STC DC rating (kWdc)
Q.TRON – Rooftop	376,125	54.74	36.82%	387.0
Q.PEAK – Rooftop	356,586	51.90	34.91%	408.0
Q.TRON – Combined	397,968	57.92	38.96%	403.1
Q.PEAK – Combined	376,245	54.76	36.84%	422.5
Increment from Window PV, Q.TRON	21,843	3.18	2.14%	16.1
Increment from Window PV, Q.PEAK	19,659	2.86	1.92%	14.5

For each rooftop and window PV, the DC rating was computed by the following equations:

Array STC DC rating (kWdc) = Module STC power (kW) × Module count (1)

Window PV rating (kWdc) = Window PV area (m²) × Wp/m² at STC (2)

To aid comparison across schools and designs, Table 1 reports energy generation normalized by floor area (kWh/m²-floor) and the percent of the building's annual electricity load offset. Relative to the 1,021,410 kWh/year baseline, rooftop PV offsets ~35–37% of annual electricity, while combined rooftop + window PV offsets ~37–39%. The incremental contribution from window PV alone is ~1.9–2.1% of annual load. Normalized by floor area (6,871 m²), combined configurations deliver ≈58 kWh/m²-floor (Q.TRON) and ≈55 kWh/m²-floor (Q.PEAK) per year.

Rooftop PV installations slightly increased cooling loads due to added surface heat absorption, though the effect was modest (<2%). In contrast, window-integrated PV reduced solar heat gain through façades, providing minor improvements in thermal comfort. For classrooms with south-facing windows, predicted mean vote (PMV) values remained within 0.75-1.19, indicating acceptable comfort with marginal improvements when PV glazing was present. We report simple payback (SSP) for comparability with practice, and we examine sensitivity to key drivers. Using installed costs of $3.0/W

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(Q.TRON) and $2.8/W (Q.PEAK), a retail electricity price of $0.12/kWh (Alabama), and a 30% Federal ITC treatment applicable to schools via transfer/credit mechanisms, the base-case SSP is shorter for Q.PEAK (~10.4 years) than Q.TRON (~11.4 years). We then vary: (i) CAPEX ±20% (e.g., procurement variance): SSP shifts approximately ±20%. (ii) Electricity price $0.08–$0.18/kWh (tariff/TOU uncertainty): SSP varies by ~±30–35% across the range, making the rate the largest single driver. (iii) Degradation 0.5–0.7%/yr and O&M 0.5% of CAPEX/yr: modest SSP changes (<±5%). Across cases, combined systems shorten SSP relative to rooftop-only only when the marginal façade generation aligns with higher on-site rates (or demand charges) or when façade installation costs are reduced via bundling with envelope renewal. Table 2 summarizes the SSP ranges. These results suggest that rooftop PV remains the most effective option for maximizing annual electricity generation in primary school buildings. Window PV systems provide additional, though smaller, contributions while enhancing façade utilization and occupant comfort. Between the two panel models, Q.TRON is advantageous where roof space is limited, while Q.PEAK provides better economic value under typical cost structures. Future studies will examine advanced semi-transparent PV glazing systems to balance daylighting, optical properties, and electricity generation. This will help quantify trade-offs between energy and visual comfort. Also, incorporating more climatic conditions and varying façade orientations will improve the understanding of the system robustness. Sensitivity analysis of window-to-wall ratios and PV transparency will be included in the future direction. We also plan to validate the EnergyPlus simulation results through laboratory and on-site experiments to test the electrical, thermal, and optical performance under real-world conditions.

Table 2. SSP sensitivity summary (years)

Case	Q.TRON Rooftop	Q.TRON Combined	Q.PEAK Rooftop	Q.PEAK Combined
Base Assumptions	~11.4	≈ similar or slightly shorter	~10.4	≈ similar or slightly shorter
CAPEX −20%	↓ ~9.1	↓	↓ ~8.3	↓
CAPEX +20%	↑ ~13.7	↑	↑ ~12.5	↑
$0.08/kWh	↑	↑	↑	↑
$0.18/kWh	↓	↓	↓	↓

4. Conclusions

This study shows that, for a DOE Primary School in Climate Zone 3A, rooftop PV provides the largest annual generation and the largest share of load offset, while window-integrated PV delivers incremental energy and modest thermal benefits by reducing façade solar gains. Normalized to the school's total load, rooftop arrays offset roughly 35–37%, and combined rooftop + window systems offset ~37–39%. Implications for schools include prioritizing rooftop PV to maximize generation per dollar and per hour of design effort. Consider window PV where (i) south- and west-facing classroom façades have high exposure/WWR, (ii) shading/daylighting control is beneficial, and (iii) envelope renewals can absorb incremental façade-PV costs. This study has limitations: results reflect a single climate (3A), the DOE K–12 archetype, and prototype semi-transparent glazing properties; glare/daylighting quality, detailed tariff structures, and demand charges were not modeled. As commercial semi-transparent products emerge, measured optical, thermal, and electrical data should replace prototype inputs. Future work should expand to multiple climates, incorporate demand-charge tariffs, and include occupant-centric daylight/glare metrics to resolve trade-offs between visual comfort and energy yield.

5. Acknowledgments

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6. References

[1] Wang, M., Zhao, X., Li, S., Yang, Z., Liu, K., Wen, Z., Li, Y., & Peng, J. (2024). Analysis of energy performance and load matching characteristics of various building integrated photovoltaic (BIPV) systems in office building. *Journal of Building Engineering*, *96*, 110313 https://doi.org/10.1016/j.jobe.2024.110313
[2] Chen, T., An, Y., & Heng, C. K. (2022). A Review of Building-Integrated Photovoltaics in Singapore: Status, Barriers, and Prospects. *Sustainability*, *14*(16) https://doi.org/10.3390/su141610160
[3] Amoruso, F. M., & Schuetze, T. (2023). Carbon Life Cycle Assessment and Costing of Building Integrated Photovoltaic Systems for Deep Low-Carbon Renovation. *Sustainability*, *15*(12) https://doi.org/10.3390/su15129460
[4] Zhang, T., Wang, M., & Yang, H. (2018). A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. *Energies*, *11*(11) https://doi.org/10.3390/en11113157
[5] Romaní, J., Ramos, A., & Salom, J. (2022). Review of Transparent and Semi-Transparent Building-Integrated Photovoltaics for Fenestration Application Modeling in Building Simulations. *Energies*, *15*(9) https://doi.org/10.3390/en15093286
[6] U.S. Department of Energy. (2025). *Commercial Prototype Building Models* [Dataset] https://www.energycodes.gov/prototype-building-models
[7] DOE. (2025). *EnergyPlus* [Computer software] https://energyplus.net/
[8] *Q.TRON XL-G2 BFG and Q.PEAK DUO ML-G12S BFG Datasheets.* (2025). Q.cells https://us.qcells.com/complete-energy-solutions/solar-panel/

 https://doi.org/10.52202/083252-0011