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A FRAMEWORK TO ANALYSE THE ENERGY AND ECONOMIC PERFORMANCE OF SHADED BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) FACADES IN LOW-RISE AND HIGH-RISE BUILDINGS IN TROPICAL CLIMATE

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SUMMARY: *The building sector being energy-intensive necessitates the transition to high performing buildings and as zero energy buildings by employing renewable strategies. The potential for photovoltaic (PV) electricity generation is particularly significant in tropical regions such as India, owing to the abundant availability of solar radiation. Building integrated photovoltaic (BIPV) systems present a promising solution when PV system installation areas are constrained. However, a primary challenge in energy generation is the shading caused by nearby buildings, which limits the energy generation potential. This study examines the impact of various shading scenarios on BIPV energy generation in both low-rise and high-rise buildings, alongside the economic viability of renewable energy adoption. A systematic approach is employed, involving the development of potential shading scenarios, modelling, and simulation of these scenarios to assess photovoltaic (PV) generation. The evaluation against building energy demand facilitates the assessment of Net/Nearly Zero Energy Building (NZEB) potential. Irradiation analysis is conducted to quantify solar gain loss due to shading compared to its base/unshaded case. Through a comparative assessment involving the study of irradiance loss due to shading and BIPV energy generation, the study evaluates the viability of BIPV systems on building facades, for achieving net-zero energy status in low-rise and high-rise structures. The study further investigates the economic feasibility of shaded PV integrated facades for both low-rise and high-rise buildings. In shaded conditions, high-rise buildings yield suboptimal results in achieving net-zero status, while shaded scenarios in low-rise buildings cover 20-40% of building energy demand. However, implementing PV integrated facades in high-rise buildings prove to be financially feasible with shorter payback periods compared to low-rise buildings. These findings provide valuable insights into the efficient utilization of BIPV technology and establish a foundation for informed decision-making in sustainable building design.*

KEYWORDS: *NZEB, BIPV, energy simulations, shading impact, LCCA.*

REFERENCE: *Aaliya Azeem & Albert Thomas (2025). A framework to analyse the energy and economic performance of shaded building integrated photovoltaic (BIPV) facades in low-rise and high-rise buildings in tropical climate. Journal of Information Technology in Construction (ITcon), Special issue: 'Smart and Sustainable Built Environment (SASBE 2024)', Vol. 30, pg. 1528-1552, DOI: 10.36680/j.itcon.2025.062*

1. INTRODUCTION

The rise in population and urbanization has led to a significant increase in building energy demand in recent years, with buildings accounting for 30–40% of global energy consumption, with the related emissions growing at an annual rate of 1% (IEA, 2021). Since energy consumption is closely linked to carbon emissions, enhancing energy efficiency in buildings and thereby reducing potential carbon emissions has become essential for mitigating climate change (Rey-Hernández et al., 2018). Within the building sector, net or nearly zero energy buildings have gained prominence as a promising solution for reducing greenhouse gas emissions and have emerged as a sustainable measure by generating on-site electricity through renewable energy sources (D'Agostino et al., 2021). Among these clean energy sources, solar photovoltaics is particularly well-suited to urban landscapes due to their compatibility with electricity load profiles and their widespread availability in many countries (Usman et al., 2021). Similarly, buildings in tropical regions have significant potential to become NZEBs due to the abundant solar irradiation available throughout the year.

Net-zero energy status in buildings is commonly achieved through the installation of photovoltaic (PV) panels on rooftops which is referred as Building-Applied Photovoltaics (BAPV), that involves the attachment of PV systems onto existing building surfaces without altering their structural components. This technique of PV installation offers a practical approach to enhancing a building's energy performance, facilitating its quick transformation into an energy-efficient building. However, the availability of space for installing these PV panels poses a challenge for buildings aiming to achieve net-zero status (Basher et al., 2023). Building integrated photovoltaic (BIPV) systems thus offer an ideal solution, as they transform the building envelope into power-generating units, eliminating the need for separate PV installation areas. The BIPV technique of integrating PV modules into the building envelope also provides the added benefit of reducing emissions by replacing conventional construction materials, which are often associated with high embodied carbon (Zhang et al., 2018).

Although BIPV systems offer the benefits of utilizing a larger portion of the building envelope for solar energy generation, their application in existing buildings is often constrained by design limitations such as structural load capacity and potential facade orientation. In addition to this, the variability in surrounding built forms, including the height and proximity of adjacent structures, introduces complex shading conditions that can substantially reduce solar access and, consequently, photovoltaic energy generation. These constraints can hinder the ability to achieve optimal system configurations, thereby resulting in comparatively lower energy performance than conventional rooftop PV installations (Yu et al., 2025). While BIPV systems may, in some cases, yield lower energy outputs compared to optimally oriented rooftop PV systems, PV integrated facades play a significant role in energy generation, given their available surface area and the advantage of contributing to peak production at different times of the day (Freitas & Brito, 2015). Moreover, when PV utilized as building façades, these systems can contribute to a reduction in operating costs, thereby offsetting a portion of the initial construction expenses (Menoufi et al., 2013).

However, practically, the application of BIPV on facades may result in some solar irradiation loss due to shading from nearby buildings. Shading from adjacent structures is often unavoidable in urban areas with space constraints and densely packed buildings. Shading impacts BIPV energy generation by reducing the amount of irradiation reaching the photovoltaic cells (Jayathissa et al., 2017), thereby diminishing energy output. A comprehensive understanding and quantification of these shading impacts on PV systems are essential for optimising the BIPV performance and informing effective design decisions during the early stages of building planning. Analysing the impact of shading entails evaluating a range of shading scenarios to assess their influence on the energy generation potential of BIPV systems. This process involves the detailed modelling of PV integrated facades under varying shading conditions, utilizing solar simulations that predicts the shading effects on BIPV system, based on the spatial characteristics such as the position and height of the nearby buildings. These simulations provide insight into how shading alters incident solar radiation and, subsequently, PV energy output.

While the integration of photovoltaic systems into building envelope offers significant advantages, particularly the availability of extensive surface area for energy generation, the associated costs remain a major barrier to its widespread adoption (Yang & Zou, 2016). One of the primary challenges is the high initial investment, coupled with the expenses incurred throughout the system's operational lifetime. Therefore, a comprehensive evaluation of the economic viability of building integrated photovoltaic systems is essential. Life Cycle Cost Analysis (LCCA), an economic assessment approach grounded in the principles of Life Cycle Assessment (LCA), provides a life-cycle perspective by accounting for all costs incurred over the entire lifespan of the BIPV system (Gholami et al., 2020). This includes capital, operational, maintenance, and replacement costs up to its end-of life, thereby offering a more accurate measure of long-term economic feasibility (Saridaki et al., 2019).

Considering the state of art in this field, the primary objective of this study is to estimate the energy generation potential of shaded BIPV systems integrated into the facades of low-rise and high-rise commercial buildings. This evaluation supports informed decision-making regarding the feasibility of adopting BIPV solutions in the early stages of building design, particularly with the aim of achieving net/nearly zero energy performance. The study proposes a methodology for quantifying the shading-induced losses through the assessment of reduced incident radiation and the corresponding decrease in annual PV energy yield. Furthermore, the study determines the extent to which these shaded BIPV systems contribute to offsetting the building's energy demand. This study also conducts LCA-based economic analysis to evaluate the feasibility of implementing PV integrated facades in low-rise and high-rise commercial buildings subjected to various shading conditions.

2. RESEARCH BACKGROUND

Building integrated photovoltaic (BIPV) systems offer dual functionality by integrating photovoltaics into the building envelope, serving both as an energy source and an architectural element (Kuhn et al., 2021). These systems have garnered significant attention in recent years. Shukla et al. (2018) examined the trend patterns and significance of BIPV applications in sustainable buildings across South Asian nations, focusing on the gradual integration of these systems as either a primary or alternative energy source in the region. The study emphasizes that although BIPV has significant potential in South Asia, there are challenges such as high initial costs and lack of awareness that need to be addressed for wider adoption. The concept of BIPV is innovative and still in its nascent stage in South Asia. Despite their cutting-edge nature, BIPV systems are infrequently implemented (Agathokleous & Kalogirou, 2020), mainly due to insufficient knowledge, awareness, and expertise. In India, although there is substantial potential for photovoltaic (PV) generation, the integration of these PV systems remains in its infancy due to a shortage of BIPV experts, insufficient knowledge and skills, policy constraints, and cost considerations (Reddy et al., 2020).

While building-applied photovoltaic (BAPV) systems offer advantages in terms of ease implementation for retrofitting existing buildings, Pillai et al. (2022) noted that BIPV systems present an ideal solution in cases of spatial limitations. In such cases, PV modules can be seamlessly integrated into facades, thereby increasing the potential PV implementable area, and enhancing photovoltaic electricity generation (Boccalatte et al., 2020). Brito et al. (2017) studied and discussed the relevance of facades and other vertical structures in solar PV generation. Similarly, Olajube et al. (2018) evaluated the performance of integrated PV at a university building in Malaysia by conducting simulations of various PV system variants and identified that Cadmium Telluride (CdTe) thin film modules yielded the highest energy output of about 1240MWh/year, resulting in a 53% reduction in electricity bills. However, the photovoltaic simulations in the study did not account for shading from nearby buildings. BIPV generation is generally influenced by factors such as PV orientation, tilt, geographic location, and local climatic conditions, including temperature and solar irradiance (Dai & Bai, 2020). Among these factors, shading is a critical determinant that influences its photovoltaic output and feasibility in urban environments (Sun et al., 2021). Partial shading resulting from surrounding elements such as trees and adjacent buildings can significantly affect the performance of photovoltaic systems, however, this impact has not been extensively examined (Calcabrini et al., 2021). Similarly, the efficiency of PV panels and their thermal performance also play a significant role. The PV design strategy necessitates that PV panels be positioned at their optimal tilt angle and orientation to harness maximum solar radiation.

