Design and Assessment of Building Integrated Photovoltaics

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Abstract

This study evaluates the potential of a third generation Building Integrated Photovoltaics (BIPVs) to enhance energy efficiency and sustainability. To find the best location for solar panels in building, energy performance was modeled in Design Builder, using the USPCASE Building as a case study. There were four Scenario examined which were conventional Photovoltaics (PVs) (22% efficient), perovskite-based PVs for windows (12% efficient), walls (16% efficient), and a combination of all three. Annual energy generation reached 23.9 MWh, 16.1 MWh, 75.4 MWh, and 115.4 MWh, respectively, corresponding to CO_2 reductions of 3.47 tons, 2.35 tons, 10.94 tons, and 16.746 tons against a baseline emission of 8.84 tons. The findings show that hybrid configurations and wall based BIPV systems offer the biggest environmental advantages, greatly reducing carbon footprints. In order to promote the implementation of BIPV technologies in sustainable building practices, these findings offer researchers, legislators, and industry stakeholder's practical insights.

Keywords*:* Building Integrated Photovoltaics, Design Builder, Third Generation Photovoltaics, Energy Performance, Carbon Dioxide Emissions.

Introduction

The "natural resource curse" the world's over-reliance on fossil fuels continues to cause economic instability, environmental harm, and energy insecurity (Mayer, 2022). Conventional energy production especially based on thermal sources releases dangerous pollutants and uses a lot of land and water resources. On the contrary renewable energy technologies such as solar and wind require minimal water and drastically reduce greenhouse gas emissions making them cleaner options for future energy systems. Although temperature control has improved building energy efficiency non-renewables still account for nearly 70% of global energy consumption, with renewables making up just over 30% (Adil et al., 2025; Ali et al., 2020). Despite its abundance, solar energy accounts for only about 2% of grid power (IRENA).

Buildings are responsible for nearly one third of global CO_2 emissions positioning them as critical sites for sustainable energy

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solutions. Building Applied Photovoltaics (BAPVs) are typically added after the construction of building whereas Building Integrated Photovoltaics (BIPVs) embeds solar technologies directly into structural elements such as tiles, windows, or facades (Corti et al., 2020; Singh et al., 2021). BIPV systems thus serve dual roles as both energy generators and architectural components, offering aesthetic and space saving advantages (Basher et al., 2024; Marchwiński, 2023; Shu et al., 2024). This study examines the utilization of third generation photovoltaic technology specifically perovskite-based Photovoltaics (PVs) for BIPV systems, which offer enhanced efficiency, reduced costs and weight, and diverse applications compared to traditional silicon-based systems. As buildings turn into active energy generators with the help of BIPV, adding advanced photovoltaic technologies like perovskite to architectural elements becomes not only a technical challenge but also a strategic necessity for sustainable urban development.

Several studies have explored BIPV integration simulation methodologies but the complete spectrum is yet to be studied. Hamzah & Go (2023) analyzed colored PV façades in Kuala Lumpur, finding that a tilt angle of 60° produced the highest annual energy generation (679.72 MW) and CO_2 savings of 10,367.66 t/year. Zhou et al. (2024) provide an overview of recent progress in semitransparent photovoltaic technologies including perovskite based, highlighting advances in material choices, optical design strategies, and device architecture optimization. Their work also emphasizes the role of optical modeling in improving performance and examines the practical hurdles that remain for bringing these solar cells into widespread use within building-integrated applications. Ritzer et al. (2023) presented translucent perovskite based PVs for façades, highlighting scalability and aesthetic values. Anber (2021) studied BISOL XL and JONSOL JSM-72 modules for an Egyptian bank which mainly targeted façade reporting efficiencies of 19.2% and 19% respectively and with CO_2 reductions of 6.9% and 5.9%. Pereira & Aelenei (2019) investigated the efficiency of BIVP/Thermal (BIPV/T) systems with phase changing materials in office façades using a Genetic Algorithm Method, reporting seasonal efficiencies of 64% in winter and 32% in summer. In another study, Srivishnu et al. (2023) reviewed semitransparent perovskite solar cells emphasizing their potential for BIPV due to low cost processing since less material required for production and high efficiency. While these studies provide valuable insights they focus on isolated configurations and lack comparative analysis across multiple integration strategies while quantifying environmental impact.

