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Evaluating the Impact of Daylight Control Systems on Renewable Energy Consumption in an Institutional Building

Dare Gabriel Arowosaye [1*], **Adekunle O Ogunnaike** [2], **Oladapo Tobiloba Toye** [3]
Department of Architecture, Caleb University Imota, Lagos State, Nigeria

* Corresponding Author: **Dare Gabriel Arowosaye**

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Abstract

Buildings account for over one-third of global energy consumption and energy-related carbon emissions, making the optimisation of renewable energy utilisation a central objective in low-carbon building design. Although photovoltaic (PV) systems are increasingly deployed in institutional buildings, renewable performance depends not only on installed generation capacity but also on the temporal alignment between electricity demand and solar generation. Daylight availability offers an opportunity to influence this demand–generation relationship, particularly in tropical academic buildings where peak solar irradiance coincides with daytime occupancy; however, daylight performance and photovoltaic utilisation are typically analysed independently. This study evaluates how daylight-responsive façade strategies influence renewable energy utilisation in a multi-storey courtyard institutional building in Lagos, Nigeria. An integrated simulation framework combining Radiance climate-based daylight modelling and EnergyPlus energy simulation was applied to five façade-control scenarios. Daylight performance was analysed across horizontal depth zones and vertical floor levels, while renewable utilisation was assessed using Renewable Energy Fraction (REF) and PV Self-Consumption Ratio (SCR). Integrated façade control increases daylight penetration and reduces annual lighting electricity consumption by 33.5%, lowering daytime electricity demand during peak solar periods. Consequently, REF increases from 19.5% to 20.5%, while grid electricity imports decline by approximately 35,100 kWh annually. These results demonstrate that daylight-responsive façade design can function as a demand-side renewable optimisation mechanism, improving photovoltaic utilisation by reshaping daytime electricity demand in institutional buildings.

Keywords: Daylight-responsive façade design, Climate-based daylight modelling, Photovoltaic utilisation, Renewable Energy Fraction (REF), PV Self-Consumption Ratio (SCR), Institutional buildings

1. Introduction

Buildings account for approximately 36% of global final energy consumption and 37% of energy-related CO_2 emissions, placing the built environment at the centre of global decarbonisation strategies (GlobalABC, 2022; International Energy Agency, 2023) [10, 14]. Educational and institutional buildings are particularly energy intensive due to extended daytime occupancy, dense spatial programming, and simultaneous lighting and cooling demand. In tropical climates, where peak solar irradiance coincides with maximum building use, the interaction between daylight availability, artificial lighting demand, and rooftop photovoltaic (PV) generation becomes structurally significant.

Deep-plan academic buildings frequently exceed the effective daylight penetration threshold of 6–8 m from façade openings, beyond which indoor illuminance declines rapidly and artificial lighting remains continuously required (Mardaljevic *et al.*, 2012; Reinhart & Walkenhorst, 2001) [25, 32]. This depth-induced attenuation creates spatial imbalance, producing overlit perimeter zones and persistently underlit interior areas. Consequently, electric lighting demand often remains high even during periods of substantial solar availability. In tropical institutional buildings, where peak solar irradiance coincides with daytime occupancy, daylight conditions directly influence both lighting demand and the utilisation of on-site photovoltaic generation.

Empirical investigations in Nigerian institutional and mixed-use contexts highlight the energy implications of insufficient environmental design integration. Studies show that inadequate application of passive environmental strategies increases operational energy intensity in campus buildings (Isaac *et al*., 2024) [16], while façade underperformance sustains reliance on mechanical cooling and artificial lighting (Adetunji *et al*., 2024) [1]. Research examining building form and environmental performance further demonstrates the influence of architectural geometry on environmental outcomes (Thomas *et al*., 2024) [38], while climate-responsive façade systems in tropical developments reveal the potential of envelope optimisation to regulate solar exposure (Agbaje *et al*., 2024) [2]. Additional façade-based interventions, including green façade systems, have also demonstrated environmental benefits in Lagos urban environments (Tolulope *et al*., 2025) [40]. However, these studies primarily address thermal mitigation and environmental comfort rather than renewable energy utilisation efficiency.

Universities are increasingly investing in rooftop photovoltaic systems as part of institutional decarbonisation strategies. Studies examining renewable deployment in Nigerian higher-education environments highlight the growing role of campus-scale photovoltaic systems (Olaoye *et al*., 2022) [29], while broader renewable integration frameworks emphasise systemic infrastructure transitions (Thomas *et al*., 2026) [39]. Research in building energy systems consistently demonstrates that renewable performance depends not only on installed generation capacity but also on the temporal alignment between electricity production and building demand profiles (Aro *et al*., 2026; Widén *et al*., 2009) [3, 43]. Net-zero energy building studies further show that indicators such as Renewable Energy Fraction (REF) and PV Self-Consumption Ratio (SCR) improve when demand-side optimisation complements renewable generation strategies (Isaac *et al*., 2024; Marszal *et al*., 2011) [15, 26].

Despite the temporal coincidence between daylight availability and photovoltaic generation, institutional buildings frequently fail to exploit this synergy. Static façade systems, the absence of daylight-responsive lighting controls, and simplified zoning strategies limit effective load matching between lighting demand and solar electricity production. Consequently, electric lighting demand often remains elevated during periods of peak solar output, reducing renewable utilisation efficiency and increasing grid dependency.

The literature therefore reveals persistent analytical fragmentation. Daylight studies rigorously evaluate spatial daylight autonomy and useful daylight illuminance but rarely extend analysis to renewable utilisation metrics. Lighting efficiency studies quantify electricity savings attributable to passive strategies without assessing their effects on REF or SCR. Conversely, renewable modelling studies evaluate photovoltaic generation and load-matching dynamics while typically treating lighting demand as a fixed boundary condition rather than a controllable variable influenced by façade performance. Furthermore, multi-storey courtyard institutional buildings common across tropical university campuses introduce vertical daylight variability due to inter-floor shading and differences in sky-view exposure. Existing daylight analyses predominantly examine horizontal daylight depth while rarely accounting for floor-level variation that materially influences internal load distributions.

Unlike previous daylight–energy investigations that primarily assess lighting energy reduction, this study explicitly models lighting demand as a controllable façade-driven variable within photovoltaic utilisation analysis. This approach enables direct evaluation of how daylight-responsive façade strategies influence renewable energy performance in institutional buildings. Accordingly, this study proposes an integrated daylight–renewable modelling framework that evaluates façade-controlled lighting demand as a dynamic variable influencing photovoltaic utilisation in multi-storey institutional buildings.