Shading from nearby buildings and obstructions affects the irradiation on PV panels, resulting in varying irradiance levels across the modules of the PV array (Laamami et al., 2017). Consequently, the amount of electricity generated from the PV decreases. Even partial shading can affect power output due to the mismatch losses it causes in series-connected cells, thereby reducing system efficiency. Furthermore, shading can increase stress on shaded cells, leading to hotspots that can damage the cells and shorten the PV system's lifespan (Pendem & Mikkili, 2018). Understanding shading patterns facilitates better design and placement of PV systems. Additionally, accurate shading analysis aids in the financial assessment of BIPV installations, providing estimates of energy yields and return on investment (Zomer & Rüther, 2017). Optimal placement and design of PV systems, considering shading consequences, is therefore crucial for maximizing BIPV performance. However, cost remains a primary barrier to the adoption of PV systems, with BIPV facing additional challenges due to their higher installation costs.

Furthermore, Podder et al. (2021) conducted an economic feasibility analysis of a PV system installed on the rooftop of an academic building in Bangladesh. The study determined a payback period of 8.3 years and an internal rate of return of 120.3% for a 91kW rated system. In terms of installation type, grid-connected roof-mounted systems generally achieve the lowest Levelized Cost of Energy (LCOE) compared to other types of installations, ranging from 0.0491 USD/kWh to 0.0605 USD/kWh under a 6% discounted rate (Ludin et al., 2021). This suggests that roof-mounted systems are more cost-effective than other installation types, whether in low-rise or high-rise buildings. Meanwhile, the existing studies does not directly compare the cost-effectiveness of PV facades in low-rise versus high-rise buildings, and only suggests that PV systems, in general, are economically feasible achieving energy payback over time. Moreover, the economic viability depends on various factors such as location, system size, local incentives, and energy savings (Gholami et al., 2019). Consequently, a cost analysis specifically comparing low-rise and high-rise PV integrated facades is necessary to ascertain which configuration offers a shorter payback period.

Existing studies conducted in tropical climates, such as those in India, have performed life cycle cost analyses of rooftop solar panels, focusing on the improvements in energy consumption efficiency of buildings (Kumar et al., 2021); (Baqir & Channi, 2022). Ramanan et al. (2020) performed an economic feasibility analysis of grid-connected building integrated photovoltaic modules in Tamil Nadu, India. The study examined the performance of BIPV modules at various orientations and inclination angles, identifying east-facing facades as the optimal orientation for installing BIPV modules on facades. The findings indicate that grid-connected BIPV systems can be both economically viable and environmentally advantageous, provided that they are properly oriented and sized. Similarly, Shetty et al. (2021) investigated optimal tilt angles and various PV integration configurations on building facades to maximize energy production in conjunction with its economic feasibility analysis. While energy production is analysed extensively, the cost implications and performance impacts of shaded PV systems remain underexplored. A comprehensive integration of detailed shading analysis with economic feasibility assessments is essential to optimise both energy output and cost-effectiveness.

This study aims to evaluate the potential for photovoltaic electricity generation through PV integrated facades in representative models of commercial buildings in India, considering various shading scenarios. The novelty of the study lies in the assessment of net or nearly zero energy performance of shaded PV integrated facades across both low-rise and high-rise buildings, coupled with an economic feasibility evaluation through LCCA.

The research objectives of this study can be summarized as follows:

- To evaluate the impact of shading on the photovoltaic energy generation potential of BIPV systems through simulation-based scenarios;
- To explore the feasibility of achieving net-zero energy performance by buildings under shading, specifically in terms of meeting the building's energy demand;
- To assess the economic viability of shaded PV integrated facades for both low-rise and high-rise buildings through life-cycle cost analysis (LCCA).

The key contribution of the study is the development of a methodological framework that can be replicated for analysing the shading impact caused by nearby buildings on PV integrated facades of proposed low-rise or high-rise buildings, with a check on its economic feasibility and net-zero energy (NZE) compliance. The novelty of the proposed framework lies in its integrated approach to analysing BIPV energy generation under shading scenarios at the building level, taking into account building typologies (low-rise and high-rise) within a tropical-temperate climate context. Unlike existing studies, which often focus on single building types, rooftop systems, or generalized climate conditions, this framework offers a shading-sensitive assessment by combining building energy simulation with facade-level PV generation analysis. Furthermore, it incorporates irradiance-based shading evaluation, net-zero energy assessment, and life-cycle economic analysis, making it one of the few comprehensive methods tailored for real-world application. The replicable methodological framework developed for shaded BIPV systems provides practical guidance for architects, engineers and policymakers aiming to achieve net-zero energy buildings in urban tropical contexts.

3. METHODOLOGY

This study examines the feasibility and shading impact on BIPV energy generation in both low-rise and high-rise buildings within the tropical temperate climate zone of India. Initially, to assess building energy performance, building energy models for both low-rise and high-rise structures are developed and simulated using Design Builder software (Chang & Hsieh, 2020; Pawar & Kanade, 2018). The subsequent phase involves photovoltaic simulations, where PV integrated facades are modelled and simulated to determine annual PV energy generation. The east and west facades of the building model are configured as PV integrated facades for irradiation assessment and energy generation simulations. In this study, Rhinoceros software, along with its plugins Grasshopper and Ladybug, is employed, as these tools provide advanced PV simulations, shading pattern analysis, and irradiation assessment, surpassing other existing solar PV tools such as PVSyst and PVSol (Freitas et al., 2020). This is followed by the development of potential shading scenarios to evaluate the shading impact on PV integrated facades. Furthermore, BIPV energy generation on both facades is simulated under various shading scenarios, thereby determining the shaded PV energy generation. Under each shading scenario, both low-rise and high-rise building models are analysed to understand their generation potential under shading impact. The shaded PV energy generation is compared against the building's energy demand to assess the net-zero energy status of the building. In the final stage, the study evaluates the economic feasibility of implementing these shaded PV integrated facades in low-rise and high-rise buildings experiencing shading, through a LCCA approach. The overall methodological flow of the approach adopted in the study is illustrated in Figure 1.

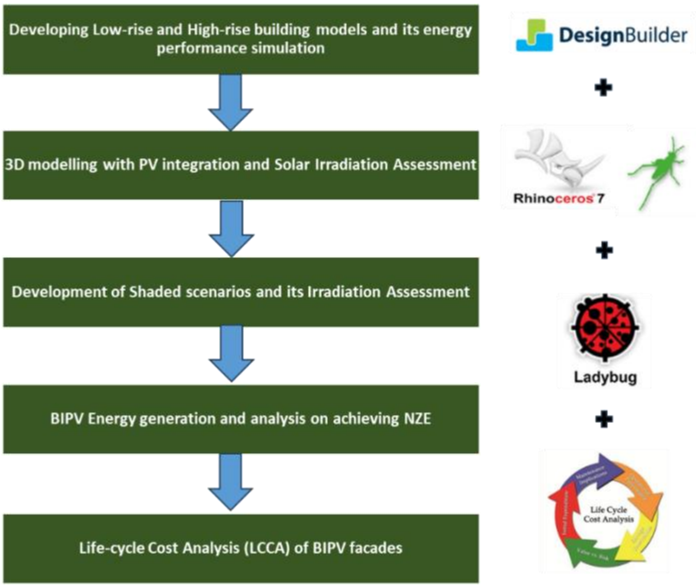


Figure 1: Methodology of the study.

The structured methodology proposed in the study is developed using a conceptual modelling approach, aimed at integrating technical simulation outcomes with sustainability objectives in PV integrated façade systems. Energy simulation serves as the core methodological tool in this study, employed to quantify façade-level PV performance, assess whole-building energy demand, and evaluate net-zero energy compliance. This directly informs the decision-support structure of the framework. The components of the methodological framework are derived from a synthesis of existing literature on building performance simulation and shading impact analysis, supported by simulation-based results generated using tools such as DesignBuilder and Ladybug in Rhino-Grasshopper (Ohene et al., 2022); (Freitas et al., 2020).

3.1 Building energy modelling and simulations

Both the low-rise and high-rise commercial building models are developed using DesignBuilder software, a dynamic simulation tool that offers a graphical user interface for the EnergyPlus simulation engine (DesignBuilder Software Ltd., 2009); (Crawley et al., 2000). For this analysis, weather data from Bangalore, India, the representative location for the temperate climate zone is utilized. The weather data file, generated by Energy Plus for this location, is downloaded for simulation runs (Katranuschkov et al., 2014). The reference building models, representing low-rise and high-rise commercial buildings in India derived in Bhatnagar et al. (2019) are employed as baseline models in this research. The low-rise and high-rise commercial building models are developed, with the parameters as tabulated in Table 1.

Table 1: Data input parameters for building energy modelling.

Parameters	Low-rise building	High-rise building
No. of floors	3	9
Length	54 m	90 m
Width	19 m	39 m
Height	11.8 m	35 m
Window-U value	2.13	2.05
Wall U-value	1.17	1.46
Roof U-value	0.4	0.46
Lighting power density	7.7 W/m^2	8.32 W/m^2
HVAC System	VRF; Duct able constant volume AHU	Screw chiller, VAV AHU
System COP	3.49	5.6

These models, along with the materials used, their thermal properties, and other significant parameters, are developed based on the values reported by Bhatnagar et al. (2019). Both building types assume an occupancy of 14 m^2 per person and a plug load of 16.14 W/m^2. The low-rise and high-rise building energy models are developed in DesignBuilder, as depicted in Figure 2. Initially, the baseline building models are generated without photovoltaics, with the building energy demand reliant on the external grid.