Against this backdrop, the present study addresses the specific problem of limited integration methodologies for advanced photovoltaic technologies particularly perovskite-based PV into building envelopes. It improves upon existing BIPV work by conducting a comparative simulation of four distinct PV integration cases, including hybrid BIPV+BAPV strategies, using a real building model as case study. The aim is to evaluate energy generation potential, CO_2 emission reduction, and the feasibility of integrating third generation perovskite PV into building envelopes. By doing so, this study seeks to bridge the gap between isolated case analyses and comprehensive integration strategies thereby contributing to the realization of self-sustaining and low emission-built environments. The 3D building model of the case study building of United States Pakistan Centre for Advanced Studies in Energy (USPCASE) was built with help of an imported DXF file of the building, followed by load profiling of all active zones. The USPCASE building was chosen because it is amongst if not the most recent and advance academic buildings in Khyber Pakhtunkhwa province, which can give a perspective on to how BIPV can be included in future advance buildings. The simulation for actual load of the building was done for a year, which gave us a target to achieve for the proposed cases. The energy generation is based on four cases: the first case uses JA Solar JAM78S30 panels on the roof (reference case), two cases are based on BIPV applications, and the last is a hybrid case combining BIPV and BAPV. Among these, the hybrid strategy proved most effective, with the highest energy generation potential and a CO_2 emission reduction so substantial that it could not only offset the building's emissions but also contribute to reducing utility-source emissions. Wall based BIPV was the best single application when fully utilized, but the hybrid strategy ultimately generated the most units, underscoring its promise for sustainable and environmentally friendly energy infrastructure.

Methodology

This study employs Design Builder as the main simulation tool for assessment of BIPV's energy efficiency. Design Builder is known for both its intuitive interface and also strong simulation capabilities because it integrates thermal analysis plus day lighting and photovoltaic modeling within a unified platform giving an improved platform for Building Information Modelling (BIM). Design Builder models through visual tools that streamline data input and reliably projects energy performance without any external plugins. Transient System Simulation (TRNSYS) and EQuest can all simulate environments that don't rely on visuals and most needs plugins. Design Builder is especially good for BIPV analysis because its built-in Energy Plus engine makes sure that calculations about heat transfer and solar energy production are correct (Oguntade & Cimillo 2024).

The methodology of this study is comprised of four unique simulation scenarios aimed at evaluating the effects of incorporating various BIPV configurations on building energy consumption and corresponding carbon emissions. Below are the details of these scenarios, which are also shown in Figure 1.

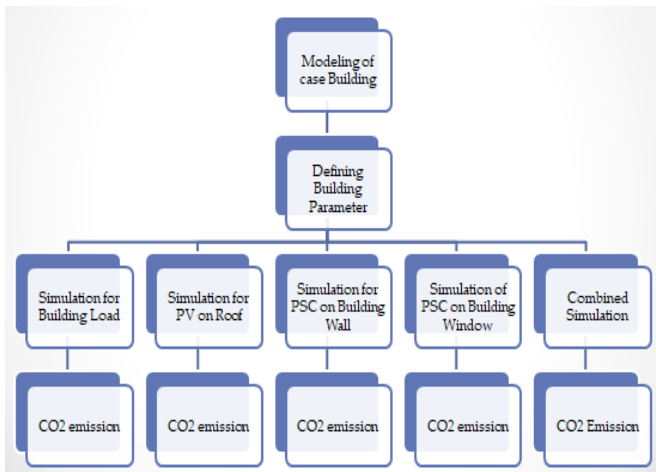

Figure 1: Summary of methodology.

Rooftop Solar Panel Integration

This scenario looks at how well standard photovoltaic panels work when they are put on the roof of a building on assuming they are about 22% efficient. This BAPV simulation serves as a reference case which will be used for evaluating energy generation potential, architectural compatibility, and the overall feasibility of integrating rooftop photovoltaic systems.

Window Integrated Perovskite BIPV

In this case, the building's window glazing has perovskite solar cells with an efficiency of 12%. The examination revolves around their impact on energy savings and CO_2 emission reductions, as well as the viability of this scenario for practical application in real time.

