OPEN ACCESS

Check for updates

JOURNAL OF ARCHITECTURAL RESEARCH AND DESIGN STUDIES
Vol. 10, No. 1, 2026, pp 17-34
p-ISSN 2580-1252; *e*-ISSN 2580-1260
DOI: 10.20885/jars.vol10.iss1.art2

Innovative Strategies for Improving Energy Efficiency and Thermal Comfort in Heritage Buildings

A Case Study of Lawang Sewu

Hassan Gbran[1*], Siti Rukayah[2], Atiek Suprapti[2], Edward Endrianto Pandelaki[2]

[1]Doctoral Program in Architecture and Urban Science, Diponegoro University, Semarang, Indonesia
[2]Departement of Architecture, Diponegoro University, Semarang, Indonesia

Correspondence*:
E-mail: gbranhassan882@gmail.com

Article History:

Submitted: April 30, 2025
1st Revised: May 27, 2025
2nd Revised: July 22, 2025
Accepted: July 22, 2025
Published: February 26, 2026

Abstract

This study introduces a novel integration of dynamic electrochromic glazing and CIGS photovoltaics tailored to the tropical heritage context of Lawang Sewu, aiming to provide a replicable retrofit model for similar Southeast Asian climates, focusing on Lawang Sewu, a colonial-era landmark in Semarang, Indonesia. The research integrates field measurements, simulation analyses, and retrofit modelling to assess indoor environmental quality across four functionally distinct rooms over one year. Retrofit interventions included electrochromic glazing, energy recovery ventilation, and Copper Indium Gallium Selenide (CIGS) photovoltaic systems—a flexible thin-film solar technology suitable for heritage facades. Results revealed that electrochromic glazing reduced heating demands, while PV integration achieved up to 90.46% annual energy savings. Seasonal variation and occupancy patterns were found to significantly influence thermal conditions. The PA_RN package—combining passive and renewable solutions—was identified as the optimal retrofit approach, balancing energy performance, thermal comfort, and heritage aesthetics. The study underscores the potential for achieving sustainability in heritage structures through context-sensitive retrofitting, offering a replicable model for similar buildings in tropical climates.

Keywords: *Energy Efficiency; Energy retrofit; Heritage building, Lawang Sewu; Photovoltaic; Thermal comfort*

Introduction

The design intent behind buildings targets long-term usage, but environmental elements eventually weaken the building envelope, causing airtightness deterioration. The solution of retrofitting serves the dual purpose of enhancing energy efficiency while guaranteeing thermal comfort maintenance or improvement. Understanding the unique nature of heritage buildings leads to different retrofit requirements because of their cultural importance; Recent studies emphasize the integration of smart technologies in heritage conservation (Hasanah & Caesarina, 2021*; Al-Habaibeh et al., 2022;*

Paramita, 2024; Gbran et al., 2025) . Heritage buildings require two main retrofitted components: enveloping structural enhancements and system infrastructure modernizations. The envelope upgrade process includes insulation application together with new window installation and phase-change material integration, while facility system enhancement requires optimized HVAC system management and operational schedule optimization(Cabeza et al., 2018). Modern retrofit solutions cannot always be applied to heritage structures, as they must preserve both the architectural design principles and the visual heritage values of cultural landmarks (Polo López & Frontini, 2014; Karimi et al., 2024; Chang et al., 2021; Gbran et al., 2025b).

The research examines Lawang Sewu as a historical building situated in Semarang, Indonesia. Lawang Sewu building arose in 1904 during the Dutch colonial rule, featuring both a red-brick facade and neo-Gothic architectural elements. The architectural status of this established cultural site brings forward complex conditions to execute energy-efficient modernization projects(Gbran & Ratih Sari, 2024). The research examines Lawang Sewu's thermal performance using infrared thermography and blower-door testing to create conservation-friendly energy-saving retrofits (Harrestrup & Svendsen, 2016; Gbran, 2024).

This project seeks three main targets: (1) the protection of architectural history and cultural significance in the building structure, (2) the improvement of resident comfort for sustainable building use, and (3) increased energy efficiency using electrochromic glazing along with photovoltaic systems. These building-scale interventions align with broader model-based engineering approaches for sustainable urban development, which integrate computational modeling and data analytics to optimize complex systems (Gbran & Alzamil, 2025). The design uses static, dynamic, and sustainable renewable approaches in combination. This research aims to demonstrate how heritage buildings like Lawang Sewu can achieve significant energy savings—up to 90.46% —while maintaining their architectural authenticity (Lidelöw et al., 2019; Gbran & Sari, 2023; Loli & Bertolin, 2018).

To support this goal, the study adopts Copper Indium Gallium Selenide (CIGS) as a photovoltaic technology integrated into the retrofitting strategy. CIGS is a thin-film solar cell known for its high energy conversion efficiency, lightweight structure, and flexibility. Unlike rigid silicon-based panels, CIGS modules can be installed on curved or angled surfaces such as awnings, canopies, or historical facades, making them particularly suited for heritage buildings where preserving architectural appearance is critical. Their ability to operate efficiently in diffuse light and under high-temperature tropical conditions further supports their application in equatorial settings such as Semarang.

Innovative Contributions

This study presents three key innovations tailored to tropical heritage architecture: (1) the integration of copper indium gallium selenide (CIGS) photovoltaic panels on 30°-tilted awnings, optimized for Semarang's zenithal solar path and applied to Lawang Sewu's facade and canopy zones; (2) a hybrid retrofit package (PA_RN) that harmonizes passive architectural strategies with renewable energy systems, achieving a 90.46% reduction in energy consumption while preserving heritage aesthetics; and (3) the deployment of electrochromic glazing calibrated for equatorial humidity, offering adaptive solar control superior to temperate-climate applications (L. C. A et al., 2024). Field testing of CIGS panels was conducted on the front facade between Lawang Sewu's twin minarets—an area without canopy coverage and directly facing the main staircase—as well as on adjacent canopies angled at 30°, addressing the high solar elevation unique to Semarang. This approach marks a departure from previous studies that primarily focused on temperate or generalized climatic contexts, offering a localized strategy for the sustainable retrofitting of tropical heritage buildings.

Literature Review

Sustainable architecture faces two major challenges, which include historic building maintenance and increased energy performance of structures. Various studies have examined how energy retrofit techniques affect heritage buildings by maintaining both energy performance gains and cultural architectural elements.

Improving the Thermal Envelope Performance of Historic Buildings

Thermal envelope improvements stand as the most beneficial methods for improving energy efficiency in heritage properties (Hidayat et al., 2024; Gbran, 2025). The conservation measures involve insulating exteriors and roofs as well as substituting single-pane windows for double-glazed or electrochromic glazing systems and implementing enhanced exterior entry systems. Internal insulation applied to historic wooden buildings reduces energy usage between 20-65% according to

(Arumägi et al., 2015) but maintains structural compatibility with the original design of the building.