The study addresses the following research questions:

RQ1. What patterns of daylight penetration occur horizontally and vertically within a multi-storey courtyard institutional building?

RQ2. How do daylight-responsive façade strategies influence electric lighting demand across depth zones and floor levels?

RQ3. How does reduced lighting demand influence Renewable Energy Fraction (REF) and PV Self-Consumption Ratio (SCR)?

RQ4. To what extent can daylight-responsive façade strategies reduce the photovoltaic capacity required to achieve defined renewable energy performance targets?

2. Literature Review and Theoretical Framework

2.1. Daylight Performance in Deep-Plan and Courtyard Buildings

Previous research has extensively examined daylight performance, lighting control strategies, and photovoltaic load-matching mechanisms to understand how daylight availability influences building energy demand. Climate-based daylight modelling (CBDM), derived from daylight coefficient methods, has become the dominant approach for evaluating daylight performance because it enables annual daylight simulation under realistic climatic conditions (Chatzikonstantinou, 2025; Reinhart *et al*., 2006) [6, 31]. Recent studies integrate spatial daylight autonomy (sDA), annual sunlight exposure (ASE), and useful daylight illuminance (UDI) within dynamic simulation workflows that account for climatic variability, façade configuration, and occupancy schedules (Reinhart & Wienold, 2011; Savvakis *et al*., 2022; Vaisi *et al*., 2024; Wang *et al*., 2024) [33, 35, 41, 42]. Although these metrics quantify spatial daylight availability, they do not directly evaluate how daylight variability affects renewable energy utilisation within building energy systems. Recent research increasingly links daylight metrics with whole-building energy simulations to evaluate simultaneous impacts on lighting and cooling demand (Berkouk, 2025; Li *et al*., 2024; Nazari & Matusiak, 2024) [5, 23, 28]. However, most studies still focus primarily on spatial illuminance performance and lighting reduction rather than examining their implications for renewable energy utilisation.

Deep-plan institutional buildings remain constrained by geometric daylight penetration limits. Under typical glazing and interior reflectance conditions, daylight rarely penetrates beyond 6–8 m from façade openings without optical redirection systems (Jakubiec & Reinhart, 2012; Sorooshnia *et al*., 2023) [17, 36]. This limitation produces spatial imbalance: perimeter zones often receive excessive daylight during peak solar periods, whereas interior zones rely on artificial lighting during occupied hours. Courtyard configurations partially mitigate these limitations by increasing façade exposure. However, multi-storey courtyard buildings introduce vertical daylight variability caused by inter-floor shading and differences in sky-view factors (Kalaimathy *et al*., 2025; Mardaljevic, 2012) [18, 24]. While horizontal daylight attenuation has been widely studied, vertical floor differentiation remains insufficiently incorporated into daylight analyses linked to renewable energy utilisation. Studies on façade design and environmental performance further demonstrate the influence of building envelopes on energy behaviour. Research in Nigeria confirms that façade configuration affects solar exposure, passive cooling performance, and operational energy demand (Adetunji *et al*., 2024; Agbaje *et al*., 2024; Isaac *et al*., 2024) [1, 2, 16]. However, these investigations primarily address thermal performance and occupant comfort rather than the implications of daylight-responsive design for renewable energy utilisation.

2.2. Daylight Control Systems and Lighting Energy Reduction

Daylight control systems reduce electric lighting demand by regulating indoor illuminance in response to daylight availability. These systems operate through daylight-responsive façade strategies and automated lighting controls that adjust indoor lighting levels according to daylight conditions. Researchers commonly classify daylight control approaches into three categories based on their operational mechanisms, as summarised in Table 1.

Table 1: Classification of daylight control systems

Category	Examples
Optical systems	Light shelves, reflective louvers
Dynamic façade systems	Automated shading devices, electrochromic glazing
Control systems	Daylight-linked dimming, sensor-based zoning

Source: Author’s synthesis (2026)

Among these approaches, daylight-linked dimming combined with adaptive shading systems typically achieves the greatest lighting energy reductions. Empirical studies report lighting savings of 20–45%, depending on control sophistication and daylight availability (Kaminska, 2020; Lee & Kang, 2024; Papinutto *et al*., 2022; Swathika *et al*., 2021) [19, 22, 30, 37].

However, glare-related trade-offs may limit these savings. Excessive solar penetration can increase discomfort glare and cooling demand, reducing overall energy benefits (Vaisi *et al*., 2024) [41]. Simulation outcomes also depend on reflectance assumptions, occupancy modelling, and dimming algorithms (Kim & Jeon, 2024; Mostafavi *et al*., 2022) [20, 27]. While these studies demonstrate the potential of daylight control systems to reduce lighting demand, few investigate how such reductions influence renewable energy utilisation in buildings equipped with photovoltaic systems.

2.3. Renewable Energy Utilisation in Institutional Buildings

Recent renewable energy research emphasises demand–generation alignment rather than installed generation capacity alone. Photovoltaic self-consumption depends primarily on the temporal relationship between electricity demand and PV generation (García-suso & Molina-garcía, 2026; Garrido-Herrero *et al*., 2024; Reis *et al*., 2019; Widén *et al*., 2009) [8, 9, 34, 43]. Buildings with identical photovoltaic capacity can therefore achieve different renewable utilisation levels depending on their electricity demand profiles (Arranz *et al*., 2024) [4].

Within Nigerian higher-education contexts, campus-scale renewable deployment has begun to attract increasing research attention. Studies examining photovoltaic integration in university infrastructure highlight the potential for on-site solar generation to reduce grid dependency in institutional facilities (Olaoye *et al*., 2022) [29]. Broader renewable integration frameworks further emphasise the need for systemic energy transitions in educational infrastructure across developing economies (Thomas *et al*., 2026) [39]. Complementary architectural studies provide contextual insight into spatial configuration and envelope performance in Nigerian institutional and residential environments. Circulation analyses (Ekolama *et al*., 2024) [7], demographic housing research (Ibitoye *et al*., 2023) [11], and investigations of building material performance (Ibitoye, 2025; Ibitoye *et al*., 2022) [12, 13] contribute to understanding how spatial planning and envelope characteristics influence environmental performance in tropical buildings. However, these investigations do not examine how daylight-responsive façade strategies interact with renewable energy systems through modifications to building electricity demand.

Two indicators commonly used to evaluate renewable electricity utilisation in buildings are PV Self-Consumption Ratio (SCR) and Renewable Energy Fraction (REF). SCR represents the proportion of photovoltaic generation consumed on-site, while REF represents the share of total building electricity demand supplied by on-site PV generation. These indicators provide a suitable basis for evaluating how daylight-responsive lighting demand influences photovoltaic performance. Recent co-simulation studies show that reducing lighting demand during daylight hours can increase PV self-consumption by 8–22% in educational and office buildings without battery storage (Berkouk, 2025; Li *et al*., 2024; Nazari & Matusiak, 2024) [5, 23, 28].