Wall Integrated Perovskite BIPV

In this scenario, the building’s outside walls have perovskite modules that work at 16% efficiency. The simulation looks at how much they help with energy harvesting and how much they help with building loads and CO_2 emissions savings in this example.

Hybrid BIPV Deployment

The last scenario looks at how well rooftop panels, window-integrated perovskite cells, and wall-mounted perovskite modules work together. This hybrid configuration is analyzed to explore the synergistic effects of multiple BIPV with BAPV (reference case) systems and their cumulative impact on building energy efficiency and carbon footprint reduction.

Simulation Setup

The Case study building was modeled using DXF (Drawing Exchange Format), which is the file format for Automatic Computer-Aided Design (AutoCAD). DXF file is imported from AutoCAD for Ground, 1st and 2nd floor, as shown in the Figure 2.

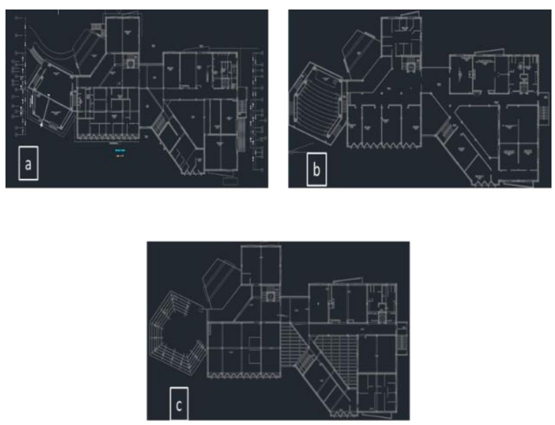

Figure 2: Plans for case study building: (a) Composite layout showing the Ground floor; (b) First floor; (c) Second floor.

The Ground Floor includes a total of 19 distinct sections and the 1st Floor comprised of 20 sections while the 2nd floor consists 24 sections. Functional areas like faculty offices, classrooms, laboratories, reception spaces, open corridors, the cafeteria, and also administrative offices incorporate these spatial divisions, the load profiling was done for these zones which will be discussed later. Figure 3 depicts individual floor plans. It can also give a detailed representation for the building layout.

Furthermore, shading cause from the adjacent building was considered for all simulation by incorporating the buildings around case study building which include Peshawar Institute of Cardiology (PIC) to the east, University department to the south and 2 building to south west as shown in Figure 4 for month of October.

Design Builder relies on Energy plus Weather (EPW) weather data formats for building performance simulation. This data was at that point incorporated into the simulation model for the purpose of the research. Heating, Ventilation and Air Conditioning (HVAC) demands are calculated via the software based on actual environmental conditions using this localized dataset.

Selection of BIPV Material

Solar Panel for Rooftop

The JAM78S30 module functions as a typical solar panel example and the manufacturer's datasheet thoroughly details its thermal and electrical performance parameters (Solar). For the Design Builder environment, users will directly apply key specifications like open-circuit voltage, short-circuit current and maximum power point. Because accurate simulation depends on these inputs, they are critical. Since it does incorporate a module well-established as well as thoroughly documented like JAM78S30, that provides a reference, dependable to evaluate photovoltaic technologies emerging, including technologies based on perovskite materials. The performance model used was equivalent-one diode model and its parameters are shown in Table 1.

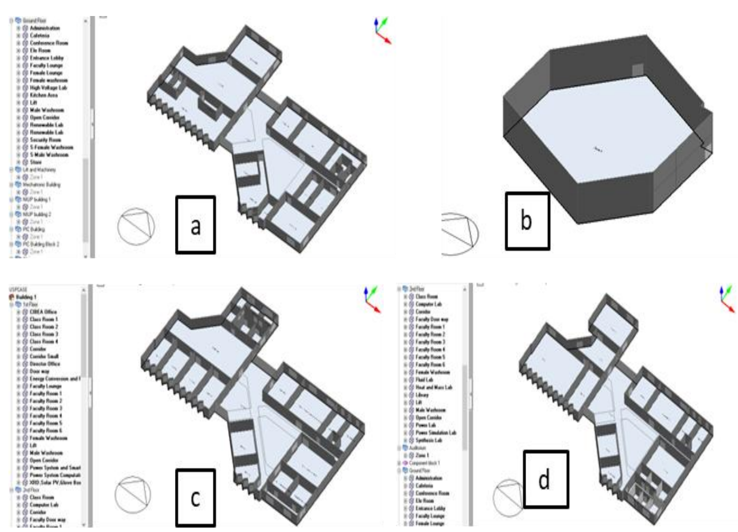

Figure 3: ***(a & b) Internal zones of case study building showing Ground floor; (c) First floor; (d) Second floor.***