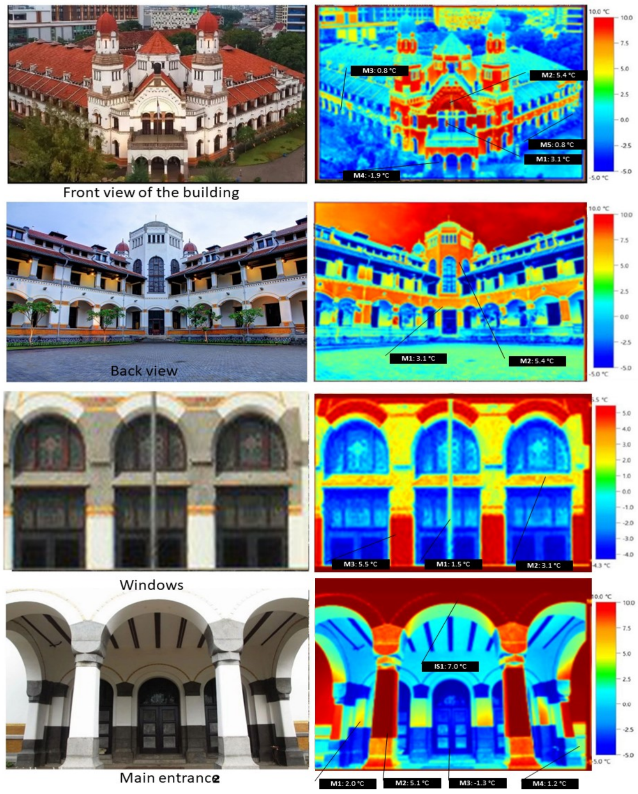


Figure 1. Performance of Thermal Insulation in the Building Envelope.
Source: Author

In the figure, (1) above the temperature scale from –5.0 °C to 10.0 °C reflects a simulated thermal gradient generated under standardized boundary conditions using EnergyPlus software. This scale serves to visualize relative differences in heat transfer between insulated and non-insulated facade components. The data is not derived from direct field measurements, but from comparative simulation outputs aimed at evaluating retrofit scenarios.

The visual presentation shows how building envelope thermal insulation operates through displays of different performance levels, including additional insulation walls and superior glazing technologies. The improvements achieve heat loss reduction and improved thermal comfort through measures that keep the architectural qualities intact. The results underline choosing materials that match historical design principles since they ensure the building keeps its visual appeal.

The research by (Harrestrup & Svendsen, 2016), proved that internal insulation solutions used in multi-story brick-wall buildings led to a 63% decrease in energy consumption. The official document stresses that poor implementation of insulation methods may lead to internal humidity increases and mold development. The building owner needs to perform a comprehensive evaluation to ensure success before making any changes.

Thermal envelope improvements stand as an essential method to boost energy efficiency at Lawang Sewu since this structure, originating from 1904, displays its distinctive stone exterior. Materials selected for retrofit applications must be compatible with existing stone construction to avoid compromising the building's historical integrity and visual character (Cabeza et al., 2018).

Ventilation Systems and Energy Efficiency Improvement

User comfort and energy saving demand proper execution of natural and mechanical ventilation systems. Presented evidence that exposure to the microbiological agents found in non-conditioned indoor spaces results in Sick Building Syndrome (SBS) symptoms. A recommendation exists to implement ventilation systems for enhanced indoor air quality and minimized air conditioning system heat loads (Menteşe, 2022).

ERV technologies, according to (Cabeza et al., 2018), improve indoor air quality through ventilation and reduce facility energy requirements simultaneously. These systems might raise thermal building loads, so building impact assessments need to be conducted for proper installation (Hassan Gbran, 2026).

The Lawang Sewu building should use energy recovery ventilation systems to enhance ventilation based on original building design elements. Natural ventilation serves two purposes: it enables the use of nearby air currents for improved thermal comfort, and it decreases the need for air-conditioning systems.

Integration of Renewable Energy Technologies in Heritage Buildings

Integrating renewable energy technologies, such as solar panels, is a modern approach to improving energy efficiency in historic buildings without affecting their architectural character. According to a study by(Polo López & Frontini, 2015), using integrated solar energy technologies can reduce energy consumption by up to 50%, with visual design considerations to maintain the building's aesthetic value.

Another study by (A & B, 2022), indicated that using electrochromic glazing can reduce thermal loads in the dry Season by 20%, contributing to improved thermal comfort and reduced reliance on air conditioning systems. This technology is a promising option for heritage buildings due to its ability to control the amount of light and heat entering without affecting the exterior design.

Application to Lawang Sewu:

Given the high solar altitude in Semarang due to its equatorial position, CIGS panels are more effective when integrated on shaded roof elements or awnings rather than vertical windows. This strategy ensures optimal solar exposure without excessive indoor heating. Additionally, the use of electrochromic glazing techniques further enhances thermal comfort by regulating daylight and solar heat gain. Together, these solutions provide a sustainable energy source while preserving the building's historical character.

Challenges and limitations in improving energy efficiency in heritage buildings

Enhancing energy efficiency in historic buildings involves technical, legal, and economic challenges that must be addressed without compromising cultural significance. Although retrofit technologies offer clear benefits, their application is often limited by strict heritage regulations that restrict alterations to original structures (Nair et al., 2022; Avellanosa et al., 2024; Silvero et al., 2018).

Ventilation issues also arise when using insulation methods that reduce airflow, potentially causing moisture buildup and mold, which threaten both occupant health and building preservation (Herrera-Avellanosa et al., 2024). Additionally, the high upfront cost of advanced technologies—such as electrochromic glazing and integrated photovoltaic systems—remains a major barrier, particularly for buildings where economic return is secondary to cultural value (Cabeza et al., 2018).

For Lawang Sewu, a protected heritage site in Semarang, these challenges are especially critical. Any proposed intervention requires careful economic and regulatory evaluation to ensure energy gains align with conservation standards and local policies (Karimi et al., 2024b).

A balanced approach is needed—one that integrates passive design, appropriate insulation, and renewable energy solutions without altering the building’s historic character. Technologies like electrochromic glazing and CIGS thin-film solar panels offer promising paths forward, as they enhance energy efficiency while respecting architectural integrity (Herrera-Avellanosa et al., 2024).

Integration of Renewable Energy Technologies in Heritage Buildings

The implementation of renewable energy technologies that incorporate solar panels presents a contemporary method to enhance historic buildings' energy efficiency without changing their architectural aesthetics. Research published by(Polo López & Frontini, 2015), shows integrated solar energy systems decrease building energy consumption by 50%, while designers must consider the visual aesthetics of the structure.

Research conducted by (A & B, 2022) proved electrochromic glazing lowers dry Season thermal loads by 20% while improving thermal comfort and diminishing air conditioning requirements. Buildings with heritage value benefit from electrochromic glazing because this technology enables exterior design preservation while controlling light and heat entry.

Lawang Sewu could integrate eco-friendly CIGS thin-film solar panels onto its rooftop or embed them into window structures through electrochromic glazing systems. This combination of solutions allows the building to maintain historical characteristics while generating sustainable energy.

Methodology

The research investigates the thermal comfort status together with energy use analysis of Lawang Sewu, which stands in Semarang, Indonesia, as a heritage site. Lawang Sewu was built during the Dutch colonial time in 1904 and stands out because of its unique red-brick walls along with neurotic architecture. The research utilizes field evaluation alongside simulation modeling and retrofit blueprint development to study Lawang Sewu existing condition as well as create sustainable conservation methods for sustaining its historical legacy.

Data Collection

The assessment of Lawang Sewu indoor environments required multiple in-depth measurements accumulated throughout a one-year period by using both field instruments and sophisticated monitoring tools. Temperature and relative humidity measurements spanned across two office rooms (Rooms 107 and 201) and two conference rooms (Rooms 102 and 208) at the Lawang Sewu building. Selection of the spaces occurred because their utilization patterns and occupant activities differed from one another. The building received continuous thermal parameter tracking through environmental sensors installed for this purpose.