2.4. Methodological Gaps in Daylight–Renewable Coupling Research

Despite advances in daylight modelling and photovoltaic load-matching analysis, these research domains remain analytically fragmented. Daylight studies typically conclude with lighting energy estimates, while renewable modelling studies treat lighting demand as a fixed input rather than a façade-controlled variable. Table 2 summarises how previous research integrates daylight modelling, lighting demand reduction, photovoltaic analysis, and spatial differentiation.

Table 2: Comparative synthesis of research domains in daylight–renewable modelling literature

Research domain	Daylight metrics	Lighting reduction	PV modelling	Spatial differentiation	Integrated analysis
Daylight modelling studies	✔	✔	✗	Rare	✗
Lighting efficiency studies	✔	✔	✗	✗	✗
Renewable modelling studies	✗	Indirect	✔	✗	✗
Nigerian context studies	Partial	✔	Limited	✗	✗
Present study	✔	✔	✔	✔	✔

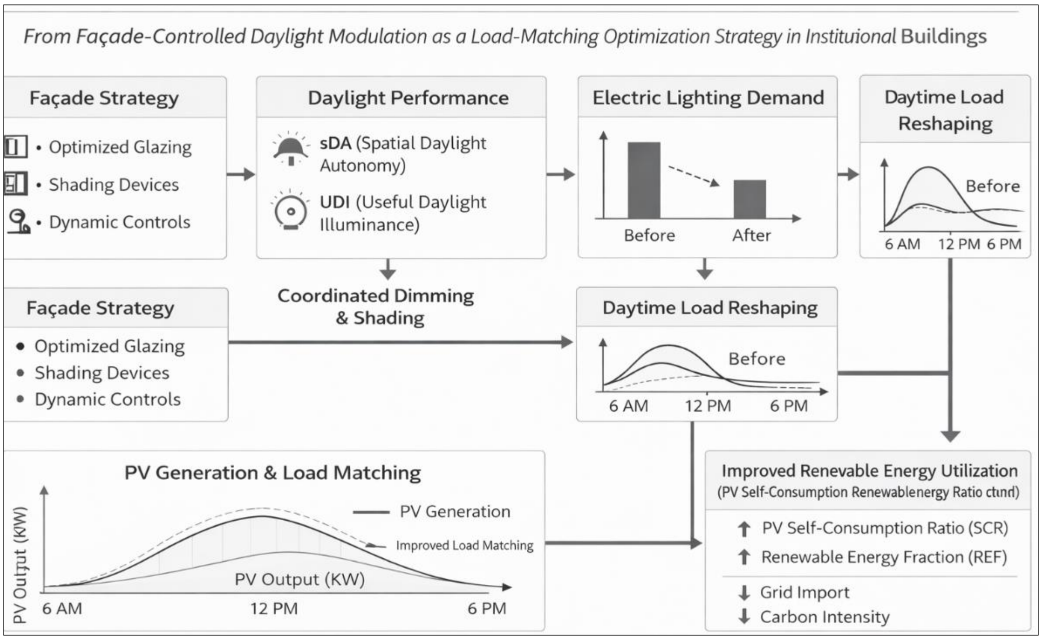
Source: Author's synthesis (2026)

Despite these advances, the interaction between daylight-responsive façade strategies, lighting demand reduction, and photovoltaic utilisation remains insufficiently examined within a unified analytical framework. Existing studies typically treat lighting demand as a fixed input in renewable modelling or focus solely on daylight performance without evaluating its implications for renewable energy utilisation. To address this gap, this study proposes a framework that conceptualises daylight-responsive façade design as a demand-side mechanism for improving photovoltaic utilisation through modifications to daytime electricity demand profiles.

2.5. Theoretical Framework: Daylight as a Renewable Optimisation Mechanism

This study proposes a demand-side renewable optimisation framework in which daylight-responsive façade strategies reshape daytime electricity demand to improve renewable energy utilisation. Within this framework, façade strategies increase useful daylight availability measured through spatial daylight autonomy (sDA) and useful daylight illuminance (UDI) thereby reducing electric lighting demand through automated dimming and shading controls. Lower lighting demand modifies the daytime electricity load profile during peak photovoltaic generation hours, improving alignment between electricity demand and PV production. This alignment increases renewable utilisation indicators such as PV Self-Consumption Ratio (SCR) and Renewable Energy Fraction (REF) while reducing grid electricity imports.

Figure 1 illustrates the interaction between daylight penetration, lighting demand reduction, and photovoltaic utilisation. To operationalise this framework, the study applies controlled parametric simulation to evaluate daylight penetration, lighting demand variation, and renewable energy utilisation across horizontal depth zones and vertical floor levels. Unlike previous studies that analyse daylight performance and photovoltaic utilisation separately, this research integrates climate-based daylight modelling, daylight-responsive lighting control, and photovoltaic performance analysis within a unified simulation framework. By linking spatial daylight variability with renewable utilisation metrics, the study positions daylight-responsive façade design as a demand-side mechanism for improving photovoltaic utilisation in institutional buildings.



Source: Author's synthesis (2026)