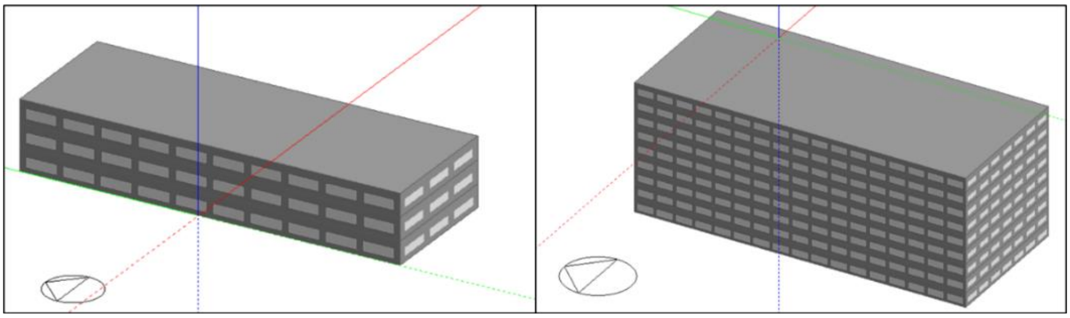


Figure 2: Low-rise and high-rise baseline building models.

Since the concept of NZEB involves achieving a net-zero energy balance over a year, the building models are simulated to assess their annual energy consumption. The energy simulations provide insights into the energy usage associated with the overall functioning of the buildings, including cooling, lighting, and other energy uses. In this study, the annual building energy consumption is simulated for both the baseline models of low-rise and high-rise buildings.

3.2 Shaded BIPV energy simulations

Both the low-rise and high-rise commercial building models are modelled with photovoltaic integrated facades for its potential renewable energy generation. For PV simulations, the computational tool Rhinoceros, along with its plugins Grasshopper (GH) and Ladybug (LB), is employed to integrate parametric modelling with comprehensive solar analysis (Robert McNeel & Associates, 2019). Rhinoceros is a 3D CAD software that facilitates to develop complex 3D models or other geometries and offers numerous plugins for conducting desired PV simulations (Jing Yang et al., 2024); (Zou et al., 2025). Grasshopper serves as a graphical user interface that integrates with Rhino's

3D modelling tools, enabling automated, parameter-driven generation of project elements and aids in quick virtual modelling (de Sousa Freitas et al., 2019). The Ladybug plugin, which depends on Energy Plus, is utilized for energy simulations based on the geometry model created in Rhino, Grasshopper, and the Energy Plus Weather (EPW) file for that location (Roudsari & Pak, 2013). Ladybug tools provide a sun path diagram to help understand the sun's position throughout the year and include components for computing incident solar radiation. Additionally, Ladybug features specific photovoltaic components that simulate the detailed performance of PV systems.

For both the low-rise and high-rise building energy models, the representative building models are developed in Rhino with dimension inputs provided through the Grasshopper user interface. BIPV systems are modelled on facades by inputting east and west facades into the PV surface input of the LB photovoltaic components. Consequently, BIPV energy generation is simulated due to PV integration on the east and west facades of the building model.

Ladybug tools and components enable detailed analysis of PV generation under diverse shading scenarios. The PV system is modelled in Ladybug with consistent parameters across both low-rise and high-rise scenarios to ensure comparability. The façade surface is fully utilized for PV integration (100%), of which 90% is accounted as active module area. Mismatch losses are partially accounted for through the DC-to-AC derate factor (with a static 2% loss), however, detailed string-level mismatch due to partial shading or inverter clipping is not explicitly modelled. In this study, PV system parameters are kept constant across all scenarios to ensure that performance differences arose solely from the influence of shading. The PV simulation input parameters (Ladybug Tools., 2025) and modelling assumptions adopted in this study are summarised in Table 2.

Table 2: Key input parameters for PV integrated façade simulations.

Parameter	**Value/ Design consideration**
Module technology	Mono-crystalline silicon BIPV
Module efficiency	15%
System Capacity	Low-rise: 86.02 kW; High-rise: 425.25 kW
PV integrated façade area	Low-rise: 637.2 m²; High-rise: 3,150 m² (individually for east and west)
Array orientation/ Tilt	Fixed tilt, 90° (vertical façade), East & west orientations
DC-to-AC derate factor	0.85
Temperature coefficient	–0.5%/°C

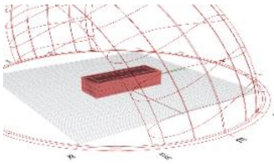
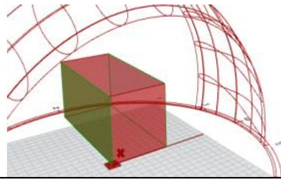
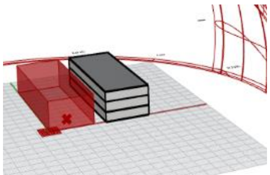
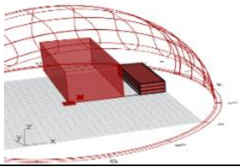
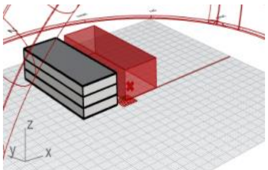
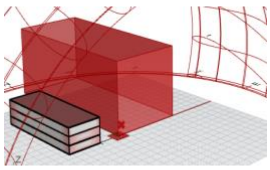
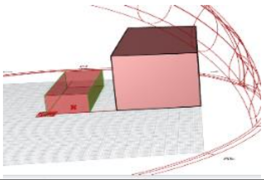
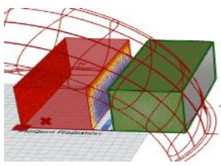
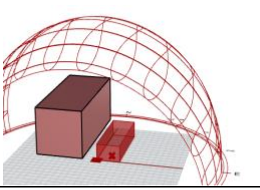
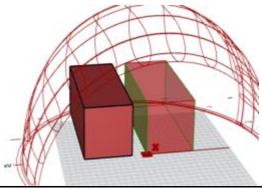
In this study, eight potential shading scenarios are generated for the building model, considering possible shading from adjacent low-rise or high-rise buildings. These shading scenarios are developed in accordance with building regulations and standards. These shading possibilities are formulated as scenarios for analysis, as depicted below in Table 3.

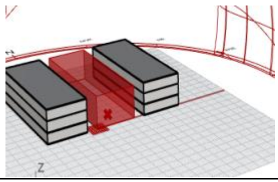
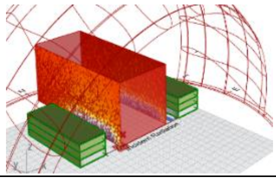
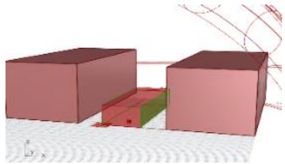
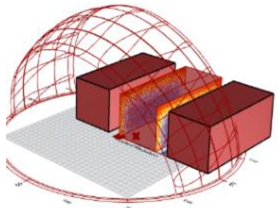
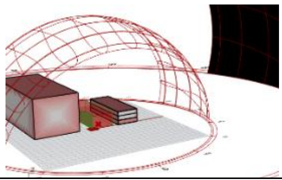
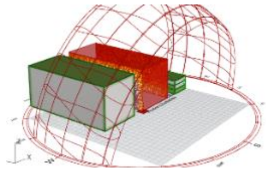
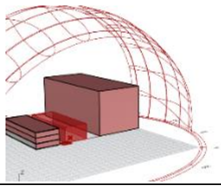
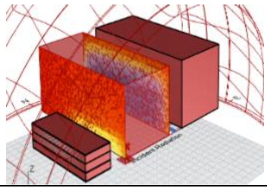
The nearby buildings that contribute to shading on Building Integrated Photovoltaic (BIPV) facades are modelled based on the offsets permitted by building code regulations and permits (Bangalore Development Authority., 2007). These regulations specify the minimum distance that must be maintained from the building on the front, rear, and sides, for any nearby construction or structure. For shaded PV generation, models of nearby buildings that contribute to shading are incorporated as shading context, enabling analysis of PV generation on shaded facades. In this context, models of nearby low-rise and high-rise buildings are developed based on allowable offset specifications. For the analysis of low-rise building models with a height of 11 metres, a minimum offset distance of 5 metres is provided to the shading context building. Conversely, for the analysis of high-rise building models with a height of 35 metres, a minimum offset distance of 12 metres is provided. In each of these shading scenarios, BIPV energy generation is simulated on east and west facades to assess the loss of solar irradiation and the consequent reduction in energy generation due to shading. A total of nine simulation scenarios is evaluated: one without shading (i.e. unshaded) and eight scenarios with shading on east and west, designed for both low-rise (LR) and high-rise (HR) building typologies. The “Unshaded” scenario serves as a baseline or reference point for comparing each of the shading scenarios. The model orientations of the unshaded reference case and shading scenarios developed for low-rise and high-rise are as presented in Table 4.

Table 3: Shading scenarios developed for east and west facades.

Shading Scenario	**Shading on East façade**	**Shading on West façade**
Scenario-1	Low-rise building	No shading
Scenario-2	No shading	Low-rise building
Scenario-3	High-rise building	No shading
Scenario-4	No shading	High-rise building
Scenario-5	Low-rise building	Low-rise building
Scenario-6	High-rise building	High-rise building
Scenario-7	Low-rise building	High-rise building
Scenario-8	High-rise building	Low-rise building

Table 4: Model orientations of the unshaded reference case and shading scenarios for low-rise and high-rise.

Sl.No.	**Shading Scenarios**	**Scenario Description**	**3D Model Orientation of LR**	**3D Model Orientation of HR**
1	Unshaded	No shading on both sides		
2	Scenario-1	LR on East; No shading on West		
3	Scenario-2	LR on West; No shading on East		
4	Scenario-3	HR on East; No shading on West		
5	Scenario-4	HR on West; No shading on East		

6	Scenario-5	Both sides- LR		
7	Scenario-6	Both sides- HR		
8	Scenario-7	LR on East; HR on West		
9	Scenario-8	HR on East; LR on West		

In this study, solar irradiation analysis is initially performed for both low-rise and high-rise building models without any nearby shading. Subsequently, the analysis is extended to various potential shading scenarios, where the irradiation on PV integrated facades is simulated to evaluate the loss of incident radiation caused due to shading. Additionally, along with the irradiation analysis, BIPV energy generation is simulated with the shading context assumed in each shading scenario, to quantify the impact of shading on overall energy output.