The Heat transfer measurements using infrared thermography (Testo 875-1i infrared camera) complied with ISO 9869 standards for the Heat Flow Meter method (Cabeza et al., 2018). Testing via a blower-door apparatus combined with thermal inspection methodology provided data about heat flux and insulation leakage from the building exterior. The blower-door test application faced challenges because the building contained three stories. Site supervisors helped the team establish an air blower setup in Room 201 (volume: 128 m³), which possessed the biggest air volume among all building facilities. Room 105 served as the location for thermal transmittance evaluation because all testing equipment experienced an unobstructed space during measurement operations.

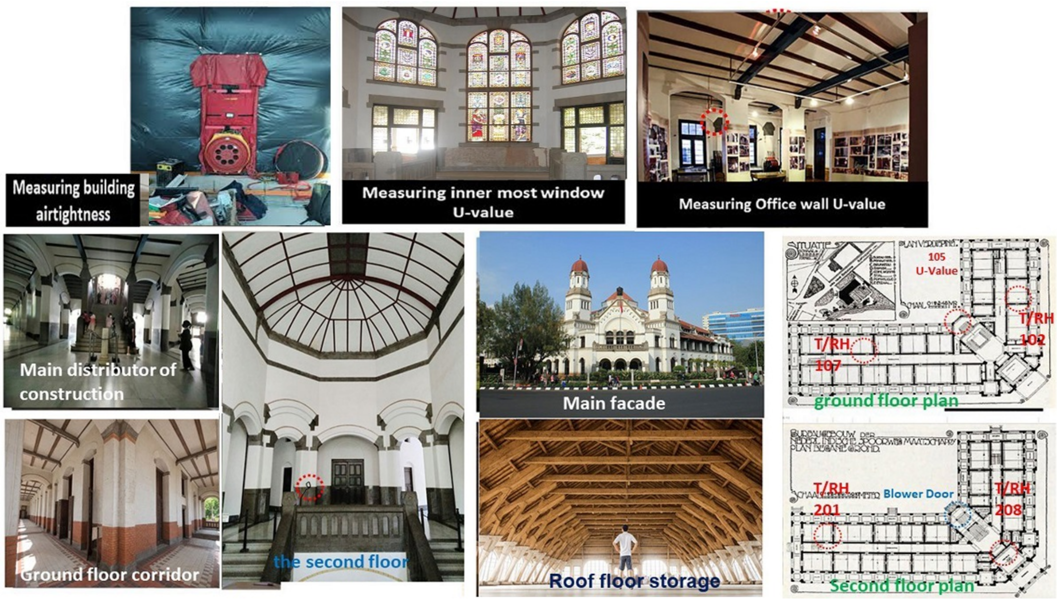


Figure 2. Building Condition and Instrumentation for In-situ Thermal Transmittance Measurements.
Source: Author

Results from these tests demonstrate how heat energy dissipates across each component of the building envelope. The analysis revealed areas that needed attention for enhanced thermal efficiency while protecting the historic value of the building.

Simulation Analysis

Researchers employed EnergyPlus simulation software (v9.4.0), a validated tool developed by the U.S. Department of Energy for thermal and HVAC performance analysis, to assess various retrofitting scenarios at Lawang Sewu and estimate their energy efficiency outcomes. The simulation model incorporated comprehensive input data, including envelope specifications, HVAC system parameters, and renewable energy configurations. To preserve architectural authenticity, the baseline model retained Lawang Sewu's original features—stone and concrete walls, double-glazed windows, and Spanish tile roofing. Occupant behavior profiles and lighting schedules were embedded to reflect realistic usage patterns. Thermal comfort assessments adhered to ISO 7730 standards through application of the Fanger Equation via the Predicted Mean Vote (PMV) index. The simulation also integrated Copper Indium Gallium Selenide (CIGS) photovoltaic panels, enabling evaluation of their contributions to energy utilization and indoor environmental quality enhancement (Cabeza et al., 2018; Gbran et al., 2025c).

Retrofitting Strategies

Multiple retrofit design solutions were evaluated for Lawang Sewu to achieve better energy performance without compromising its historical significance. This evaluation divided the strategies into three groups, which included passive measures alongside active implementations and renewable technologies.

- Electrochromic glazing served as a passive system designed to improve insulation properties and decrease heating needs. The system provides real-time solar heat gain management to maintain suitable indoor temperatures in all seasons.
- The installation of an Energy Recovery Ventilator (ERV) served two essential functions by enhancing indoor air quality while minimizing ventilation energy consumption. Heat recovery through the ERV system extracts waste heat from exhausted air to decrease heating or cooling requirements.
- The building incorporated CIGS PV panels on roofs and window blinds to develop renewable power systems, which diminished its dependency on traditional energy sources. Two scenarios were analyzed: one where the PV panels were installed directly on the roof surface and another where they were integrated into external awning blinds.

The benefit of this method is its ability to provide stable performance throughout the year without affecting the architectural aesthetics of the building.

Integrating photovoltaic panels into external shading structures – In this scenario, the panels are installed on exterior awnings or shading devices instead of the roof. This method creates a balance between shading and electricity generation, as the panels reduce the thermal radiation entering the building, decreasing the cooling demand.

a. Performance was evaluated using several indicators, including:
b. Predicted Mean Vote (PMV), a measure of occupants' thermal comfort based on temperature and humidity conditions.
c. Energy consumption (kWh/m²), assessing the impact of the new systems on reducing electricity demand.
d. Indoor temperature and humidity ranges, monitoring climate variations before and after implementation.
e. Thermal comfort limits, ensuring the modifications do not negatively impact the quality of indoor environments.

The study demonstrated that integrating solar panels into external shading devices helped reduce reliance on conventional energy sources while maintaining indoor thermal comfort, whereas rooftop installations showed better performance in terms of sustainable energy production. Let me know if you would like more details on a specific aspect.

Seasonal Influence on Indoor Environment

Data collection within the study was done according to seasonal patterns to analyze seasonal effects on indoor environmental conditions. The temperature variations between office rooms and conference rooms became more aligned because building heating and cooling systems remained inactive in rainy season. Researchers attributed this variation to both the number of building occupants and their consumption patterns because occupants emit heat within the building (Habaibeh et al., 2022).

The intense dry Season humidity in conference rooms resulted in thermal discomfort and raised the likelihood of mold growth. As a result, ensuring adequate ventilation—whether through natural or mechanical means—became critically important. The heated office environment maintained lower relative humidity values than unheated conference rooms due to higher temperature characteristics of water vapor pressure (Cabeza et al., 2018).

Evaluation of Retrofit Packages

The proposed retrofit packages received assessment through measurements of their effects on energy usage and thermal comfort conditions. Electrochromic glazing reduced heating energy demand by 7.83% while causing a rise in cooling energy demands by 11.19%. After integrating ERV systems, the energy consumption for heating and cooling simultaneously grew as heating energy usage increased by 26.62%. Major energy savings emerged from implementing CIGS PV systems in combination with other renewable energy technologies (Cabeza et al., 2018) . The application of PV systems on top of the roof surface delivered energy savings that reached 90.46% during yearly use compared to the reference building. By adding PV blinds to the building facade, the energy-saving potential rose through reduced cooling energy consumption by 17.93% at the expense of slightly more heat consumption because of shading effects (Cabeza et al., 2018).