Fig 1: Daylight–Renewable Interaction Framework

3. Methodology

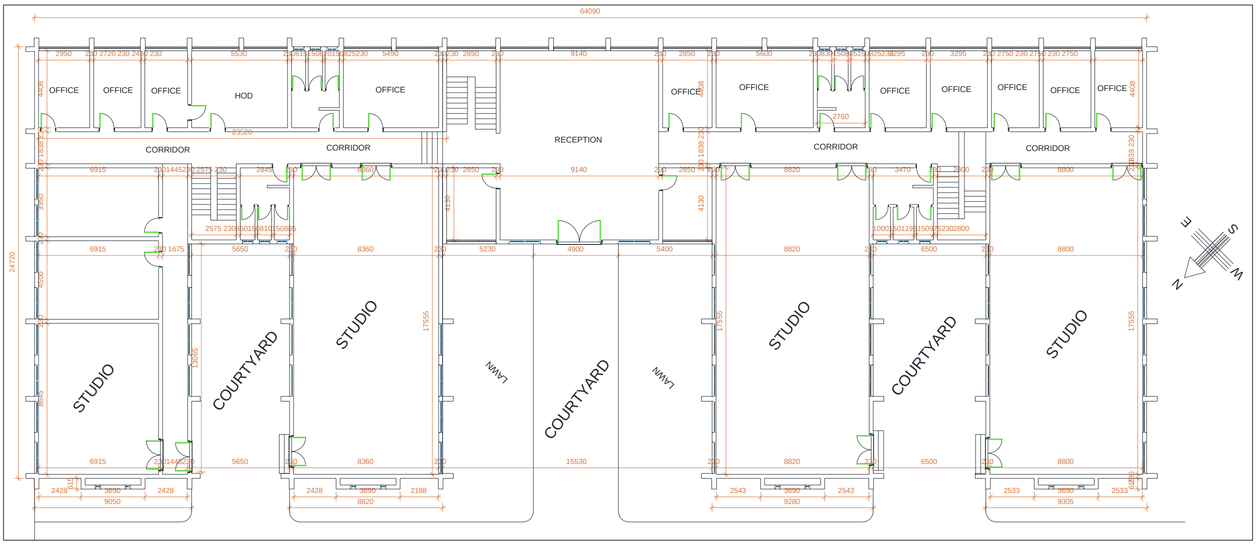
3.1. Research Design

This study employs a controlled parametric simulation framework to evaluate how daylight-responsive façade strategies influence lighting demand and renewable energy utilisation in a multi-storey institutional building in Lagos, Nigeria. Building geometry, envelope properties, internal loads, occupancy schedules, HVAC representation, and photovoltaic (PV) capacity were held constant across simulations, while only daylight-control strategies varied. This approach allows changes in lighting demand, PV Self-Consumption Ratio (SCR), and Renewable Energy Fraction (REF) to be directly attributed to daylight-driven load modulation.

Five scenarios were analysed: a baseline case without daylight control (S0), light shelves (S1), automated external shading (S2), daylight-linked dimming (S3), and integrated shading with dimming (S4). All non-daylight parameters remained identical across scenarios.

3.2. Case Study Description

The case study examines the College of Environmental Sciences building at Caleb University, Lagos, Nigeria. The building is a three-storey academic facility organised around a central open courtyard and reconstructed digitally from architectural drawings. The ground floor plan presented in Figure 2 illustrates the spatial configuration and courtyard arrangement used to construct the digital simulation model. Because the upper floors maintain a consistent layout and façade configuration (see figure 3), the ground floor geometry provides a representative basis for modelling daylight distribution and energy performance across the building.



Source: Author’s synthesis (2026)

Fig 2: Ground Floor Plan of the Case Study Building

Source: Author’s synthesis (2026)

Fig 3: Building Elevations of the Case Study Building

The structure measures approximately 64 m in length and 17–25 m in depth, forming a double-loaded corridor configuration around the courtyard. Total floor area is approximately 5,800 m², with a window-to-wall ratio (WWR) of about 35%.

Design studios represent the primary daylight-sensitive spaces, while offices, laboratories, and circulation areas serve as secondary zones; service cores were excluded from daylight-priority analysis. The building accommodates approximately 580 occupants during peak operation. Teaching spaces were modelled with an occupancy density of 0.20 persons/m², with internal gains representing sedentary academic activity.

The model was aligned to true north using architectural drawings, and simulations employed the Lagos Typical Meteorological Year (TMY) climate dataset. Key geometric parameters include a 3.30 m floor-to-floor height, 0.90 m window sill height, 1.20 m glazing height, and 2.10 m window head height. The pitched roof was modelled with a 15° tilt angle.

3.3. Spatial Zoning Strategy

A horizontal–vertical zoning framework was applied to capture daylight variability and its influence on lighting demand. The zoning structure was derived from the spatial layout illustrated in Figure 2, which shows the courtyard configuration and façade orientations that influence daylight penetration patterns within the building.

Horizontally, interior spaces were classified by façade depth into perimeter (0–6 m), intermediate (6–8 m), and deep-core

(>8 m) zones, consistent with established daylight penetration limits in deep-plan buildings. Courtyard-facing façades were treated as distinct exposure conditions because of their unique daylight access characteristics. Vertically, the Ground, First, and Second floors were analysed independently to account for inter-floor shading and differences in sky exposure. This zoning framework enables spatially resolved evaluation of lighting demand distribution and its interaction with renewable energy utilisation.

3.4. Simulation Setup

This study evaluated the interaction between daylight availability, lighting demand, and photovoltaic utilisation using an integrated simulation workflow that combines Radiance for climate-based daylight modelling with EnergyPlus for whole-building energy simulation. The digital model was constructed directly from the architectural geometry illustrated in Figure 2 to ensure that façade orientation, courtyard configuration, and spatial layout represent the physical building form. This integration enables accurate daylight prediction while capturing whole-building energy dynamics. Both simulation environments used identical geometry and envelope definitions to maintain consistency between daylight availability and energy demand modelling. Daylight performance was assessed using Spatial Daylight Autonomy (sDA300/50%), Annual Sunlight Exposure (ASE1000/250), and Useful Daylight Illuminance (UDI100–2000 lux). Metrics were calculated on a 0.80 m workplane using a 0.5 m sensor grid. Radiance parameters were set to ambient bounces = 5, ambient divisions = 2048, ambient super-samples = 256, and ambient accuracy = 0.15. Interior reflectances were 0.80 for ceilings, 0.55 for walls, and 0.25 for floors.

The baseline envelope included 225 mm plastered sandcrete block walls (U = 2.2 W/m²·K), a roof assembly with aluminium sheet on timber truss (U = 3.2 W/m²·K), and single tinted glazing (VT = 0.55, SHGC = 0.45, U = 5.8 W/m²·K). Infiltration was set at 0.7 ACH. Energy simulations used six timesteps per hour (10-minute resolution). Occupancy followed a weekday schedule from 08:00 to 16:00 with reduced occupancy from 12:00 to 13:00. Lighting Power Density values were 10 W/m² for studios, 9 W/m² for offices, 11 W/m² for laboratories, and 5 W/m² for circulation areas. Plug loads were 6, 10, 18, and 1 W/m² respectively. Cooling demand was represented using an Ideal Loads Air System with a 24°C cooling setpoint. Daylight-linked dimming used a 300 lux setpoint with a minimum power fraction of 0.10. Automated shading activated when solar radiation exceeded 250 W/m², while light shelves were modelled with a depth of 0.60 m.

Photovoltaic modelling used roof geometry from the simulation model. Installed capacity was approximately 100 kWp (≈520 m² array area, 40% roof coverage). Module efficiency was 19%, inverter efficiency 96%, and performance ratio 0.78. The roof tilt remained 15°. Battery storage was excluded and surplus electricity was exported to the grid. The Self-Consumption Ratio (SCR) represents the share of PV generation used on-site, while the Renewable Energy Fraction (REF) represents the share of building electricity demand supplied by on-site PV.