3.3 Life Cycle Cost Analysis (LCCA) of PV integrated facades

The study evaluates the life cycle costs of BIPV facades that enables in realizing the feasibility of their implementation. Life Cycle Cost Analysis (LCCA), an economic assessment approach grounded in the principles of Life Cycle Assessment (LCA) based on the standardized frameworks ISO 14040 and ISO14044, provides a life-cycle perspective by accounting for all costs incurred over the entire lifespan of the BIPV system (*ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework*, 2006); (*ISO 14044:2006 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines*, 2006). LCCA is a systematic method in accordance with ISO 15686-5, which provides guidance on service life planning and economic evaluation. This approach accounts for all relevant costs incurred throughout the system lifecycle including initial investment, operation and maintenance, energy savings, replacement and end-of-life disposal costs (*ISO 15686-5:2017 - Buildings and Constructed Assets — Service Life Planning — Part 5: Life-Cycle Costing*, 2017). By integrating both cost and performance considerations over time, this method enables a comprehensive understanding of the economic viability of BIPV façade systems.

The components of BIPV life cycle cost analysis include all the cost expenses and cost savings involved at different stages of its life-time, including: initial cost of PV integrated facades, cost of operating and maintaining the photovoltaic integration over their lifetime, annual energy cost savings during its utility phase, inverter replacement costs every 10 years and salvage value cost at its end-of-life phase, as shown in Figure 3.

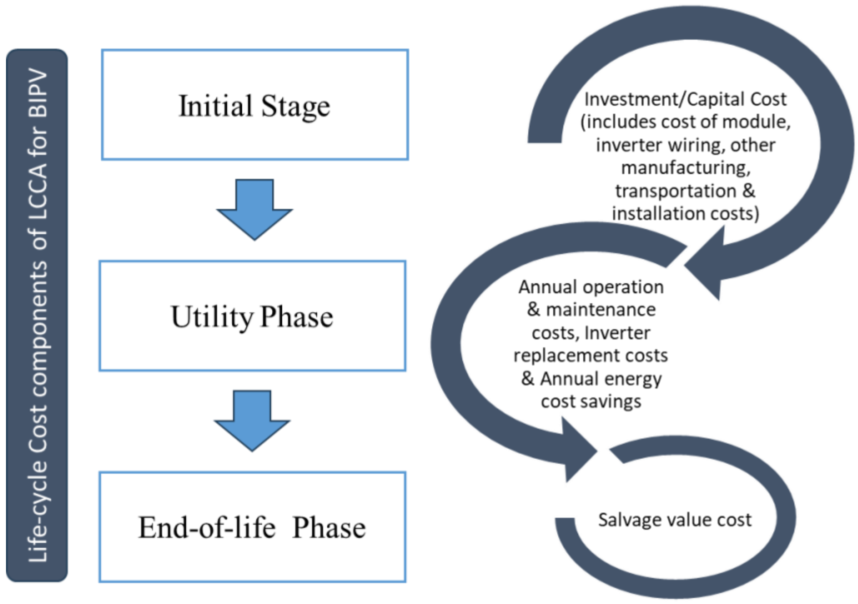


Figure 3: Life-cycle cost analysis (LCCA) components for BIPV.

The economic feasibility of the PV integrated facades was evaluated using LCCA, incorporating key financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Simple Payback Period (SPP), as per the standard LCCA methodology. The cost assumptions and parameters used in the analysis are summarized in Table 5. These components of LCCA are calculated based on the relevant codes and building integrated photovoltaics cost references. In 2010, Central Electricity Regularity Commission (CERC) has implemented the BIPV feed-in tariff of INR 17.9/kWh (Reddy et al., 2020).The calculations consider a PV system lifetime of 30 years, with a discount rate of 3%, annual operation and maintenance costs every year and inverter replacement cost every 10 years. The cash inflows and cash outflows are calculated in Microsoft excel, with salvage cost considered at the end of system lifetime.

Table 5: Cost component calculation parameters for LCCA of BIPV.

Components of LCCA	**Modelling Calculation parameters**	**BIPV Cost References**
Capital cost/ Initial Investment (INR)	(For facades, 450 Euro/m^2)	(Gholami & Røstvik, 2021)
O&M cost (INR)	USD 9.13 per kW per year	(Tidball et al., 2010); (Corti et al., 2020)
Capital cost of Inverter (INR/kW)	8400 INR/KW	(Shankar & Bukya, 2023)
Inverter Replacement cost (INR)	10% replacement of Inverter cost every 10 years	(Gholami & Røstvik, 2021); (Rethnam & Thomas, 2023)
Salvage value (INR)	USD 0.32 per Wattage	(Rethnam & Thomas, 2023); (Mccabe, 2012)
Discount rate (%)	3%	(Gholami & Røstvik, 2021)
Energy degradation (%)	0.50%	(Gholami & Røstvik, 2021)
Energy Cost/Electricity Tariff (INR/kWh)	17.9 INR/kWh	(Reddy et al., 2020)

The assessment of life-cycle costs involves computation of different cost metrics such as SPP, NPV and IRR, which are commonly used in economic evaluations of energy systems (Fuller & Petersen, 1996); (Rethnam & Thomas, 2023). Simple payback period is a metric which enables to determine how long it will take for an investment to become profitable, based on the cash inflows it generates, and is evaluated as given in the equation (1).

$$\text{Simple payback period (SPP)= Initial investment cost /Annual cash inflows} \quad (1)$$

SPP does not take into account the time value of money. While there is a similar cost metric termed, discounted payback period (DPP) that represents the time needed to recover initial investment, considering the time value of money using a discount rate. The net present value (NPV) is defined as the sum of the present values of incoming and outgoing cash flows over the system life-time. NPV examines the net economic benefits as it determines the profitability of an investment, with the evaluation of all costs and benefits of that project. NPV is sensitive to the future cash inflow reliability that an investment will yield. The project becomes profitable, if it yields a positive NPV value. NPV is calculated by the equation (2). below, where CF is the net cash flow occurring at the end of the year (t = 0, 1…. n), n is the project's lifetime in years, and DR is the discount rate.

$$NPV = \Sigma CF/ (1+DR)^t; \ t = 0 \text{ to } n \quad (2)$$

The Internal Rate of Return (IRR) is the discount rate at which the NPV of all cash flows from a project or investment equals zero and is calculated as given in equation (3).

When NPV =0 and IRR= DR,

$$0= \Sigma CF/ (1+IRR)^t \quad (3)$$

The project with highest IRR value is considered as the most economical and profitable investment, while an IRR below the required rate of return suggests that the project is not viable. IRR can also be used as a financial metric to rank different project scenarios, of which the highest IRR scenario would be considered as the most desirable one. With the evaluation of these time-based financial metrics, the study enables in determining the economic viability of these PV integrated facades, in low-rise and high-rise commercial buildings, under different shading scenarios.

4. RESULTS AND DISCUSSION

4.1 Building energy simulations

The energy consumption of the low-rise and high-rise building models are simulated to analyse their annual energy demand. The annual energy consumption of building is simulated using DesignBuilder software, which estimates the overall electricity consumption required for the building’s operation, including all end-use utilities. This reflects the total energy demand that a net/nearly zero energy building must ideally meet or nearly offset through on-site energy generation. Based on the simulated annual energy consumption and respective floor area, energy use intensity values (in kWh/m^2/year) are calculated for both low-rise and high-rise buildings, as presented in Table 6.

Table 6: Annual building energy demand.

Sl.No.	Building Type	Energy use Intensity (kWh/m^2/year)	Annual building energy consumption (kWh)
1	Low-rise building	96.09	295783.6
2	High-rise building	160.02	5055075

High-rise buildings consume significantly more energy due to the obvious reasons of increased floor area, number of occupants and other system requirements in HVAC and lightening. Comparing energy performance intensities, despite larger area and vertical design, these buildings exhibit higher Energy Performance Index (EPI), suggesting relatively less energy efficiency per unit area than the low-rise. Generally, commercial buildings in India have an EPI between 200-400 kWh/m^2/year (Shivhare & Pandey, 2017). However, energy-conscious buildings can achieve EPIs of 100-150 kWh/m^2/year, with a national benchmark of 180 kWh/m^2/year for Energy Conservation Building Code (ECBC) compliance (Imran K and Rajesh Shetty, 2023). Therefore, the representative low-rise and high-rise building models utilized in this study are indicative of energy-efficient building designs.

4.2 Shading impact on BIPV energy generation

To assess the impact of shading on the irradiation of a PV integrated façade surface and its subsequent photovoltaic performance, simulations are performed using location-specific EPW weather data, through Ladybug tools within the Grasshopper-Rhino environment. The building models are initially simulated without any shading and termed as its 'Unshaded' case. Both the low-rise and high-rise building models are then subjected to different shading scenarios developed, indicating a loss of incident radiation on PV integrated facades. The irradiation analysis in both low-rise and high-rise in its 'Unshaded' case yielded almost the same value as the irradiation on a specific location would be the same with the influencing factors being fixed. While, in each of these shading scenarios, the nearby building becomes the shading context that act or serve as a shading element, obstructing incident radiation on PV facades, leading to a loss of incident radiation on the shaded area of facades. The incident radiation loss on PV integrated facades in low-rise and high-rise commercial buildings due to shading in each scenario, compared to that of unshaded scenario, is illustrated in Figure 4.