Consideration of Design ability

The designers focused their work on ensuring the design ability of proposed retrofit solutions because the building carries valuable cultural and aesthetic importance. CIGS PV panels on exterior awnings served the purpose of energy generation, but they struggled to blend with Lawang Sewu's historical look and feel (Cabeza et al., 2018). The dark appearance of these elements created a stark contrast with the existing red-brick structure, thus creating an unacceptable visual impact on the building's appearance. An extra evaluation process took place to achieve a balance between energy performance and both thermal comfort and design possibilities. A combination of passive and renewable energy systems without external blinds (PA_RN package) proved to be the optimal solution for Lawang Sewu according to the evaluation results (Cabeza et al., 2018).

Result

The research investigation analyzed both the energy performance and thermal comfort levels at Lawang Sewu, situated in Semarang, Indonesia. The researcher obtained results through field measurements and simulation analyses and evaluations of different retrofitting approaches. This research details the results according to an organized and documented format.

Indoor Environmental Conditions

The study conducted a field assessment spanning one year, which measured temperature alongside humidity in different spaces of Lawang Sewu. The research examined two offices in Rooms 107 and 201 and two conference facilities in Rooms 102 and 208. Occupant numbers and the scheduling of space usage showed major effects when evaluating temperature conditions in different areas.

This figure 3 presents the measured environmental changes along with their correlation to building usage patterns and seasonal fluctuations of temperature and humidity.

See figure 3 illustrates the annual variations in indoor temperature and humidity for offices (Rooms 107, 201), the conference room (102), and the main entrance (208) of Lawang Sewu. The offices exhibit relatively stable temperatures

(24°C–30°C) due to thermal mass effects and consistent occupancy, while the conference room shows wider fluctuations (22°C–28°C) due to intermittent HVAC use. The main entrance experiences the most significant swings (26°C–32°C) from direct solar exposure and frequent door openings.

Humidity data reveal peak levels in the conference room during the wet season (up to 90% RH), humidity levels were recorded using HOBO UX100-011 sensors installed in selected rooms (see Section 3.1), *and compared across seasons based,* raising mold risks, while offices maintain steadier conditions (60–70% RH). These findings highlight the need for improved ventilation and shading in intermittently occupied zones, as discussed in the thermal comfort analysis (Section 4.3). Data was collected using HOBO UX100-011 sensors, with margins of ±0.5°C (temperature) and ±5% (humidity).

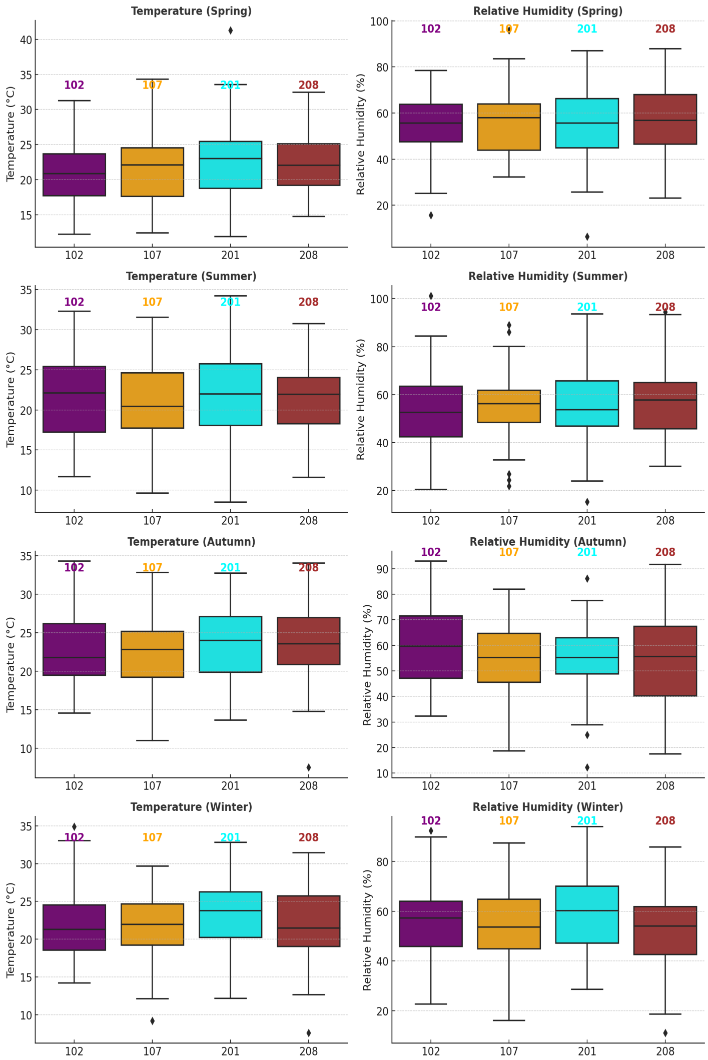


Figure 3. Changes in the internal environment of the offices (107, 201), the conference room (102) and the main entrance (208).
Source: Author.

During weekdays from 9:00 AM to 6:00 PM, office rooms were continuously occupied, while remaining largely unoccupied on weekends. Indoor temperatures within the building spaces ranged from approximately 24°C to 30°C, primarily influenced by the tropical climate, internal heat gains from occupants and lighting, and the lack of active cooling systems in some areas of Lawang Sewu (Koh et al., 2018). The temporary conference rooms were only conditioned during use, resulting in a wider temperature variation ranging from about 22°C to 28°C. Outdoor temperatures significantly affected indoor conditions across different seasons due to the building's limited insulation and natural ventilation strategies. Throughout the milder dry season months, both office and conference rooms exhibited less temperature fluctuation as mechanical cooling systems were generally inactive, relying on passive design features. The research team attributed the variations in temperature primarily to the number of occupants generating internal heat, which plays a critical role in indoor thermal dynamics in tropical office buildings (Havinga & Schellen, 2018).

During dry Season months, the conference rooms showed increased humidity, which caused both discomfort to occupants and made mold formation more probable. Studied research indicates natural or mechanical ventilation strategies as solutions to resolve these problems (Havinga & Schellen, 2018). Heated office areas experienced lower relative humidity levels than conference areas exposed to outdoor temperatures because high temperatures affect the behavior of vapor pressure (Cabeza et al., 2018).

Impact of Retrofitting Strategies on Energy Consumption

The research examined the energy usage modifications achieved through different retrofitting methods at Lawang Sewu. Heating energy decreased by 7.83% through the installation of double-layer electrochromic glazing; these energy consumption values were simulated using the EnergyPlus model (Section 3.2), where electrochromic glazing performance was parameterized based on real-world SHGC data from field analysis.

However, this strategy increased cooling energy usage by 11.19%. Including an electrochromic SHGC in the windows enabled enough sunlight to enter buildings during rainy season months to improve thermal energy efficiency (Arumägi et al., 2015).

The implementation of energy recovery ventilation systems as a mold prevention strategy resulted in higher energy consumption throughout the heating and cooling season. The energy consumption for building cooling rose by 13.55% over the existing building design, but the heating energy consumption surged by 26.62% (Harrestrup & Svendsen, 2016). Energy savings became significant when renewable energy technologies were combined through the installation of Copper Indium Gallium Selenide (CIGS) photovoltaic systems. Analysis shows that installation of CIGS panels on roof surfaces enables buildings to use 90.46% less annual energy than reference buildings (Arumägi & Kalamees, 2014). The external application of CIGS panels as building blinds lowered cooling energy needs by 17.93% but caused a 3.92% heating energy usage hike (Tagliabue et al., 2012).