3.5. Model Validation and Robustness

Model plausibility was evaluated by comparing simulation outputs with reported performance ranges for institutional buildings in tropical climates. Simulated lighting energy intensity fell within the 20–40 kWh/m²/year range reported for comparable academic buildings, and daylight attenuation patterns were consistent with the widely reported 6–8 m daylight penetration threshold. Robustness was further assessed through one-at-a-time sensitivity analysis of key parameters, including envelope thermal properties, glazing characteristics, infiltration rates, lighting power density, PV roof coverage, roof tilt, shading activation thresholds, and dimming efficiency. Table 3 summarises baseline parameters and the variation ranges applied during sensitivity testing.

Table 3: Baseline model parameters and variation ranges used in the sensitivity analysis.

Parameter Category	Parameter	Baseline Value	Variation Range
Envelope – Walls	Wall U-value	2.2 W/m²·K	1.8–2.8 W/m²·K
Envelope – Roof	Roof U-value	3.2 W/m²·K	2.0–4.5 W/m²·K
Glazing	Visible Transmittance (VT)	0.55	0.55–0.70
Glazing	SHGC	0.45	0.45–0.62
Air Infiltration	Air Changes per Hour (ACH)	0.7	0.4–1.2
Lighting System	Lighting Power Density (LPD)	5–11 W/m²	±15%
Plug Loads	Equipment Load Density	1–18 W/m²	±20%
HVAC Operation	Cooling Setpoint	24°C	24–26°C
Daylight Control	Light Shelf Depth	0.60 m	0.45–0.90 m
Daylight Control	Shading Activation Threshold	250 W/m²	200–350 W/m²
Daylight Control	Minimum Dimming Fraction	0.10	0.05–0.20
Photovoltaic System	Roof Coverage	40%	30–50%
Photovoltaic System	Module Efficiency	19%	17–21%
Photovoltaic System	Performance Ratio (PR)	0.78	0.72–0.82
Photovoltaic System	Tilt Angle	15°	10–25°

Source: Author’s synthesis (2026)

3.6. Statistical Analysis

One-way analysis of variance (ANOVA) was used to evaluate differences in annual lighting demand, SCR, and REF across simulation scenarios (S0–S4). Monthly simulation outputs (n = 12 per scenario) formed the dataset for statistical testing. Statistical significance was assessed at $p < 0.05$, and effect sizes (η^2) were calculated. Tukey HSD post-hoc tests identified significant pairwise differences between daylight-control strategies.

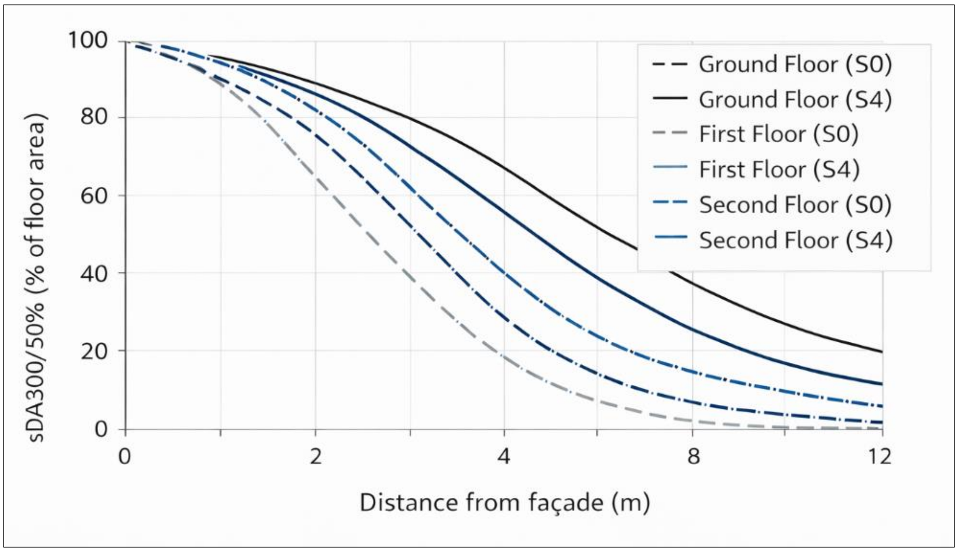
All scenarios used identical baseline models, with only daylight-control parameters modified between simulations. The resulting dataset forms the basis for analysing daylight performance, lighting demand reduction, and photovoltaic utilisation across scenarios in Section 4.

4. Results and Discussion

4.1. Daylight Availability and Spatial Penetration

Climate-based daylight modelling shows a consistent decline in daylight availability with increasing distance from façade openings across all floors. Under baseline conditions (S0), spatial daylight autonomy (sDA300/50%) exceeds recommended thresholds within perimeter zones (0–6 m) but decreases rapidly beyond the intermediate zone (6–8 m), with the lowest values occurring in deep-core zones (>8 m). Figure 4 presents depth-dependent daylight penetration curves for the Ground, First, and Second floors under baseline (S0) and integrated façade control (S4). Across all floors, daylight availability declines progressively with façade depth. Under the integrated façade strategy, however, daylight penetrates further into interior zones relative to baseline conditions.

On the Second floor, sDA decreases from approximately 94% at the façade to 16% at 12 m depth under S4, compared with 89% to approximately 14.5% under S0. Similar attenuation occurs on the First and Ground floors. Vertical variation is also evident: courtyard-facing zones on upper floors exhibit slightly higher daylight availability due to improved sky exposure and reduced courtyard obstruction. These results indicate that daylight performance in courtyard institutional buildings is governed by both horizontal depth attenuation and vertical floor position. These spatial daylight patterns establish the conditions under which façade control strategies influence interior daylight distribution.



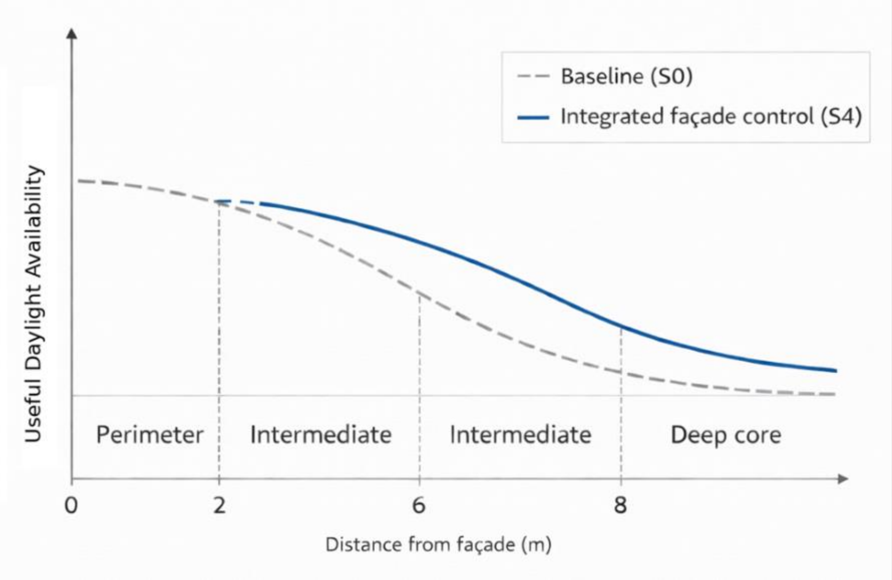
Source: Author's synthesis (2026)

Fig 4: Depth-dependent daylight penetration curves across floors under baseline (S0) and integrated daylight control (S4).