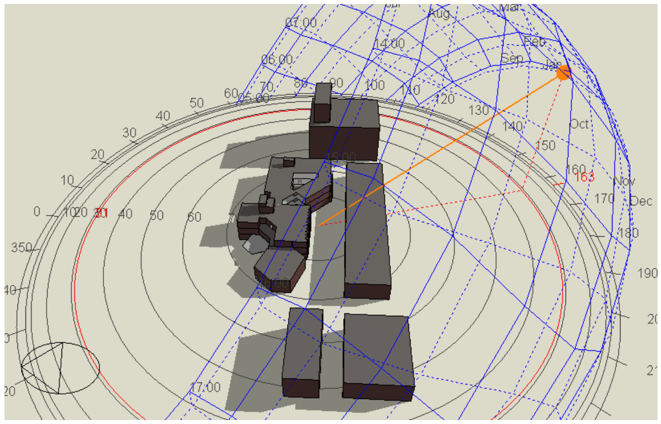

Figure 4: Shadow imposed by surrounding Building on USPCASE Building.

Table 1: Electrical parameters of conventional solar panels.

S. No	*Parameter*	*Value*
1	Series of Cell	26
2	Active Area	2.64
3	Transmittance absorptance product	0.9
4	Semiconductor bandgap(eV)	1.8
5	Shunt resistance (ohms)	1000
6	Reference Temperature (°C)	25
7	Reference Insulation (W/m^2)	1000
8	Module Heat loss coefficient (W/m^2-K)	30
9	Total Heat capacity(J/m^2-K)	1000
10	Rated electric power output (W)	605
11	Short Circuit current (A)	11.30
12	Module Current at max power (A)	10.60
13	Temperature coefficient of short current (A/K)	0.00634
14	Open circuit voltage (V)	60
15	Module Voltage at max power (V)	50.5
16	Temperature coefficient of short current (V/K)	-0.147
17	NOCT ambient temperature (°C)	25
18	NOCT cell temperature (°C)	45
19	NOCT insolation (W/m^2)	800

Semi Transparent Perovskite for Windows

Semi-transparent perovskite materials address a new issue for window-integrated PVs as they unite energy generation with day lighting. Their partial transparency is suited to urban applications in which natural light is necessary even with assumed 12% efficiency. Design Builder simulations capture both electrical (IV characteristics) along with thermal behavior because they do reflect real-world performance. This dual functionality supports their potential in BIPV systems so it balances aesthetics, energy output, for occupant comfort. Table 2 shows the performance model shown for the selected window integrated perovskite. Only the updated parameters have been shown compared to Table 1 which consist all the parameters and the serial number has not been changed so it's easy to track for comparison in Table 1.

Table 2: Electrical parameters of semi-transparent perovskite for windows.

S. No	Parameter	Value
3	Transmittance absorptance product	0.8
10	Rated electric power output (W)	316
11	Short Circuit current (A)	8.80
12	Module Current at max power (A)	8
13	Temperature coefficient of short current (A/K)	0.001
14	Open circuit voltage (V)	47.5
15	Module Voltage at max power (V)	39.6
16	Temperature coefficient of short current (V/K)	-0.005

Flexible Perovskite for Walls

Flexible perovskite PV modules, adaptable also and easy to install, were selected for wall integration with assumed 16% efficiency. Since these lightweight modules conform to some irregular surfaces plus reduce structural load, they are ideal for many diverse architectural applications, unlike any rigid panels. Their outdoor durability has improved since UV along with moisture resistance has advanced. Roll-to-roll manufacturing gives cost benefits over silicon PV. These features are incorporated within Design Builder simulations in order to assess thermal behavior with energy output inside the building envelope. Experimental findings support their mechanical resilience and stable performance under varying environmental conditions, reinforcing their suitability for BIPV wall applications (Liang et al., 2021). Table 3 shows the performance model for respective photovoltaic material. Only the updated parameters have been shown compared to Table 1 which consist all the parameters and the serial number has not been changed so it's easy to track for comparison in Table 1.