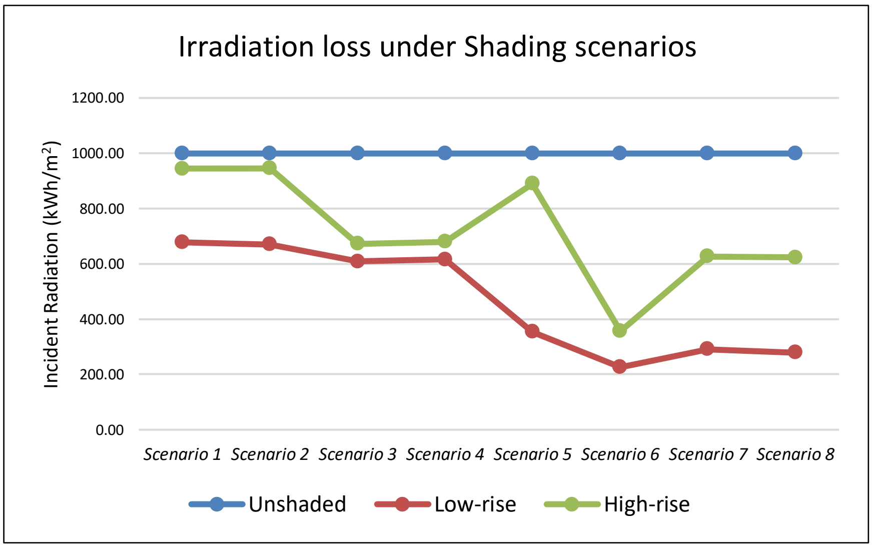


Figure 4: Irradiation loss due to shading in low-rise and high-rise buildings.

The low-rise building model, analysed for solar irradiation, yields a total irradiation value of 998.98 kWh/m² for the entire façade area, without any shading. Subsequently, these building models are simulated under the developed shading scenarios to assess the loss of incident radiation. The impact of shading on photovoltaic performance is evaluated by comparing the reduction in energy generation to the 'Unshaded' scenario. Further, the low-rise model is simulated for BIPV generation on the east and west facades, without shading, as a baseline comparison, resulting in a photovoltaic generation of 114,198.8 kWh/year.

While, for high-rise building model, the total irradiation the PV facades received annually accounts to 999.02 kWh/m^2. Further, the BIPV generation from both facades simulated without any shading, that considered as an 'Unshaded' scenario in high-rises, yielded a value of 564542.33 kWh annually. This acts as a base-line scenario that allows to be compared with the irradiation loss under each of the shading scenarios. In the worst-case scenario, 'Scenario-6', where the building model is shaded by high-rise buildings on both sides, the irradiance loss is 77.4% for low-rise buildings and 64.34% for high-rise buildings. Shading from adjacent buildings reduces the irradiation received by facades, thereby affecting PV generation.

To reflect temporal variation in solar availability throughout the year, a seasonal analysis of incident solar radiation is conducted for the relatively most optimal shading scenario- Scenario-2. The irradiance values are analysed over four seasons: winter, summer, monsoon, and post-monsoon, for both building typologies (Magare et al., 2016). The winter starts in the beginning of November and continues until the end of February. Summer starts from March and continues till the end of June. The period from July to September is the monsoon and October to beginning of November constitutes the post-monsoon season. Based on the seasonal analysis conducted for the better shading scenario- Scenario-2, distinct variations in incident solar irradiance are observed across different times of the year for both low-rise and high-rise buildings, as illustrated in Figure 5.

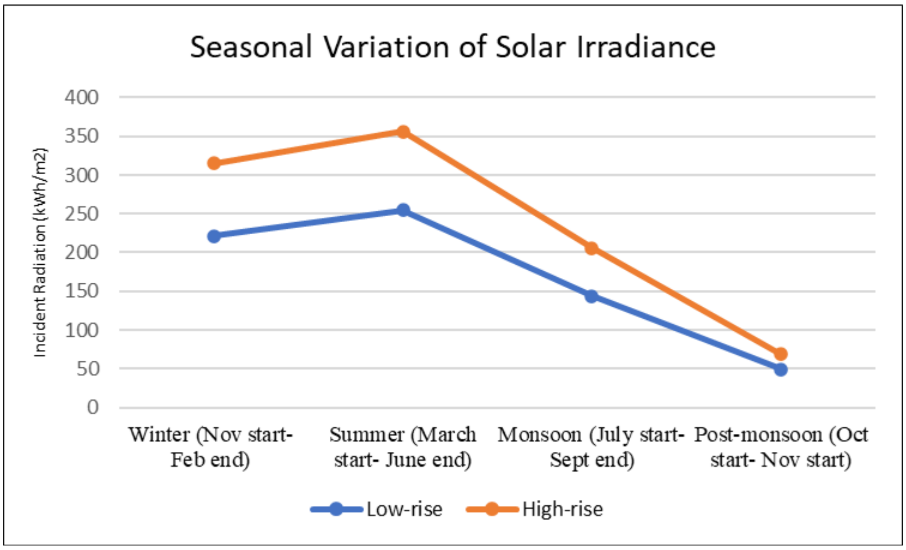


Figure 5: Seasonal variation of solar irradiance in low-rise and high-rise.

The results reveal that the highest irradiance occurs during summer (March to June), followed by winter, with significantly lower values during the monsoon and post-monsoon periods. High-rise buildings consistently receive higher seasonal irradiance due to reduced shading from surrounding structures. This seasonal comparison, highlights the importance of factoring in dynamic temporal trends during the design phase of BIPV façades, especially for energy yield prediction and system sizing.

As a consequence of shading, the loss of solar irradiation incident on the PV integrated facades leads to a decrease in its photovoltaic electricity generation. Under each of these shading scenarios, there is a significant drop in BIPV energy generation due to the shading on the PV integrated facade. The PV energy generation on the east and west façades of both low-rise and high-rise building models, across eight shading scenarios, is depicted in Figure 6 and Figure 7, respectively.

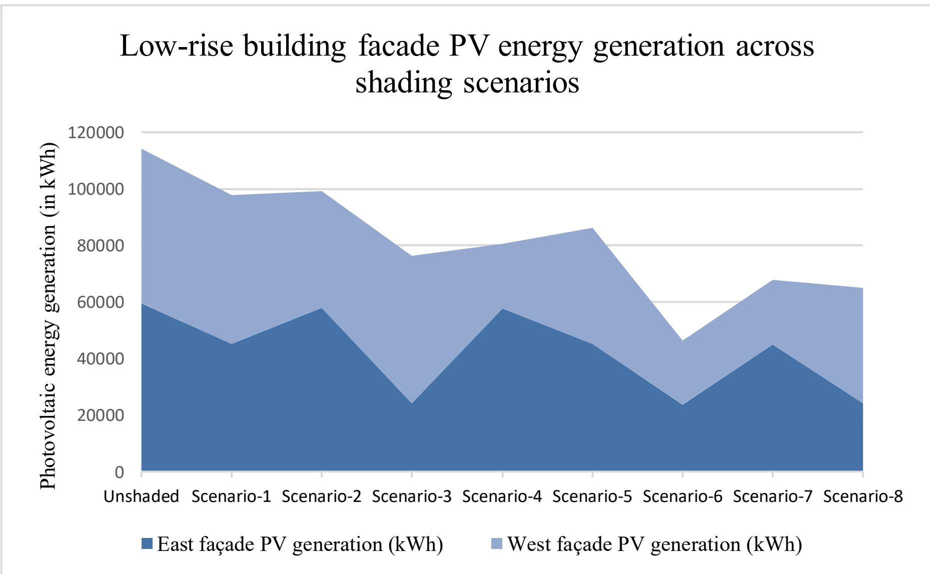


Figure 6: Photovoltaic energy generation across shading scenarios in low-rise buildings.

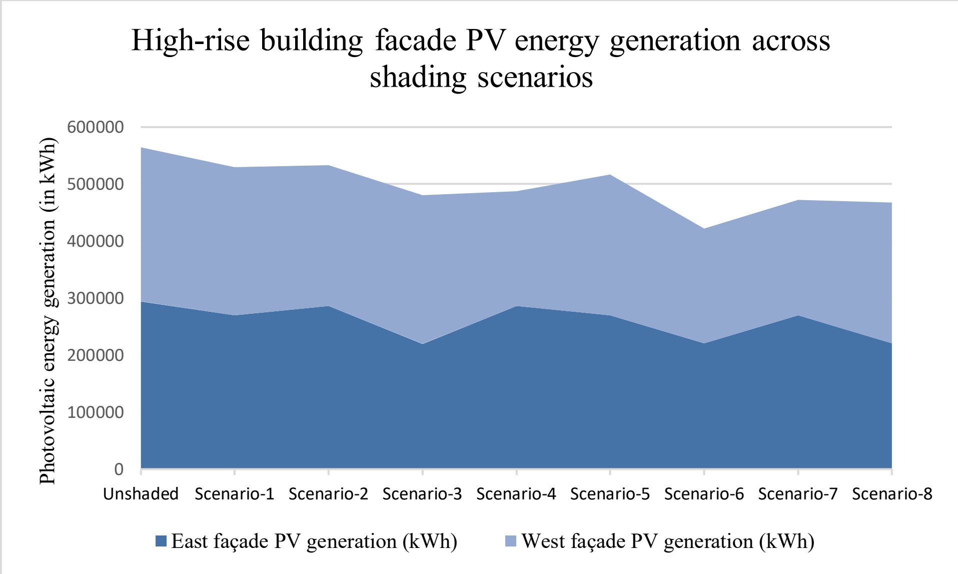


Figure 7: Photovoltaic energy generation across shading scenarios in high-rise buildings.

In the low-rise model, the total PV energy generation experiences a significant decline across most shading scenarios when compared to the unshaded scenario. Notably, Scenario-6 and Scenario-8 result in the greatest energy loss, primarily due to substantial reductions on the east façade. In contrast, Scenario-2 and Scenario-1 maintains generation levels close to the unshaded condition, indicating minimal impact on both façades. These findings underscore that east-facing façades are more susceptible to shading effects in low-rise buildings, as evidenced by their larger variance across scenarios. West-facing façades exhibit relatively moderate and consistent performance, although substantial drops are observed in Scenarios 4–6, likely due to obstruction patterns aligned with afternoon sun paths.