4.2. Integrated Daylight Behaviour Under Façade Control

Figure 5 compares daylight behaviour under baseline and integrated façade control scenarios. Under baseline conditions, daylight declines sharply beyond approximately 3–4 m from the façade, particularly on the Ground floor where courtyard obstruction reduces sky exposure. The integrated façade strategy moderates this decline. The combined operation of light shelves, automated shading, and daylight-responsive dimming redistributes daylight and reduces glare-driven shading events, allowing useful daylight to penetrate further into interior zones.

Vertical markers at 6 m and 8 m indicate transitions between perimeter, intermediate, and deep-core zones. Improvements are most pronounced within intermediate zones, where daylight levels increase sufficiently to activate lighting dimming controls. Consequently, façade-based daylight strategies extend the functional daylight zone deeper into the building plan and increase the proportion of floor area receiving adequate daylight. The improved daylight distribution directly affects electric lighting operation during occupied hours.



Source: Author's synthesis (2026)

Fig 5: Comparative daylight penetration behaviour under baseline (S0) and integrated façade control (S4).

4.3. Lighting Energy Demand Reduction

Improved daylight availability produces substantial reductions in electric lighting demand through daylight-responsive dimming control. Annual lighting electricity consumption decreases from 112,000 kWh under baseline conditions (S0) to 74,500 kWh under the integrated control scenario (S4), representing a 33.5% reduction (Table 4). Lighting reductions vary spatially across the building. Intermediate zones experience the largest proportional reductions because daylight levels frequently exceed dimming thresholds in these areas, whereas deep-core zones exhibit smaller reductions due to limited daylight penetration. Vertical variation is also observed: upper floors achieve greater reductions than the Ground floor due to improved sky exposure. Under the integrated scenario, lighting demand decreases by approximately 38% on upper floors, compared with about 19% in deep-core zones. Statistical testing confirms significant differences across scenarios ($p < 0.05$) with large effect sizes.

These reductions modify the building's daytime electricity demand profile, particularly during peak solar hours.

Table 4: Annual lighting electricity consumption across daylight-control scenarios.

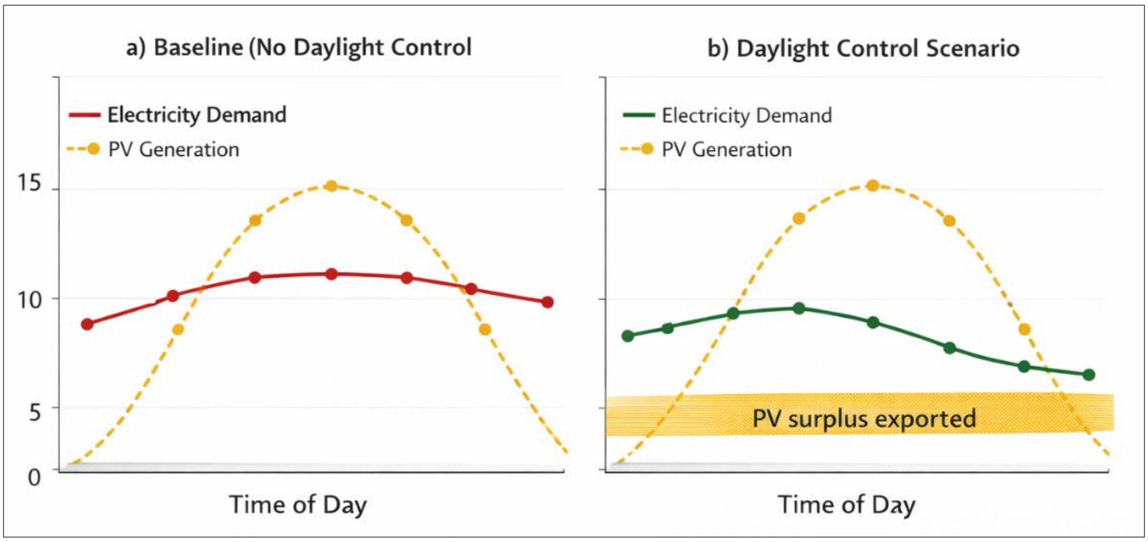
Scenario	Total Lighting (kWh)	Reduction vs S0
S0 – Baseline	112,000	—
S1 – Light shelves	103,000	8.0%
S2 – Automated shading	98,000	12.5%
S3 – Daylight dimming	81,000	27.7%
S4 – Integrated control	74,500	33.5%

Source: Author's synthesis (2026)

4.4. Electricity Load Profile Modification

Daylight-responsive lighting control lowers electric lighting output as daylight availability increases, reducing electricity demand during daytime occupancy and particularly during peak solar periods. Figure 6 compares building electricity demand relative to photovoltaic (PV) generation under baseline operation and daylight-responsive control. Under baseline conditions (Figure 6a), electricity demand remains relatively constant because lighting operates independently of daylight availability. As solar irradiance increases, PV generation rises while electricity demand changes only slightly, producing substantial overlap between demand and PV output.

Under daylight-responsive control (Figure 6b), electric lighting demand decreases during daylight hours as interior spaces receive sufficient natural illumination. This reduction lowers the daytime electricity load profile while PV generation remains unchanged, widening the gap between PV production and building demand during peak solar hours. The shaded region represents photovoltaic surplus exported to the grid. These load-profile changes alter the interaction between building electricity demand and photovoltaic generation.