Table 3: Electrical parameters of flexible perovskite for walls.

S. No	Parameter	Value
10	Rated electric power output (W)	421
11	Short Circuit current (A)	11.58
12	Module Current at max power (A)	9.27
13	Temperature coefficient of short current (A/K)	0.001
14	Open circuit voltage (V)	53.6
15	Module Voltage at max power (V)	45.6
16	Temperature coefficient of short current (V/K)	-0.005

Simulation Parameter and Assumptions

The building of University of Engineering and Technology (Peshawar), USPCASE was taken into consideration for purpose of this study. Its floor has an area of 4674 m^2 and enclosed a volume of 19412 $m^{3.}$ The simple performance model was used for HVAC system of building and the thermal control parameters for HVAC were developed with a heating set point of 25° C and a setback of 18° C while cooling condition was set on a set point of 26° C and setback on 35° C. For Peshawar, climate data was sourced from Climate Onebuilding website (Onebuilding), plus the data extends from 2009 until 2023.

The efficiency for semitransparent perovskite based BIPV application was assumed 12% and 16% for flexible perovskite for wall based BIPV application. The Simulation was carried out over the course of one year and daily performance trend of energy was analyzed including building load. The load of equipment/components was estimated based on typical daily routine assumptions for a university building. Although the actual number of these load components is significantly higher, a reduced quantity was considered in the analysis because not all units are utilized. The building operational schedule was established to run from 8 in the morning till 4 in the afternoon, Monday to Friday which is synchronized with a study done by Ahmad et al. (2014) and Ahmad (2014). The load profiling was done extensively in accordance with real time load of the building as much as possible which is shown in the tables. Table 4 shows the zones considered all across the building. The load that is continuously on 24/7 for the entire building is illustrated in Table 5. While the remaining considered load is described in the Table 6.

The PV panels for reference case were tilted at 34° with a 180° azimuth to maximize their solar exposure. Windows were strategically placed to reduce direct sunlight which is a part of building design meant to lower cooling cost in summer while having maximum lighting, limiting solar output from window integrated systems. Shading from nearby buildings was accounted for, and net metering allowed surplus energy to feed back into the grid.

To ensure realistic simulation for quality results, consistent assumptions were applied here. Efficiency values for perovskite-based BIPV systems were estimated, while specs for conventional panels are based on the JA Solar JAM78S30 model (Solar). Voltage and current parameters are adjusted to reflect target efficiencies here. Flexible and semi-transparent perovskite PVs were treated separately based on their uniqueness of performance, influencing their suitability for walls or windows.

Emission Calculation

For the CO_2 emissions analysis, the method that was applied is weighted average emission factor which is consistent with the approach used by Butt et al. (2021) in their study on Pakistan's energy sector. From December 2024, coal, gas, and oil collectively accounted for approximately 56.05% of electricity generation, based on data from National Electric Power Regulatory Authority (NEPRA), as shown in Figure 5 (NEPRA, (2024).

Table 4: Zones of case study building for real time load.

S.No.	Zones	Quantity
1	Classrooms	4
2	Labs	6
3	Faculty offices	2
4	PMU	1
5	Dir. Office	1
6	Library	1

Table 5: 24 hours load of case building.

S.No.	Load component	wattage	Quantity
1	Camera	25	24
2	Modems	25	8
3	Smoke Sensors	10	26
4	Motion Sensors	8	32
5	Emergency Lights	10	41

Table 6: Variable load profile of considered zones.

S.No.	Load Component	Wattage	Quantity	Days/week
1	Lighting	36	111	5
2	Interior Equipment	350	5	5
3	Fan	75	12	5
4	Computer	300	26	5
5	Lab Equipment	3000	1	1
6	Auxiliary load (pumps, cooler etc.)	9700	1	5
8	Heating	Simple HVAC model		4
9	Cooling	Simple HVAC model		4

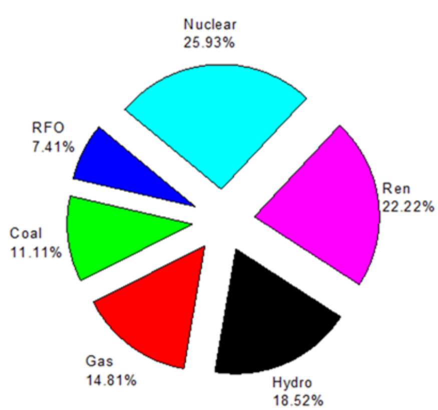

Figure 5: Fuel source contribution to national grid (NEPRA, 2024).