Thermal Comfort Analysis

The Fanger Equation (PMV index) helped assess occupant comfort during several retrofitting situation analyses for thermal comfort analysis. The first floor thermal comfort zone rested near the median standard more than the second floor comfort zone did. The researchers attributed this variation to the diverse characteristics that the ceiling surfaces encountered (Mainini et al., 2015).

These PMV values were derived from hourly indoor temperature and humidity data collected during the field monitoring phase (Section 3.1), and analyzed using the EnergyPlus simulation model based on ISO 7730 standards, as described in Section 3.2.

The installation of windows with high solar gain coefficients in Room 107 created better thermal comfort because it reduced cold temperature discomfort and brought PMV values into the comfort zone. The installation of external awning blinds caused occupants to experience colder feelings due to created shadows (Al-Habaibeh et al., 2022).

Thermal comfort in the first-floor corridor changed substantially based on seasonal variations because this area lacked air conditioning equipment. The installation of AHU systems and improved windows in stairwell areas worked effectively to improve the comfort experience of building users (Al-Habaibeh et al., 2022). Across the observation period, PMV values scored a remarkable improvement for occupants of the hallway and remained within the −0.5 to +0.5 range (Walker & Pavía, 2015). However, the occupants' comfort in general office spaces registered a slight decrease. According to A and B, (2022), external canopy blinds were evaluated as a factor that only increased the thermal discomfort of residents.

Design ability Considerations

The implementation of energy recovery ventilation systems as a mold prevention strategy resulted in higher energy consumption throughout the heating and cooling season. The energy consumption for building cooling rose by 13.55% over the existing building design, but the heating energy consumption surged by 26.62% (Harrestrup & Svendsen, 2016). Energy savings became significant when renewable energy technologies were combined through the installation of Copper Indium Gallium Selenide (CIGS) photovoltaic systems. Analysis shows that installation of CIGS panels on roof surfaces enables buildings to use 90.46% less annual energy than reference buildings (Arumägi & Kalamees, 2014). The external application of CIGS panels as building blinds lowered cooling energy needs by 17.93% but caused a 3.92% heating energy usage hike (Tagliabue et al., 2012).

Thermal Comfort Analysis

The Fanger Equation, expressed through the Predicted Mean Vote (PMV) index, was employed to evaluate occupant thermal comfort across various retrofit scenarios. Results indicated that the first-floor thermal comfort zone aligned more closely with the median PMV standard compared to the second floor. This discrepancy was attributed to the differing thermal behaviors of ceiling surfaces, which influenced radiant heat exchange and overall comfort conditions ((Mainini et al., 2015).

Summary of Key Results

- The application of CIGS PV systems on the roof reduced annual energy consumption by up to 90.46%, demonstrating the significant potential of renewable energy technologies in heritage buildings (Arumägi & Kalamees, 2014).
- Retrofitting strategies such as electrochromic glazing and AHU systems improved occupant comfort, particularly in spaces with high occupancy (Habaibeh et al., 2022).
- External awning blinds with CIGS panels posed challenges in terms of visual compatibility with the building's historic appearance (Rebec et al., 2022).
- The PAR_R package was identified as the most balanced solution, considering energy efficiency, thermal comfort, and preservation of architectural aesthetics (Organization & Standardization, 2014), (Ahmad et al., 2015).

Thermal comfort in the first-floor corridor changed substantially based on seasonal variations because this area lacked air conditioning equipment. The installation of AHU systems and improved windows in stairwell areas worked effectively to improve the comfort experience of building users (Mankibi et al., 2015). Across the observation period, PMV values scored a remarkable improvement for occupants of the hallway and remained within the −0.5 to +0.5 range(Walker & Pavía, 2015). However, the occupants' comfort in general office spaces registered a slight decrease.

Discussion

This study examines the impact of retrofit strategies on the energy consumption and thermal comfort of Lawang Sewu, a heritage building in Semarang, Indonesia. The findings highlight the interplay between occupant behavior, seasonal variations, and applied retrofit techniques, demonstrating how these factors collectively contribute to sustainable solutions that balance historic preservation with functional enhancement in architectural heritage.

Impact of Retrofit Package Composition on Energy Consumption

The researchers evaluated the Lawang Sewu energy needs for passive, active, and renewable energy packages as retrofit options. A stable indoor environment received priority status for the heritage building thanks to the package terminal heat pump (PTHP). An upgrade of the building envelope along with facility systems needed installation to minimize heating energy usage(Havinga & Schellen, 2018).

Given the high humidity levels in Semarang, particularly during the wet season (December to March), building envelopes with low permeability and high ventilation potential are critical to prevent condensation and mold growth. This observation aligns with studies on tropical heritage buildings in Southeast Asia, which emphasize passive cross-ventilation as a core design strategy.

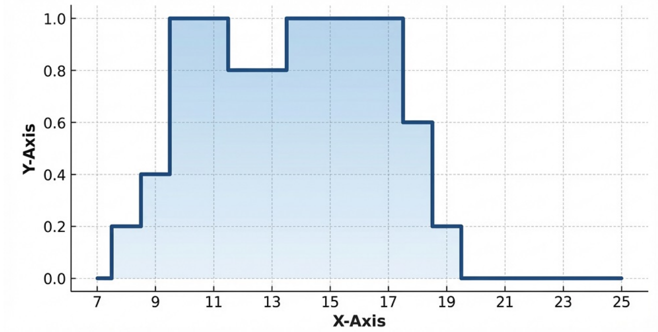
The retrofit plan excluded modifications to wall layers for the purpose of preserving heritage value (Table 1 provides a summary of key strategies). Results showed:

1. Single-pane window replacement by double-layer electrochromic glazing
2. (SHGC ≥ 0.77) decreased heating energy by 7.83% yet raised cooling energy by 11.19%(Wi et al., 2020).
3. ERV implementation led to a heating and cooling energy use rise of 26.62% and 13.55% relative to the non-retrofitted building operation.
4. Researchers investigated the integration of photovoltaic panels based on copper indium gallium selenide (CIGS), either mounted on rooftops or integrated as window blinds, and observed varying performance outcomes across configurations.
   - The application of roofs had a minimal effect on both heating and cooling energy requirements.
   - Exposure of blinds to sunlight resulted in heating energy increasing by 3.92% along with cooling energy reduction by 17.93% because of shading (Park et al., 2019).

The implementation of PA_RN without PV blinds demonstrated the best retrofit solution because it produced between 85.91 and 90.46% total energy savings (B et al., 2021). The near-zenith solar angle during midday throughout the year in Semarang significantly influences solar gain patterns. Thus, horizontal shading elements and PV integration on sloped awnings are more effective than vertical facade applications.

Table 1. Input parameters for the simulation used in energy and thermal comfort evaluation.