The high-rise model exhibits greater resilience to shading effects, with more stable PV generation across scenarios. While, Scenario 6 shows noticeable declines in energy generation, though, the magnitude of loss is relatively smaller compared to the low-rise case. The broader vertical extent and elevated positioning of high-rise façades likely reduce the degree of shading impact from surrounding elements.

The radar plot depicted in Figure 8 illustrates the comparative impact of eight shading scenarios on PV energy generation performance for both low-rise and high-rise building models. The results are normalized against the unshaded scenario, which serves as the benchmark at 100%.

Scenario-1 and Scenario-2 are identified as the most favourable shading conditions for both building types, retaining over 85% of the PV generation potential. In contrast, Scenario-6 exhibits the most severe energy losses, with low-rise buildings experiencing a 40% reduction compared to the baseline, highlighting their vulnerability to certain shading configurations. High-rise buildings, however, retain approximately 70% of their energy potential even under the most obstructive scenarios, indicating their superior resilience to facade-level shading.

The analysis of the plot demonstrates that the high-rise building consistently maintains photovoltaic performance across most scenarios, with values generally exceeding 70% of the baseline generation. In contrast, the low-rise building exhibits significantly greater sensitivity to shading, with several scenarios resulting in performance falling below 50% of the unshaded baseline. This facilitates an effective visual ranking of shading scenarios based on relative energy loss, emphasizing the importance of building height and design in mitigating the adverse impacts of urban shading on BIPV performance.

The study further investigates the net/ nearly zero energy potential of low-rise and high-rise buildings. Under each scenario, the total PV energy generation from both facades is compared with the annual energy consumption of the building. This is to determine the percentage of building energy demand met or offset by PV generation from the facades. In this study, the percentage of building energy demand offset or covered by the renewable PV generation is defined as the Net-Zero Energy (NZE) percentage. Net-Zero energy percentage (NZE%) of a building is calculated by the given equation (4).

$$\text{Net-Zero Energy (NZE) \%} = (\text{Annual PV energy generation} / \text{Annual Building energy demand}) \times 100 \quad (4)$$

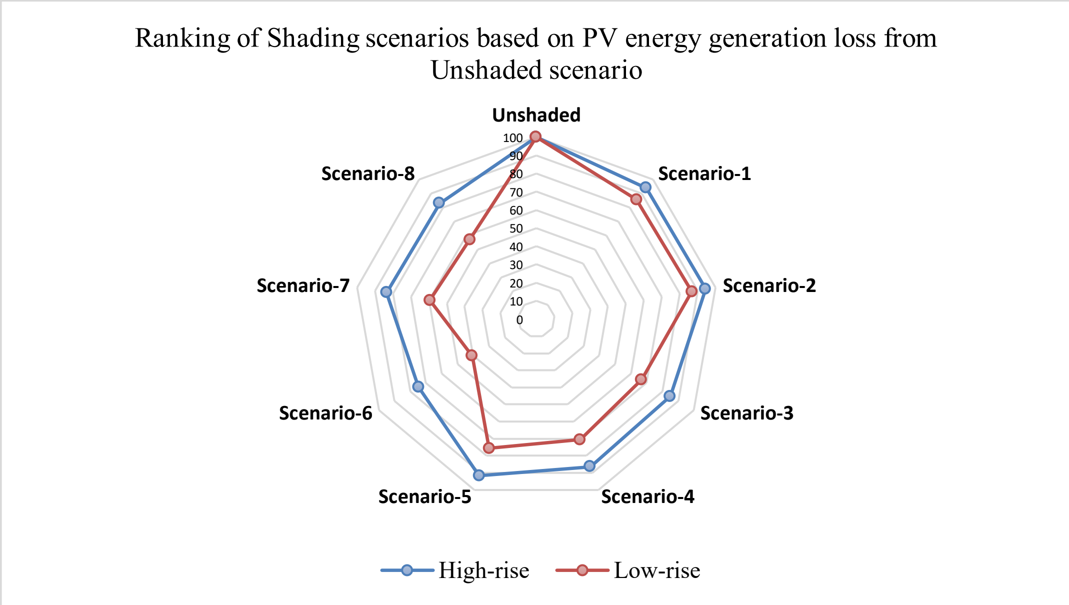


Figure 8: Relative PV generation across shading scenarios in low-rise and high-rise buildings.

The metric NZE% is introduced as a measure defined to represent the ratio of annual photovoltaic (PV) generation to the annual energy demand of a building. A value of 100% indicates complete demand coverage, values below 100% indicate partial coverage, and values above 100% indicate a net positive building (Gergely et al., 2025). This metric is conceptually consistent with similar NZEB indicators used in the literature (Kim et al., 2019; Madathil et al., 2021; Rethnam & Thomas, 2023).This formulation provides a transparent means of quantifying a building's net/nearly zero energy performance under different façade PV scenarios. The net/nearly zero energy potential of low-rise and high-rise buildings under each of the shading scenarios, expressed in NZE%, are as given in Figure 9 and Figure 10.

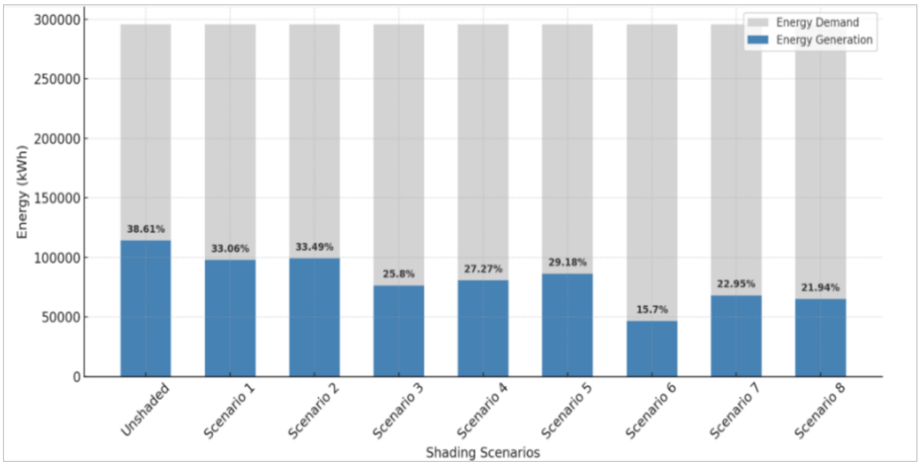


Figure 9: Net Zero Energy (NZE) percentage of shaded low-rise buildings.

The results indicate a substantial reduction in Net Zero Energy (NZE) performance under various shading scenarios. In the unshaded scenario of low-rise buildings, the PV system is able to meet 38.61% of the building's total energy demand. Scenarios with one-sided shading due to low-rise obstructions, as observed in Scenarios 1 and 2 showed moderate reductions, with NZE percentages of 33.06% and 33.49%, respectively. Scenarios-3,5,7 and 8 form a mid-range group, showing varying degrees of shading impact. However, all shaded scenarios demonstrate a significant decrease in energy generation. Notably, Scenario 6, characterized by high-rise obstructions on both the east and west facades, yields the lowest NZE performance at 15.7%, highlighting the critical importance of unobstructed solar access for façade-integrated PV systems. These findings underscore that for low-rise buildings in dense urban environments, minimizing façade shading—particularly from adjacent high-rise constructions—is essential for optimising PV performance.

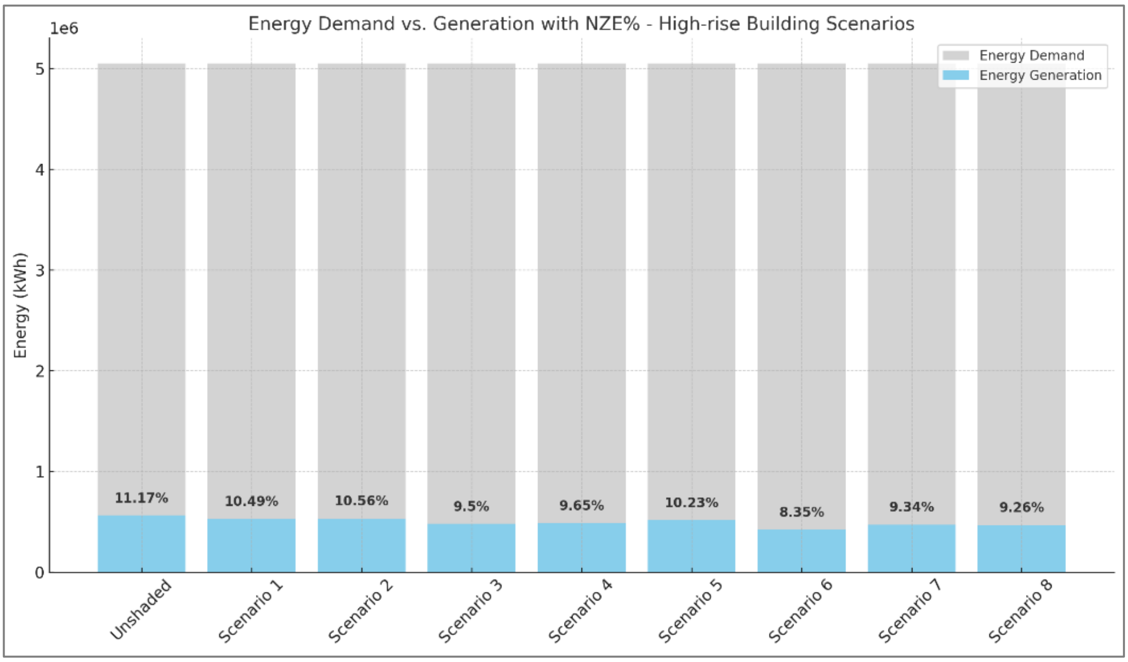


Figure 10: Net Zero Energy (NZE) percentage of shaded high-rise buildings.