Fuel specific CO_2 emission factors were initially derived following the guidelines from International Panel on Climate Change, which report values of 72.2 Mt CO_2/EJ for oil based fuel, 97.2 Mt CO_2/EJ for coal, and 56.1 Mt CO_2/EJ and natural gas (IPCC, 2006). However, since the analysis requires these factors to be expressed in terms of electrical energy (kWh) a conversion from energy content in Exajoule (EJ) to kilowatt hours (kWh) was performed. This allows for direct comparison and integration into electricity-based emission calculations.

$$1Mt = 1 \times 10^{9} kg$$

$$1Ej = 1 \times 10^{18} \text{ W}$$

Where Mt is Megaton and Ej is Exajoule

$$1Ej = \frac{1\times10^{18}}{3.6\times10^{6}} kWh$$

The emission factor per kWh will become;

Coal;

$$EFc = \frac{97.2\times10^{9} kgCO_2}{2.78\times10^{11} kWh} \approx 0.35 kgCO_2/kWh$$

Oil;

$$EFo = \frac{72.2\times10^{9} kgCO_2}{2.78\times10^{11} kWh} \approx 0.26\ kgCO_2/kWh$$

Gas;

$$EFg = \frac{56.1\times10^{9} kgCO_2}{2.78\times10^{11} kWh} \approx 0.20 kgCO_2/kWh$$

The following formula is used to determine the grid emission factor, which is the weighed sum of each fuel's emission factor;

$$EF_{grid} = \sum_i (f_i \times EF_i)$$

Where EF_i the CO_2 emission factor for the fuel is type i and f_i is the percentage of contribution in the grid energy mix by fuel type i.

$$EF_{grid} = ((0.2687\times0.202) + (0.1695\times0.350) + (0.1223\times0.26) + (0.2833\times0) + (0.082325\times0) + (0.073\times0))$$

Because we concentrate on emissions connected to combustion, we assume that hydro, nuclear, and renewable energy sources have virtually nil direct CO_2 emissions for calculating operational CO_2 emission.

$$EF_{grid} = 0.1451\ KgCO2/kWh$$

Results

The energy simulation findings for the US Pakistan Center for Advanced Studies in Energy (USPCASE) building case study give a full picture of its electrical needs and how different PV technologies affect energy production and carbon emissions. A baseline study finds the most important loads for lighting, cooling, heating, and equipment. We looked at three ways to integrate PV: traditional solar panels (BAPV), semi-transparent perovskite windows, and flexible perovskite walls. The Hybrid case was also analyzed in which case all of the three previous cases were combined into one.

The BAPV configuration handled 39.2% of the annual load, and the semi-transparent (for letting light in) window integrated PVs added 26.5%. Flexible perovskite walls having met 123% of the building simulated load. The hybrid system worked better than expected, providing 189% of the building's electrical consumption, which was more than the overall demand. This can greatly impact in reducing the building's reliance on grid energy.

Carbon dioxide (CO_2) emissions were significantly diminished, with individual BIPV systems accounting for 10% to 30% reduction depending on the case, and the hybrid design yielding the most substantial effect. These results show how BIPV technology could help current buildings become more energy-efficient and environmentally friendly.