Categorization	Items	Description
Reference	Stone and concrete construction, paired with dual-pane glazed windows, a packaged terminal heat pump (PTHP) system, domestic hot water (DHW) solutions, and electrochromic glazing technology.	- Thermal transmittance [W/m²K]: 0.926 for walls and 0.513 for floors. - Window thermal transmittance [W/m²K]: ±2.9. - Coefficient of Performance (COP) for the packaged terminal heat pump: 4.0 in heating mode and 3.2 in cooling mode. - Domestic hot water (DHW) system COP: 0.87 (LPG-based). - Light transmission ratio: 0.804.
Active system	Energy recovery ventilator (ERV)	- Solar energy gain factor (SHGC): 0.77. - Heat transfer coefficient [W/mK]: 0.87, with an operational efficiency of 82%.
Renewable system	CIGS PV roof CIGS PV blinds	Pmax=277 W, Efficiency: 22% Efficiency: 82% Pmax=277 W, Efficiency: 22% Pmax=277 W, Efficiency: 22%



Inhabitants	Hot Water Systems, Climate Control, and Artificial Lighting	The building's operational schedule was set from 08:00 to 20:00 daily. Internal activity was classified as 'light office work' (ASHRAE activity level 03), corresponding to low metabolic rates typical of administrative tasks. During simulations, distinct seasonal parameters were applied—identified as dry Season 06' for cooling periods and rainy season 1.2' for heating loads. Indoor air velocity was maintained at an average of 0.138 meters per second. The ventilation rate was simulated at 22.02 Air Changes per Hour (ACH), indicating a high-performance ventilation system designed to ensure optimal indoor air quality in line with comfort and health standards.
seepage	PMV (Fanger equation)	-

Source: author, Data: (Chang et al., 2021b), (Gigliarelli et al., 2022), (Cabeza et al., 2018)

To conduct a systematic assessment of the building's energy performance and thermal comfort under various retrofit scenarios, the technologies implemented were categorized into three strategic groups: passive design measures, active control systems, and renewable energy solutions. Table 2 outlines the scope and function of each strategy, specifying its contribution to building envelope enhancement, occupant well-being, and energy efficiency optimization. This tripartite classification enables a structured comparative analysis of retrofit combinations, supporting evidence-based decisions aimed at advancing sustainable architectural practices.

Table 2. Technical Characteristics of Retrofit Technologies Applied to Heritage Buildings.

Category	System Composition	Strategic Objective
PA	Smart electrochromic window systems (EC)	Enhancing the performance of the building envelope while reducing heating-related energy loads.
AC	Energy recovery ventilation system (ERV)	Maintaining high levels of thermal comfort and indoor air quality for occupants.
RN	CIGS-based photovoltaic blinds integrated into roof and window assemblies	Achieving substantial reductions in annual energy demand through on-site renewable energy generation.
PA–AC	Combined electrochromic glazing and energy recovery ventilation (EC + ERV)	Integrating envelope optimization with improved indoor comfort performance.
PA–RN	Electrochromic glazing coupled with CIGS photovoltaic systems (EC + CIGS)	Lowering yearly energy consumption through advanced façade design and renewable energy integration.
AC–RN	Energy recovery ventilation combined with CIGS photovoltaic blinds (ERV + CIGS)	Improving indoor environmental quality to support prolonged daily operational periods.
PAR	Integrated electrochromic glazing, energy recovery ventilation, and CIGS photovoltaics (EC + ERV + CIGS)	Providing a comprehensive retrofit strategy that simultaneously addresses energy conservation and functional adaptability.

Source: author, (Cabeza et al., 2018) (Rahmaniya & Dwiyanto, 2024)

The implementation of energy recovery ventilation as a protective measure for building structures and mold prevention resulted in increased loads on both heating and cooling systems. When facility systems have high installation costs, there still exists potential to integrate new and renewable energy (NRE) sources. NRE sources were utilized for solar power generation as a major choice within renewable energy technologies during this research. The photovoltaic system was utilized as thin film strips instead of standard CIGS panels. CIGS is ranked as the top thin-film solar cell technology with a maximum photoelectric conversion efficiency of 22.6% (Park et al., 2019). Utilization of CIGS material on the rooftop surface yielded minimal effects on these energy parameters because the roof surface lacked an awning.

Installation of blinds requires thorough evaluation before retrofitting projects because they might diminish the aesthetic appeal of building facades. A complex combination package was built for each technology after taking results from energy analysis into consideration. A thorough examination of the elements' package composition and energy results confirmed that passive technology decreases heating energy consumption, yet active technology increases heating energy consumption. Vacuum insulation pans have higher energy losses but must be implemented as other elements play crucial roles in both comfort levels and mold prevention practices. Application of the PA_RN package without PV blinds led to total energy savings from 85.91% to 90.46% during validation testing (Cabeza et al., 2018).

Variations in Thermal Comfort for Occupants

Occupant comfort evaluations relied on the Fanger equation to assess both heritage building energy analysis and retrofit package outcomes. The first floor thermal comfort zone displayed tighter proximity to its median comfort level compared to the second floor due to potential ceiling surface characteristics (López & Frontini, 2014).

The unconditioned storage area directly above the second floor underwent unexpected rapid shifts in temperature and humidity because of external air dynamics. Analysis of this area compared the effects between these elements on occupant comfort through testing Room 107 and first-floor hallway sections as model spaces containing air conditioning and non-air conditioning systems. In Room 107, the analysis of occupant comfort showed that substituting the high solar-gain coefficient window with additional insulation resulted in higher comfort standards by eliminating thermal discomfort from cold situations. The retrofit work on building infrastructure did not lead to improved occupant comfort because the measured thermal comfort index manifested cold leanings. Research results demonstrate that using air handling units (AHUs) in rooms with numerous people present should not be deployed. A study by (Khan & Bhattacharjee, 2021) showed external awning blinds led to a higher likelihood of occupants feeling cold since shadows were created by the blinds during application.

Quantities of inhabitants were higher in Room 107, but the corridor's few occupants worked without air conditioning. Users in this area had to deal with substantial changes in comfort due to seasonal temperature shifts. The research investigated how retrofitting technologies affect the thermal comfort of building occupants within these spaces. The implementation of PA technology reduced the negative effects of cold temperatures while slightly increasing the effect of heat for participants. The retrofitting method showed effective results after modification of the stairwell window despite not being implemented on corridor windows. The application of the AHU system delivered the best overall results regarding retrofitting (Arumägi et al., 2015).

Let's examine how standards of thermal comfort reduced in typical office areas, although the hallway maintained consistent PMV values between −0.5 and +0.5 throughout most of the monitoring period. External awning blinds functioned independently as the sole element responsible for creating more discomfort during thermal experiences among occupants.

Unlike temperate climates where thermal discomfort stems from extreme cold, occupants in Semarang typically experience discomfort due to prolonged heat retention and lack of night cooling. Retrofit strategies must therefore address diurnal thermal lag through insulation and strategic ventilation.

The study implemented refined retrofit strategies, integrating renewable energy components across multiple architectural elements. Simulations were conducted in two distinct scenarios during the rainy season: one incorporating CIGS photovoltaic materials on the roof only, and the other combining roof and external blinds. Thermal comfort analysis revealed that the most favorable indoor conditions were achieved when passive architecture (PA) and air conditioning (AC) systems were jointly applied with CIGS insulation on both surfaces—specifically in Room 107 and the adjacent corridor. The retrofit sequence showed consistent performance rankings: PA_AC yielded the highest comfort, followed by PA alone, then PA_RN_R+B. Notably, the addition of external awnings altered simulation outcomes significantly, suggesting that retrofit effectiveness may vary under different climatic conditions (Cabeza et al., 2018).

Analysis of Differences with a Focus on Design Integration

The research examined the essential architectural foundations of performance quality alongside building stability and appearance. Researchers executed a supplementary assessment of CIGS external awning blinds to measure both energy efficiency and occupant comfort, specifically regarding their suitability for heritage structures. Builders primarily focus on architectural preservation of historical sites during retrofitting activities (Valagussa et al., 2021). The dark color scheme of CIGS external awning blinds creates an oppositional visual effect against the established heritage building style.