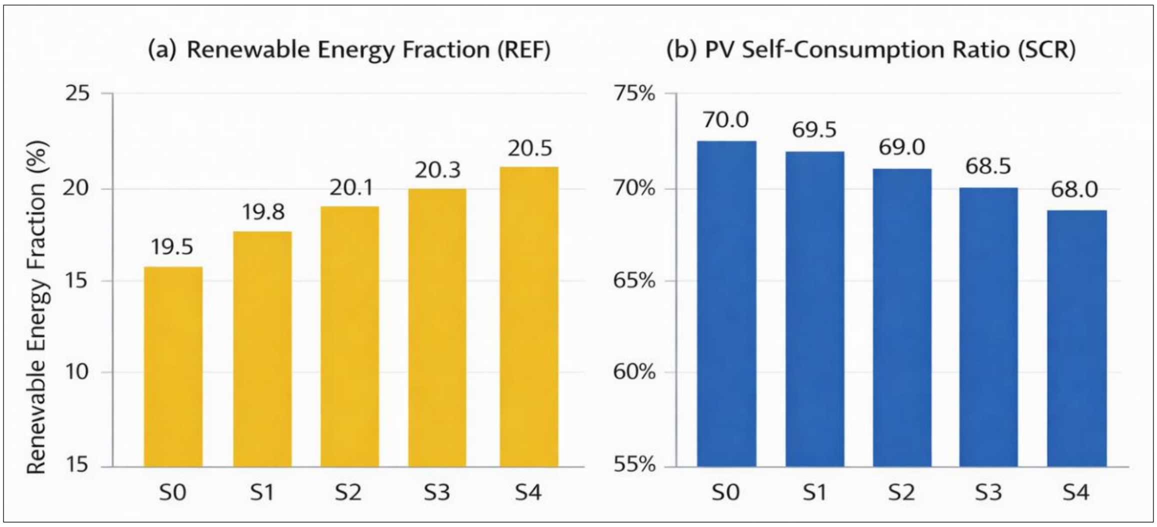
Source: Author's synthesis (2026)

Fig 6: Comparison of building electricity demand relative to photovoltaic (PV) generation under (a) baseline operation and (b) daylight-responsive lighting control.

4.5. Renewable Energy Utilisation Performance

Photovoltaic generation remains constant across scenarios at approximately 145,000 kWh annually. Differences in renewable utilisation therefore arise directly from the lighting reductions described in Section 4.3 and the load-profile modification identified in Section 4.4. Renewable performance was evaluated using Renewable Energy Fraction (REF) and PV Self-Consumption Ratio (SCR). Figure 7 summarises both indicators across daylight-control scenarios. REF increases from 19.5% under baseline conditions (S0) to 20.5% under the integrated scenario (S4). In contrast, SCR decreases slightly from 70.0% to 68.0%, reflecting increased photovoltaic surplus export during peak solar periods as daytime electricity demand declines.

Grid electricity imports decrease from 418,500 kWh under baseline conditions to 383,400 kWh under integrated control, representing an annual reduction of approximately 35,100 kWh. These results indicate that daylight-responsive façade strategies improve renewable energy utilisation primarily through demand-side load modulation, reducing electricity demand rather than expanding generation capacity (Aro *et al*., 2026; Le *et al*., 2022; Widén *et al*., 2009) [3, 21, 43]. These improvements can also be interpreted in terms of photovoltaic capacity requirements.



Source: Author's synthesis (2026)

Fig 7: Renewable energy performance across daylight-control scenarios. (a) Renewable Energy Fraction (REF) increases as daylight-responsive control reduces daytime electricity demand. (b) PV Self-Consumption Ratio (SCR) decreases slightly due to increased photovoltaic surplus export during peak solar generation.

4.6. Equivalent Photovoltaic Capacity Offset

Renewable performance improvements achieved through daylight control can be expressed as equivalent photovoltaic capacity requirements. The model includes a 100 kWp PV system producing approximately 145,000 kWh annually. Achieving the 20.5% REF observed under the integrated scenario using the baseline demand profile would require approximately 104.8 kWp of installed capacity, an increase of 4.8 kWp (4.8%).

This result indicates that integrated daylight control strategies can offset part of the photovoltaic capacity otherwise required to achieve the same renewable contribution by reducing electricity demand rather than expanding generation infrastructure. To evaluate the robustness of these results, sensitivity analysis was conducted across key modelling parameters.

4.7. Sensitivity and Robustness Analysis

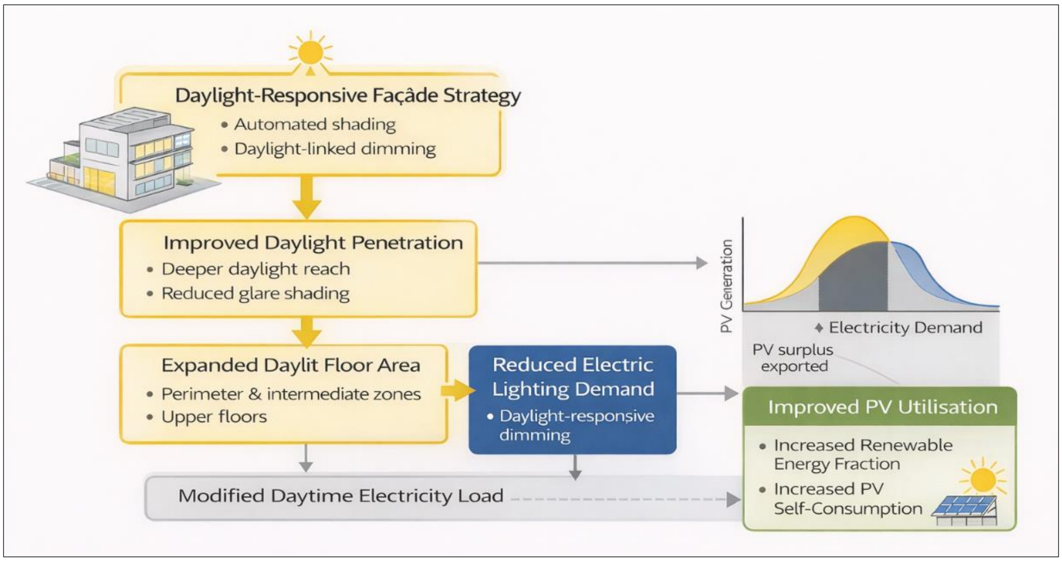
Sensitivity analysis assessed the influence of key modelling parameters on renewable utilisation outcomes. Lighting Power Density (LPD) produced the largest variation in REF values, reflecting the strong relationship between lighting demand and renewable energy utilisation. Variations in photovoltaic roof coverage affected absolute REF values but did not alter the ranking of daylight-control scenarios, while changes in shading depth and dimming efficiency produced smaller proportional effects. Across all tested parameter ranges, the integrated daylight control scenario consistently maintained higher REF values than the baseline configuration, indicating that the renewable performance improvements remain robust under plausible variations in building parameters and system assumptions.