Simulation Results of Generations from Different Cases

The results of the energy simulation give a full picture of the USPCASE building's yearly energy use, which is 60,924.87 kWh, or almost 82% of the actual units used between April 2024 and March 2025. Cooling is the biggest load, using 23,965.3 kWh per year, 96.3 kWh of which is for running the fan. This shows that the building needs a lot of cooling because of the weather in the area. The biggest part of the energy use comes from inside equipment, which uses 32,291.7 kWh. This includes Auxiliary loads for example water pumps and freezers. The heating and lighting loads are not very high they are 1,919 kWh and 1,963 kWh, respectively. Every year domestic hot water uses 785 kWh of electrical energy. The simulation results demonstrate that while individual PV technologies such as rooftop solar panels (BAPV application and semitransparent perovskite windows (BIPV application) can significantly reduce grid dependency, meeting 39.2% and 26.5% of the building’s annual demand respectively, the flexible perovskite wall modules stand out by generating surplus energy amongst the mentioned BIPV cases, exceeding the building’s requirement by 23%. The BIPV window application generates the least amount of energy because of the buildings unique windows configuration which do not allow direct sunlight. However, the hybrid configuration (BIPV + BAPV) integrating rooftop PV, window integrated PV, and flexible wall mounted modules proved to be the most effective solution, producing 115,414 kWh of net usable electricity annually, equivalent to 189.4% of the building’s 60924 KWh demand. This configuration not only ensures complete coverage of the building load but also delivers substantial excess clean energy to the grid, making it the most impactful and practical option among those evaluated.

Detailed generation and efficiency values for each case are presented in Table 7.

Table 7: Monthly energy generation for different cases.

Month	Load (kWh)	Solar Panel (BAPV) (kWh)	BIPV Window (kWh)	BIPV Wall (kWh)	Hybrid (BAPV+BIPV) (kWh)
Jan	3359	1890	1570	7328	10733
Feb	2844	1419	1118	5183	7710
Mar	2666	2396	1566	7569	11520
Apr	3875	2303	1335	6495	10125
May	6789	2451	1292	5885	9623
Jun	8255	2186	1152	5006	8339
Jul	8007	1675	1025	4433	7129
Aug	7188	1627	1061	4914	7598
Sep	7009	2061	1351	6566	9969
Oct	4919	2272	1621	7701	11582
Nov	3135	1892	1518	7061	10459
Dec	2872	1759	1581	7254	10579

Table 8: Monthly CO_2 emissions from different cases.

Month	Load (kg)	Solar Panel (BAPV) (kg)	BIPV Window (kg)	BIPV Wall (kg)	Hybrid (BAPV+BIPV) (kg)
Jan	487	213	259	-575	-1075
Feb	412	206	250	-339	-706
Mar	386	38	159	-711	-1284
Apr	562	228	368	-380	-906
May	985	629	797	131	-411
Jun	1197	880	1030	471	-12
Jul	1161	918	1013	518	127
Aug	1043	806	889	329	-59
Sep	1017	717	820	64	-429
Oct	713	384	478	-403	-966
Nov	454	180	234	-569	-1062
Dec	416	161	187	-635	-1118

Simulation Results of CO_2 Emission from Different Cases

The carbon emission analysis for the case study building reveals distinct differences across the evaluated PV configurations. Conventional rooftop solar panels reduced annual emissions to 5,370 kg, with seasonal peaks in July due to cooling loads, while the semitransparent perovskite windows performed less effectively, yielding higher yearly emissions of 6,490 kg because of limited generation capacity and reduced exposure to direct sunlight. In contrast, flexible perovskite wall modules achieved a net negative balance of –2,100 kg resulting in fully off-setting the building's carbon footprint and contributing surplus clean energy to the grid. The hybrid case proved most impactful, lowering emissions further to –7,906 kg and establishing a continuous net negative scenario. The entire quantity of CO_2 emissions each year is about 8,840 kg. This progression underscores the superior environmental benefits of integrated PV systems. The monthly values of CO_2 emission are shown in Table 8 above.

Discussion

The comparative analysis of the hybrid PV configuration in this study highlights its distinctiveness when set against recent studies, which have primarily examined isolated applications of perovskite PVs in building envelopes. For example, Ritzer et al. (2023) explored translucent perovskite based PVs for façades, emphasizing scalability and aesthetics but without quantifying whole building energy autonomy. In contrast to it our work demonstrates that wall integrated perovskite modules not only surpass façade only strategies but also achieve surplus generation that offsets grid reliance of the case study building. Similarly, Jin et al. (2024) stabilized semitransparent perovskite solar cells using polymer composite hole transport layers, addressing material level durability challenges but stopping short of building scale integration. Our study extends this by embedding semitransparent glazing into a real building model, showing its limited contribution compared to walls and rooftops while considering the shade from buildings surrounding. Li et al. (2023) reviewed progress and challenges in flexible perovskite solar cells, highlighting mechanical stability and roll-to-roll manufacturing as critical enablers for commercialization. We objectify these insights by simulating flexible wall mounted modules, proving their dominance as the single most effective BIPV surface in terms of net energy surplus.