The study conducted an evaluation to understand how the blinds would affect energy efficiency alongside occupant comfort. The findings led to a decision about including these strategies in the Lawang Sewu retrofit plan. Energy consumption data from new renewable energy technology applications showed results for different configurations named PA, AC, and PA_AC. The combination of PA_RN_R+B achieved the greatest reduction in energy consumption, according to (Tagliabue et al., 2012).

Thermal comfort defines a different best solution from other parameters. Table 3 reveals that thermal comfort reached its most optimal range when using both AC and PA (PAR_R) together. Retrofit package selection must strike a proper balance between energy-efficient measures and acceptable indoor environmental conditions.

Table 3. Variation in Occupant Thermal Comfort across Retrofit Package Configurations.

Classification	Details	PV installation position	PMV range (Min.) / (Max.)
Reference	-	×	–1.84 (Cool) / +1.11 (Warm)
RN_R	Renewable Systems (optimize energy consumption)	Roof	–1.84 (Cool) / +1.11 (Warm)
RN_R+B	Renewable Systems (optimize energy consumption)	Roof and Blinds	–1.89 (Cool) / +0.98 (Slightly warm)
PA_RN_R	Glazing and Renewable Systems (Manage solar heat gain and optimize energy efficiency)	Roof	–1.70 (Cool) / +1.16 (Warm)
PA_RN_R+B	Glazing and Renewable Systems (Manage solar heat gain and optimize energy efficiency)	Roof and Blinds	–1.75 (Cool) / +1.03 (Warm)
AC_RN_R	Energy Recovery Ventilator and Renewable Systems (Boost comfort and optimize energy efficiency)	Roof	–0.40 (Neutral) / +0.21 (Neutral)
AC_RN_R+B	Energy Recovery Ventilator and Renewable Systems (Boost comfort and optimize energy efficiency)	Roof and Blinds	–0.41 (Neutral) / +0.19 (Neutral)
PAR_R	Comprehensive renovation package	Roof	–0.37 (Neutral) / +0.21 (Neutral)
PAR_R+B	Comprehensive renovation package	Roof and Blinds	–0.38 (Neutral) / +0.19 (Neutral)

Source: Author, data: (Cabeza et al., 2018; Cabeza et al., 2018; Cabeza et al., 2018; Cabeza et al., 2018; Lidelöw et al., 2019; Harrestrup & Svendsen, 2016; Harrestrup & Svendsen, 2016; El Mankibi et al., 2015).

PA_RN exhibited the minimal yearly energy usage among all available configurations, yet PA_AC delivered peak indoor comfort levels to occupants. Studies show that PAR_R achieved the best combination between energy performance and design compatibility to become the optimal retrofit solution. The ultimate retrofit strategy needs careful consideration because it depends on the distinctive environmental circumstances (Al-Habaibeh et al., 2022).

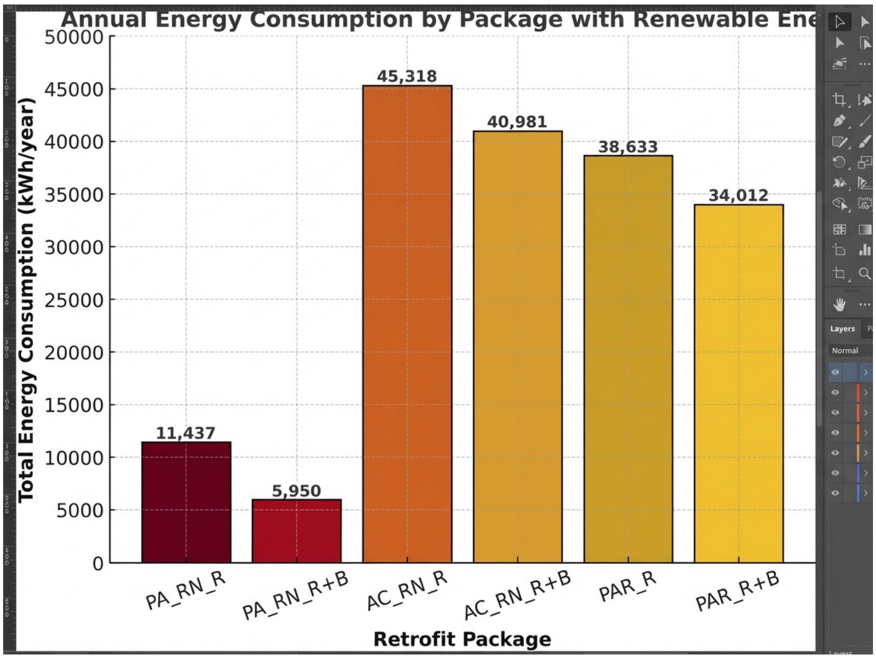


Figure 4. Annual energy consumption patterns by retrofit package, illustrating the effects of integrating new and renewable energy sources.
Source: Author

Despite these advancements, fully realizing the energy-saving potential of heritage buildings remains challenging. The research suggests that the PA_RN_R package would successfully integrate with Lawang Sewu and offer desired performance outcomes of energy efficiency alongside thermal comfort and aesthetic compatibility.

Conclusion

The primary goal of renovating heritage buildings, including Lawang Sewu in Semarang, is to preserve their historical integrity while improving environmental comfort and energy efficiency for long-term sustainability. This research highlights how seasonal changes impact underutilized spaces, revealing that humidity levels exceed 70% in rainy season and reach 90% in dry Season when measured during the wettest season and according to Indonesian weather websites. These findings underscore the need for targeted architectural and structural improvements to mitigate discomfort and prevent mold growth.

Occupant comfort was a central focus in evaluating non-air-conditioned areas. The retrofitting of hallways with facility systems effectively maintained a PMV range of −0.5 to +0.5 for most of the year. The integration of PA_AC technology proved most effective in enhancing thermal comfort, while PAR_R emerged as the most energy-efficient solution among the evaluated retrofit packages.

Despite advancements in energy-saving solutions, fully realizing the potential of heritage buildings remains challenging. The findings suggest that the PA_RN_R package presents a viable solution for buildings like Lawang Sewu, as it integrates energy conservation, occupant comfort, and architectural compatibility. However, modifications to cultural heritage buildings must align with preservation guidelines and aesthetic principles to maintain historical authenticity. Renewable energy systems should be discreetly incorporated to minimize visual impact while maximizing efficiency.

A comprehensive retrofitting approach that strategically combines passive, active, and renewable energy systems is essential for preserving Lawang Sewu's historical value while ensuring long-term sustainability and operational efficiency. By integrating modern energy strategies within conservation frameworks, heritage buildings can achieve optimal energy performance without compromising their cultural significance.

CRedit and statement of contribution:

- **Hassan Gbran**: Writing – Original Draft, Conceptualization.
- **Siti Rukayah**: Supervision, Investigation.
- **Atik Suprapti**: Supervision, Investigation.

Declaration of competing interest: 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

Acknowledgement

Acknowledgements this work was supported by a scholarship grant from Diponegoro University for doctoral studies Indonesia. Special thanks to the university president for the excellence scholarship granted to pursue this doctoral degree. Gratitude is also extended to the International Office for International Students, the supervisors represented by the Dean of the Faculty of Engineering, the heads of the doctoral program, Professor Atik Suprapti and master's program, Professor Siti Rukayah, the head of the Department of Architecture, Professor Suzanna Ratih Sari, and Dr. Edward for their valuable contributions and guidance.