The analysis of high-rise (HR) building scenarios under different shading conditions reveals a consistent decline in Net Zero Energy (NZE) performance as shading increases. The unshaded case achieves the highest NZE percentage of 11.17%, serving as the benchmark. The shading in Scenario-1 and Scenario-2 results in a marginal decrease to 10.49% and 10.56%, respectively, indicating a moderate impact likely due to partial obstruction. The remaining scenarios exhibit further reductions in NZE performance, reflecting greater hindrance to solar exposure. Notably, Scenario-6 results in the lowest NZE percentage (8.35%), emphasizing the significant adverse impact of extensive high-rise shading.

These findings underscore the importance of shading-aware design considerations in high-rise urban contexts. Even minor increases in obstruction can lead to significant declines in renewable energy contribution, thereby reducing the building's potential to achieve net-zero energy (NZE) status. Strategic planning of building orientation, spacing, and PV integration must therefore prioritize minimizing shading to enhance energy self-sufficiency in dense urban environments.

4.3 Life Cycle Cost Analysis (LCCA) of PV integrated facades

For the LCCA analysis, both the cash inflows and outflows of integrated PV system are computed throughout the system lifetime. The cash inflows are calculated based on the annual energy generation and applicable electricity tariff, while the cash outflows include the initial investment cost, replacement costs, and the salvage value accounted for at the end of the system's lifetime. The study assumed a PV system lifetime of 30 years with annual service costs every year and inverter replacement cost every 10 years. Salvage value cost is considered at the end of system lifetime. Among the various cost metrics, simple payback period (SPP) provides a rapid assessment of the cost-effectiveness of a project by relating the initial investment to the anticipated energy cost savings. SPP calculated for low-rise and high-rise buildings are compared under developed shading scenarios, as shown in Figure 11.

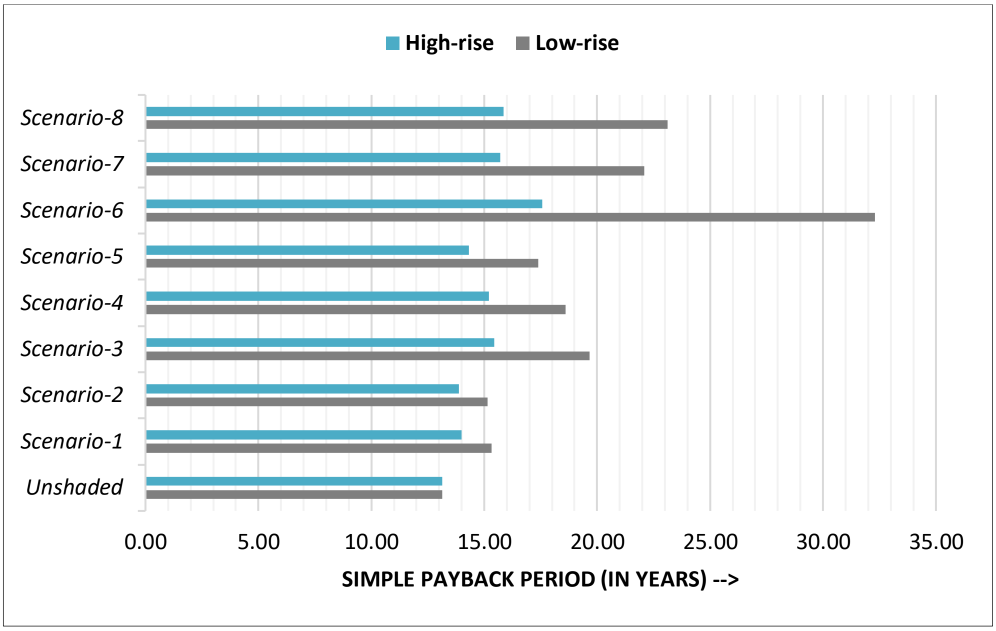


Figure 11: Simple payback period of BIPV facades in low-rise and high-rise buildings.

High-rise buildings yielded shorter payback periods compared to low-rise buildings across all scenarios. These high-rises recovered the total investment cost, within 10-20 years, with maximum payback of 15 years in all the scenarios, except the worst shading scenario of 'Scenario-6' in which the payback is achieved in 18 years.

While, low-rise buildings indicate poor economic performance, in Scenario-7 and Scenario-8, with significantly longer payback periods of more than 20 years. Additionally, in the worst shading scenario 'Scenario-6' with PV facades being subjected to shading due to high-rises on both the sides, payback period exceeds the system lifetime of 30 years. Thus, implementing PV integrated facades on a low-rise with shading conditions of 'Scenario-6' indicates a financial loss. Longer payback periods of low-rises can be attributed to severe shading losses with less solar exposure and lower energy savings.

By incorporating NPV into the LCA-based economic benefit analysis of BIPV investments in this study, the time value of money is also put into consideration to produce more meaningful analysis results and then identifying the profitable ones among different investment scenarios. NPV determines the investment feasibility by comparing the present value of future cash inflows with the initial investment cost. The NPV comparison of low-rise and high-rise commercial buildings, across shading scenarios, is as given in Figure 12. Unshaded scenarios provide highest profitability for both building types. Low-rise buildings suffer loses with negative NPV values in scenarios, Scenario-3, 4, 6, 7 and 8. While, high-rise buildings remain profitable with positive NPV values in all scenarios, but shows a decline in NPV as shading increases.

Internal rate of return (IRR) calculations enabled to compare the profitability of these investment shading scenarios. While low-rise buildings become economically not feasible with negative NPV values and IRR less than discount rate, in most of the shading scenarios, high-rise buildings become mostly good profitable investment options with IRR greater than discount rate across shading scenarios. Unshaded scenario has the highest IRR value indicating the most profitable option, for both building types, while among shading scenarios, Scenario- 1 and 2 are relatively the best investment projects.

While Scenarios-1, 2, and 5 represent profitable investments in low-rise buildings, all high-rise shading scenarios demonstrate economic feasibility, indicating strong investment resilience. Scenarios-1 and 2 emerge as the most reliable and robust options under shading conditions, offering up to 50-54% of the maximum NPV in low-rise buildings and retaining over 77% of the maximum NPV in high-rise buildings.

The LCCA results reveal that the NPV of building integrated photovoltaic system is 9964308.12 INR in low-rise buildings and 4,92,58,495.97 INR in high-rise buildings with an IRR of 6%. In its Unshaded scenario, the SPP of the system comes to 13 years and DPP to 20 years. The unshaded conditions yielded the shortest payback for both building types. This reinforces the impact of shading on financial viability of BIPV systems.

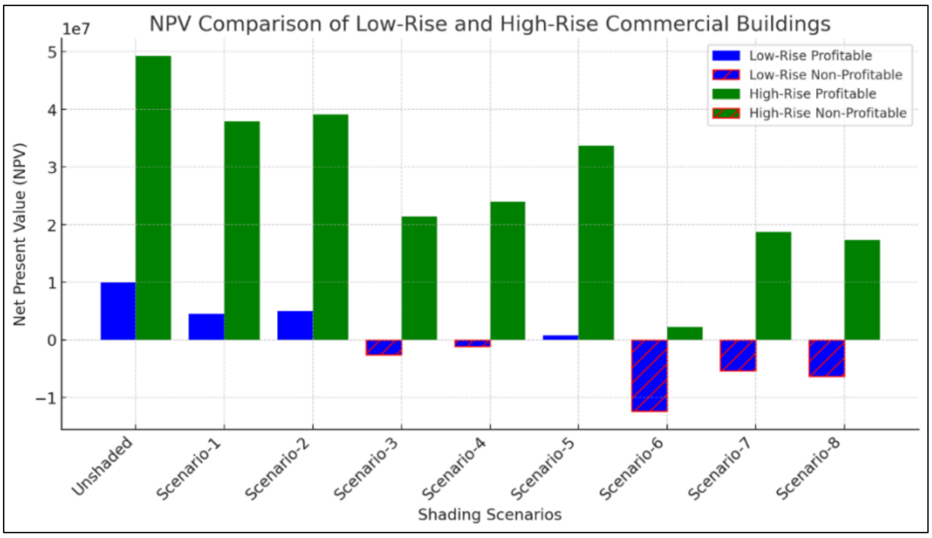


Figure 12: NPV comparison of low-rise and high-rise commercial buildings.

4.4 Validation through literature-based case studies and proposed pilot deployment

The findings of the study are validated with relevant case-studies for low-rise and high-rise buildings (*Indian BIPV Report 2022: Status and Roadmap - Solarchitecture*, 2022). Although the study does not incorporate real-time monitored data, findings are consistent with trends reported in existing literature. For, low-rise commercial building, the administrative building covered with high-efficiency double glass semi-transparent BIPV facades, is considered, as shown in Figure 13. The measured annual PV energy generation is estimated to be 17,000 kWh, transforming the building into a low-energy building. The building generates 50% of the building energy requirement, which indicates the building achieves half of net-zero energy status with its PV integrated facades. The payback time of these PV integrated facades covering an active cladding area of 92.9 square metres is 4.3 years.

(a) (b)

Figure 13: Low-rise and high-rise case-study buildings (a) Ponnore group. Source: Top Sun (b)CTRLS BIPV façade Source: U-Solar.

For high-rise commercial building, CTRLS data centre building with the integration of BIPV glazed modules is considered. The centre has the largest building integrated vertical solar PV system, with the active cladding surface area of about 4784.97 m^2. The active façade area is about 7-8 times of that of the roof area. The measured PV energy generation is estimated to be 5,93,014 kWh per year. The report (Corti & Bonomo, 2022) indicates high energy demand of the datacentre, that the self-consumption rate is 100%, which means that the entire PV energy generated is utilized. However, only 2% of the building energy demand is met by the generated renewable energy. Despite of the huge PV integrated façade area and potential energy generation, the building does not achieve net/nearly-zero energy compliance, due to its extensive building energy demand. The system payback time is 4.3 years, which is less with the investment consideration involved for larger PV façade system and PV area.