Rostamzadeh & Montazeri (2024) proposed a multiscale computational framework for scaling up perovskite PVs from cell to building integration, yet their work remained theoretical and their work did not incorporate external shading or realistic occupancy schedules. Keeping that in mind our study accounts for surrounding structures, case study building's shading structure, HVAC loads, and daily operational patterns of an academic building, thereby producing results that are directly translatable to institutional contexts. Also, it helps to picture why window integrated PVs despite their promise in laboratory settings, contribute modestly in practice compared to walls and rooftops. Such insights are critical for policymakers and designers aiming to deploy BIPV in dense urban environments where ideal solar exposure is rarely achievable.

Noman et al. (2024) provided a comprehensive review of perovskite solar cell advancements, highlighting efficiency and transparency tradeoffs in semitransparent devices. While their review underscores the promise of perovskite glazing, our findings demonstrate that in practice, window integrated PVs contribute modestly compared to walls and hybrid systems. Shu et al. (2024) conducted a scientometric analysis of BIPV research trends, noting the lack of comparative integration studies across multiple envelope elements. Our work directly addresses this gap by quantifying energy and carbon outcomes for rooftop, wall, window, and a hybrid strategy within a single case study by applying weighted emission factors derived from Pakistan's energy mix, our study demonstrates that hybrid BIPV deployment can achieve a net negative emissions profile, off-setting not only the building's demand but also contributing clean energy back to the grid.

Our data, which go beyond laboratory measures to show observable environmental benefits under real world conditions, gives a shot to bolster the case for BIPV as a climate mitigation tool by include month-by-month CO_2 reduction trends. Collectively, these comparisons show that while recent literature advances materials, optics, and theoretical frameworks, our study is unique in demonstrating the operational feasibility and environmental superiority of hybrid BIPV deployment in a real institutional building, thereby bridging the divide between laboratory innovation and practical sustainability outcomes.

Conclusion

This study demonstrates the potential of perovskite-based PV solutions to increase the building energy efficiency while reducing operational carbon emissions. Among the scenarios assessed in this study the hybrid configuration (Case 4) proved most effective, as it maximized the use of available building surfaces and achieved substantial energy generation and carbon reduction. Along with these indications, it is important to highlight the practical contribution of flexible perovskite wall modules, which enable greater integration opportunities due to their adaptability to diverse architectural surfaces. Beyond the quantitative outcomes, the results provide a benchmark for future applications of BIPV. They provide a perspective into how BIPV can transform conventional buildings into energy assets which offers both environmental and economic advantages. By demonstrating the feasibility of large-scale perovskite integration, this research contributes to the broader discourse on sustainable building design and supports the transition toward low carbon urban development.

This study is subject to several limitations. First, the findings are based on simulation of a single case study building, which may not fully capture real world variability in occupant behavior, climate conditions, and installation practices. Second, the efficiencies considered for Perovskites are assumptions and also while perovskite PV technologies offer promising efficiency gains, their long-term stability and large-scale manufacturability remain unresolved, limiting immediate applicability.

Third, although CO_2 emission reductions were estimated, a comprehensive and economic feasibility analysis were beyond the scope of this work. Fourth, while Life Cycle Assessment (LCA) studies are important they are not part of this study which can be researched in length. Finally, the study did not address policy, regulatory or broader urban-scale impacts, which represent important areas for future research.

Further research is required to strengthen the LCA of perovskite based BIPV systems for example detailed investigations should be done into the cost of perovskite materials per square meter, their long-term degradation behavior and stability as an application, their payback period and their responses to diverse environmental conditions would contribute in valuable insights. Moreover, comprehensive studies on the economic feasibility of each case especially those incorporating perovskite modules will be highly beneficial. These analyses could offer a practical perspective on the scalability and real-world application of these scenarios therefore materializing the gap between simulation-based outcomes and implementation in actual building projects. Furthermore, exploring advanced hybrid configurations, smart grid integration, and adaptive control strategies could enhance both energy efficiency and carbon reduction potential in future applications.

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