These results support the integrated interpretation of daylight–renewable interactions presented below.

4.8. Integrated Discussion and Synthesis

Consistent with the daylight–renewable interaction framework introduced in Section 2.5, the results show that daylight-responsive façade strategies influence renewable energy utilisation through demand-side load modulation. Improved daylight penetration reduces electric lighting demand, reshaping the building electricity load profile and improving temporal alignment with photovoltaic generation. Lighting reductions are strongest in intermediate zones and upper floors where daylight availability is greatest. The integrated façade strategy combining automated shading with daylight-responsive dimming achieves the greatest performance improvement by simultaneously regulating solar exposure and adjusting electric lighting output.

Figure 8 synthesises the interaction between daylight penetration, lighting demand reduction, and renewable energy utilisation. Increased daylight availability expands daylit floor area, reduces electric lighting demand, and improves alignment between electricity demand and photovoltaic generation. Although demonstrated in a courtyard institutional building, this interaction is expected to apply to other daytime-occupied building types where daylight availability coincides with solar electricity production. These results demonstrate that daylight-responsive façade strategies influence renewable energy utilisation primarily through demand-side load modulation. The broader implications for renewable energy integration and building design are discussed in the following section.



Source: Author’s synthesis (2026)

Fig 8: Synthesis of the interaction between daylight penetration, electric lighting demand reduction, and photovoltaic utilisation in daylight-responsive institutional buildings.

5. Conclusion and Recommendations

5.1. Summary of Key Findings

This study examined how daylight-responsive façade strategies influence renewable energy utilisation by modifying the interaction between daylight penetration, electric lighting demand, and photovoltaic generation. Using a courtyard institutional building as a case study, climate-based daylight modelling and building energy simulation were employed to evaluate how façade control strategies modify daylight distribution and influence electricity demand during daytime occupancy.

The results show that daylight penetration in courtyard institutional buildings exhibits systematic horizontal attenuation and measurable vertical variation across floors. Under baseline conditions, daylight availability declines rapidly beyond perimeter zones, leaving intermediate and deep-core areas dependent on electric lighting. Integrated façade strategies combining automated shading with daylight-responsive dimming significantly improve daylight distribution by reducing glare-driven shading and allowing useful daylight to penetrate further into interior zones. These improvements are most evident in intermediate zones and upper floors where greater sky exposure increases daylight availability. Improved daylight penetration produces substantial reductions in electric lighting demand. Across the analysed scenarios, annual lighting electricity consumption decreases from 112,000 kWh under baseline conditions to 74,500 kWh under integrated façade control, representing a 33.5% reduction. These reductions occur primarily in intermediate zones where daylight levels frequently exceed dimming thresholds, enabling lighting systems to operate at reduced power levels during daytime occupancy.

The reduction in lighting demand reshapes the building electricity load profile by lowering demand during periods of peak solar availability. This change improves temporal alignment between building electricity consumption and photovoltaic generation, allowing a greater proportion of on-site solar electricity to contribute to building energy demand. Consequently, the Renewable Energy Fraction increases from 19.5% under baseline conditions to 20.5% under integrated control without increasing installed photovoltaic capacity. Although the PV Self-Consumption Ratio decreases slightly due to increased photovoltaic surplus export, the overall share of building demand supplied by on-site renewable energy improves.

The results therefore demonstrate that daylight-responsive façade design can improve renewable energy utilisation by reshaping daytime electricity demand rather than increasing generation capacity.

5.2. Contribution to Daylight–Renewable Energy Integration Research

This research contributes to studies on climate-responsive architecture and building energy systems by demonstrating how daylight-responsive façade design can influence renewable energy utilisation through changes in electricity demand patterns. While previous daylighting studies have primarily examined daylight strategies in terms of visual comfort and lighting energy savings, the present study extends this perspective by linking daylight penetration behaviour with photovoltaic utilisation dynamics. By integrating daylight performance indicators with renewable energy metrics, the study proposes a conceptual framework describing the interaction between daylight availability, lighting demand reduction, and photovoltaic electricity generation. The results show that improved daylight penetration expands the portion of interior floor area receiving useful daylight, enabling electric lighting systems to operate at reduced power levels during daytime hours. This demand reduction reshapes the electricity load profile and improves temporal alignment between building electricity consumption and solar electricity generation.

The study therefore demonstrates that architectural daylight strategies can support renewable energy integration not only by reducing energy consumption but also by improving synchronisation between electricity demand and renewable energy supply. This demand-side interaction represents an important pathway through which building design can contribute to renewable energy utilisation without requiring additional generation infrastructure.

5.3. Design Implications for Institutional Buildings

The findings provide several implications for the design of institutional and educational buildings where daytime occupancy coincides with solar electricity generation. First, façade systems integrating automated shading with daylight-responsive lighting controls allow buildings to regulate solar exposure while maintaining adequate daylight levels for visual tasks. This integration reduces glare-driven shading behaviour and enables lighting systems to operate at lower power levels during daytime occupancy. Second, façade design strategies should prioritise daylight penetration into intermediate interior zones. While perimeter areas typically receive sufficient daylight, intermediate zones represent the largest portion of floor area in deep-plan institutional buildings and therefore provide the greatest opportunity for reducing electric lighting demand. Third, building configurations that enhance vertical sky exposure—such as courtyard layouts or stepped floor arrangements—can improve daylight availability on upper floors and increase the effectiveness of daylight-responsive lighting controls. When combined with photovoltaic systems, these architectural strategies improve synchronisation between electricity demand and solar electricity generation.

These findings highlight daylight-responsive façade design as an architectural strategy for improving renewable energy utilisation through demand-side electricity load modulation. By demonstrating how daylight-responsive façade strategies reshape daytime electricity demand and improve photovoltaic utilisation, this study identifies architectural daylight design as an effective demand-side pathway for enhancing renewable energy integration in institutional buildings.

5.4. Limitations and Future Research

The analysis focuses on a courtyard institutional building typology, and the interaction between daylight penetration and renewable energy utilisation may differ in other building forms or urban contexts where solar access and daylight availability vary. In addition, the study primarily evaluates the relationship between daylight penetration and electric lighting demand, while other building energy loads such as heating, cooling, and equipment use were not included in the demand-side load modulation analysis.

Future research should therefore examine the interaction between daylight-responsive lighting control, HVAC demand, and renewable energy generation within integrated building energy systems. Additional studies across different building typologies, climates, and urban densities would help generalise the daylight–renewable interaction framework proposed in this study. Investigating the integration of photovoltaic systems with energy storage technologies and adaptive lighting controls may further enhance renewable energy utilisation in daytime-occupied buildings and support the development of low-carbon building design strategies.

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