The contrasting results of the case studies highlight that while PV integrated facades can significantly contribute towards net-zero energy compliance in low-rise buildings, their application in high-rise energy intensive buildings offers only marginal benefits in terms of energy offset. However, in both scenarios, the system demonstrates a favourable economic performance, underlining the cost-effectiveness and viability of PV integrated facades at different building scales. The high-rise building case-study achieves similar payback as that of the low-rise case study building with a massive system and higher investment., making its return on investment promising due to scale. These case studies reinforce the simulation-based conclusions of the present work and support its applicability to real-world design contexts.

The methodological framework proposed in the study can be replicated in a real-world scenario to analyse the shading impact on PV integrated facades of a building due to its nearby buildings. A hypothetical pilot-scale implementation strategy is proposed in the study, to strengthen the practical applicability of the methodology framework developed, as illustrated in Figure 14. The BIPV façade system could be deployed on a test module or a single façade of a representative building, with neighbouring structures modelled to replicate realistic shading conditions.

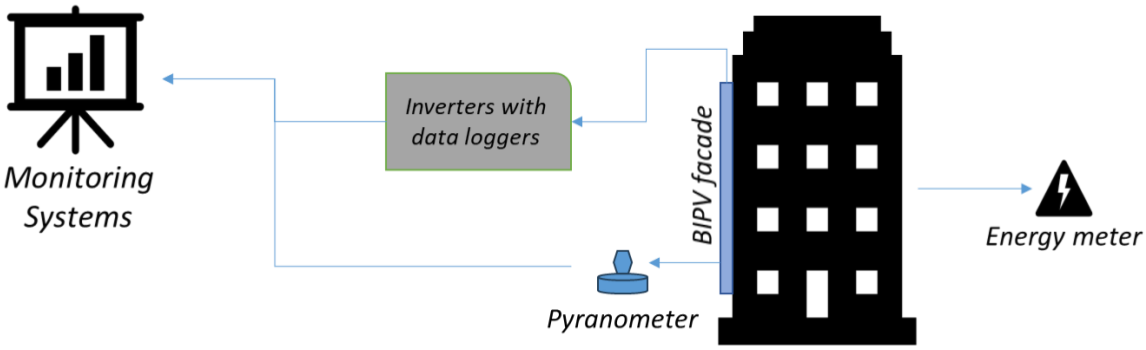


Figure 14: Hypothetical pilot-scale deployment setup for real-world validation of the BIPV simulation framework under shading scenarios.

The real-world scenario of the proposed building with PV integrated facades and its neighbouring buildings that act as shading context can be evaluated through modelling and simulations, to access the possible shading impact on irradiance and PV generation. To validate simulation results, real-time monitoring instruments such as pyranometers, inverters with data loggers and energy meters can be installed to capture solar irradiance, shading patterns and PV energy output. Building energy consumption could be recorded using smart meters, enabling the evaluation of net-zero energy compliance under actual operating conditions. A data logging system would capture hourly or sub-hourly data, allowing for temporal performance analysis and dynamic quantification of shading impacts.

The measured energy generation data can then be compared against simulation outputs using validation metrics to assess model accuracy. This enables in informed decision-making for BIPV facade design and its implementation under shading constraints. Furthermore, stakeholder input could guide broader deployment strategies in similar climate zones. While a physical pilot is beyond the scope of the current study, a conceptual pilot testing setup is presented to provide a foundation for future research, experimental validation and policy-guided pilot projects aimed at mainstreaming BIPV adoption in tropical urban contexts. Implementation of the proposed approach enables in realizing the net-zero energy compliance of buildings by integrating shading considerations into the design and evaluation of BIPV facades.

5. CONCLUSION

Net or nearly zero energy buildings (NZEBs) are typically achieved through the integration of renewable energy, predominantly via solar PV installations, with rooftop PV systems being the most commonly adopted. However, due to spatial limitations, building integrated photovoltaic (BIPV) is gaining attention. Despite its numerous advantages, a primary challenge faced by BIPV is shading, which arises from nearby buildings, structures and obstructions.

The impact of shading is examined on PV integrated facades in both low-rise and high-rise buildings, through irradiation analysis and energy generation simulations. As the study is based solely on simulations, future research could enhance the analysis by incorporating a real-time case study of an actual building. Additionally, the current study is limited to eight shading scenarios for the shading impact analysis. These scenarios help in understanding the energy generation potential and shading sensitivity of PV facades across varied urban contexts. Although the study investigates eight representative shading scenarios to analyse their impact on BIPV energy performance, it does not fully capture the dynamic and complex nature of real urban shading conditions. Future research could incorporate more detailed and temporally obstruction models, such as adjacent high-rise buildings, vegetation, or moving objects. This approach would enhance the realism and applicability of simulation outcomes within dense urban environments. While this study specifically focuses on shading impact as the primary factor influencing BIPV performance, future work could expand the framework by incorporating additional design parameters such as façade orientation, material reflectivity, and advanced shading mitigation strategies. Including parametric or sensitivity analyses on these variables would enable a more comprehensive evaluation of BIPV performance and offer broader guidance for NZEB design and implementation.

While real-time validation is not undertaken in this study, documented BIPV case studies from the literature substantiate the observed trends and serve as a validation for the study's findings. These case studies indicate that low-rise buildings can achieve near or full net-zero energy status under optimal design and energy use conditions, whereas high-rise installations, despite limited contribution to energy offset, often demonstrate favourable financial performance due to the larger available facade area and higher cumulative energy generation potential. Future research could strengthen the findings by incorporating real-time performance data from monitored BIPV installations in actual buildings.

The study identified that the irradiation loss is dependent on the level of shading. The PV energy generation under each shading scenario developed in the study is compared with the building's energy consumption to determine the extent to which on-site generated energy can offset the building's energy demand. The net or nearly zero energy status of the building model is identified in terms of this offset percentage, the net/nearly zero energy percentage (NZE%). In effect, the ability in transitioning a building into a zero-energy building is identified.

The analysis indicates that low-rise buildings are more susceptible to performance degradation due to façade-level shading, particularly on the east side. Conversely, high-rise buildings exhibit greater stability, although they still experience scenario-specific declines, underscoring the significance of shading-aware design. These findings highlight the necessity for site-specific simulations during the early design phase to evaluate façade photovoltaic performance under varying shading conditions and orientations. Although high-rise buildings perform well in terms of PV energy generation, producing more PV electricity due to larger PV areas, the analysis aligns with the understanding that high-rise buildings are challenging to convert to net-zero energy buildings, due to their substantial energy consumption. With shading, PV generation in high-rise buildings offsets approximately 5 to 15%, whereas low-rise buildings achieve an offset of about 20 to 40%. This indicates that low-rise buildings are more readily converted to net or nearly zero energy buildings due to their smaller footprint and lower energy consumption.

The economic feasibility of both the low-rise and high-rise commercial buildings analysed across different shading scenarios through life cycle cost analysis (LCCA), suggests that BIPV investments in high-rise buildings are more financially feasible, achieving payback within acceptable limits. While, low-rise buildings are more sensitive to shading, possibly due to lower façade height or limited PV area, amplifying the payback duration. Under unshaded conditions, both building types show the most favourable payback periods, with low-rise and high-rise buildings achieving a return on investment in approximately 13 years. However, as shading intensifies, the payback periods for low-rise buildings increase significantly, becoming economically non-viable in five shading scenarios, Scenario- 3,4,6,7 and 8. In contrast, high-rise commercial buildings maintain relatively stable and shorter payback durations across all shading scenarios.

While high-rise buildings exhibit lower energy offset percentages due to their greater building energy consumption, they prove more financially feasible in the long term. This is primarily attributed to their increased PV area, improved solar access at higher elevations with reduced shading, and the benefit of economies of scale in system deployment. Despite generating a lower share of the building's energy demand, the absolute PV output and better financial performance metrics, such as simple payback period (SPP), net present value (NPV) and internal rate of return (IRR) make high-rise BIPV facades a more cost-effective solution.

The future studies shall include incentives or subsidies to enhance the financial attractiveness of BIPV projects. The study recommends feasibility analysis to be conducted for the practical implementation of PV integrated facades in low-rise buildings, at its early building design stage. These findings highlight the critical influence of shading on financial performance, especially in low-rise structures, and emphasize the importance of strategic facade design and PV placement to optimise BIPV effectiveness. The study concludes that, in terms of net/nearly zero energy performance, low-rise commercial buildings have high potential for becoming net-zero energy buildings than high-rises. However, in terms of economic feasibility, investing on PV integrated facades in high-rise commercial buildings proves to be better than in low-rise buildings that are heavily shaded, as shading has significant impact on financial viability of PV integrated facades.

The findings of this study offer valuable insights for both policy makers and design professionals. From an early-stage architectural perspective, the analysis highlights the importance of accounting for façade orientation, potential adjacent shading and strategic PV placement to maximize energy generation. From a policy perspective, although low-rise buildings demonstrate a higher potential for energy offset, their economic feasibility remains lower than that of high-rise counterparts. This disparity underscores the need for targeted policy interventions to improve financial viability, such as: (i) incentive schemes or subsidies for BIPV adoption; (ii) feed-in tariffs or net metering policies tailored to support low-rise developments; and (iii) zoning regulations that prioritize solar access and minimize shading from nearby structures. These recommendations can guide both architectural decision-making at the conceptual phase and the structuring of supportive policy frameworks. By addressing these systemic barriers, urban energy strategies can effectively support the widespread deployment of BIPV technologies across diverse building typologies.

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This study did not involve any human participants or animals.

COMPETING INTERESTS STATEMENT

The authors have no competing interests to declare that are relevant to the content of this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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