References

A, E. L., & B, A. B. (2022). *Urban green rating systems: Insights for balancing sustainable principles and heritage conservation for neighbourhood and cities renovation planning*. https://doi.org/10.1016/j.rser.2022.112324

A, L. C., B, M. B., C, A. B., D, S. H. A., E, B. R., G, A. J. S. f, J, S. S. h i, & K, A. A. (2024). A comprehensive review of a building-integrated photovoltaic system (BIPV). *International Communications in Heat and Mass Transfer*. https://doi.org/10.1016/j.icheatmasstransfer.2024.108056

Ahmad, A., Maslehuddin, M., & Al-Hadhrami, L. M. (2015). In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2014.07.048

Al-Habaibeh, A., Hawas, A., Hamadeh, L., Medjdoub, B., Marsh, J., & Sen, A. (2022). Enhancing the sustainability and energy conservation in heritage buildings: The case of Nottingham Playhouse. *Frontiers of Architectural Research*, *11*(1), 142–160. https://doi.org/10.1016/j.foar.2021.09.001

Arumägi, E., & Kalamees, T. (2014). *Analysis of energy economic renovation for historic wooden apartment buildings in cold climates*. https://doi.org/10.1016/j.apenergy.2013.10.041

Arumägi, E., Pihlak, M., & Kalamees, T. (2015). Reliability of interior thermal insulation as a retrofit measure in historic wooden apartment buildings in cold climate. *Energy Procedia*, *78*, 871–876. https://doi.org/10.1016/j.egypro.2015.11.010

B, X. F. a, C, D. N., E, Q. Y. a d, E, Y. L. a d, E, X. Z. a d, F, J. H. H., G, Z. H., H, F. A., B, Q. H., E, Y. D. a d, & E, Y. S. a d. (2021). *Association between indoor microbiome exposure and sick building syndrome (SBS) in junior high schools of Johor Bahru, Malaysia*. https://doi.org/10.1016/j.scitotenv.2020.141904

Beta Paramita, M. R. N. & A. N. H. (2024). *Enhancing Facade Design to Improve Energy Efficiency of Office Towers in the Hot and Humid Climate Region (Case Study: Bandung, Indonesia)*. https://doi.org/10.1007/978-981-97-8401-1_16

Cabeza, L. F., de Gracia, A., & Pisello, A. L. (2018). Integration of renewable technologies in historical and heritage buildings: A review. *Energy and Buildings*, *177*, 96–111. https://doi.org/10.1016/j.enbuild.2018.07.058

Chang, B., Hasanah, A., & Caesarina, H. M. (2021a). Cultural ecology of heritage building adaptation in tropical cities. *IOP Conference Series: Earth and Environmental Science*, *780*(1), 012058.

https://doi.org/10.1088/1755-1315/780/1/012058

Chang, B., Hasanah, A., & Caesarina, H. M. (2021b). Cultural ecology of heritage building adaptation in tropical cities. IOP Conference Series: Earth and Environmental Science, 780(1). https://doi.org/10.1088/1755-1315/780/1/012058

El Mankibi, M., Cantin, R., & Zoubir, A. (2015). Contribution to the thermal renovation of old buildings: Numerical and Experimental approach for characterizing a double window. Energy Procedia, 78(0), 2470–2475. https://doi.org/10.1016/j.egypro.2015.11.231

Gbran, H. (2024). Preserving history in a modern setting: An adaptive redesign of Lawang Sewu for sustainable development and architectural heritage conservation. International Journal of Architecture and Urbanism, 7(3). https://doi.org/10.32734/ijau.v7i3.13748

Gbran, H. (2025). Thermal performance of glass and aluminum composite panel building envelopes. ARTEKS: Jurnal Teknik Arsitektur, 10(3), 463–482. https://doi.org/10.30822/arteks.v10i3.3582

Gbran, H., & Alzamil, W. (2025). Achieving sustainable housing in smart cities: The role of model-based engineering in developing complex systems in line with Vision 2030. Smart Construction and Sustainable Cities, 3(24). https://doi.org/10.1007/s44268-025-00062-w

Gbran, H., & Ratih Sari, S. (2024). Studying the visual impact of modern construction on historic cityscapes: A case study of the Lawang Sewu building, Indonesia. Contexto, 18(28), 15–34. https://doi.org/10.29105/contexto18.28-410

Gbran, H., Rukayah, S., Suprapti, A., & Pandelaki, E. (2025a). AI-IoT for tropical heritage conservation: Scoping review and case framework Lawang Sewu. Proceedings of the Institution of Civil Engineers – Engineering History and Heritage, 178(4), 171–193. https://doi.org/10.1680/jenhh.25.00023

Gbran, H., Rukayah, S., Suprapti, A., & Pandelaki, E. E. (2025b). 2D radiometric mapping of chromatic decay in heritage façades via photogrammetric atlases. DIMENSI: Journal of Architecture and Built Environment, 52(2), 129–144. https://doi.org/10.9744/dimensi.52.2.129-144

Gbran, H., Rukayah, S., Suprapti, A., & Pandelaki, E. E. (2025c). A hybrid framework employing deep learning for 3D decay segmentation and adaptive mapping of heritage structures: Insights from an experiment. ISVS E-Journal, 12(4), 101–135. https://doi.org/10.61275/ISVSej-2025-11-04-06

Gbran, H., & Sari, S. R. (2023). The visual impact of modern constructions on old cities in Indonesia: The Lawang Sewu building in Semarang. ISVS E-Journal, 10(2), 71–90. https://isvshome.com/pdf/ISVS_10-2/ISVSej_10.2.5_Hasan.pdf

Gbran, H., & Murtiono, H. (2026). A hybrid geometric–radiometric embedding for intelligent diagnostics of tropical heritage infrastructure. Research Square (Preprint). https://doi.org/10.21203/rs.3.rs-7889872/v1

Gigliarelli, E., Calcerano, F., Martinelli, L., Artopoulos, G., Thravalou, S., & Alexandrou, K. (2022). Methodology for the Energy Renovation of Heritage Buildings Using BIM.

Harrestrup, M., & Svendsen, S. (2016). Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick facades. *Building and Environment*, *99*, 59–72. https://doi.org/10.1016/j.buildenv.2016.01.019

Havinga, L., & Schellen, H. (2018). Applying internal insulation in post-war prefab housing: Understanding and mitigating the hygrothermal risks. *Building and Environment*, *144*(May), 631–647. https://doi.org/10.1016/j.buildenv.2018.08.035

Hidayat, M. S., Permata, S., & Damayanti, S. (2024). *Thermal Performance Evaluation and Its Effect on Visitor Comfort and Exhibits in Museum Bahari Jakarta*. *08*(02), 149–153.

Karimi, H., Adibhesami, M. A., Hoseinzadeh, S., Movafagh, S., Estalkhsari, B. M., & Garcia, D. A. (2024). Solar energy integration in heritage buildings: A case study of St. Nicholas Church. *Energy Reports*, *11*(April), 4177–4191. https://doi.org/10.1016/j.egyr.2024.03.043

Khan, N. A., & Bhattacharjee, B. (2021). Thermal and noise insulation performance interaction of building envelope during building simulation optimization in tropical climates. *Building and Environment*, *200*(May), 107948. https://doi.org/10.1016/j.buildenv.2021.107948

Koh, K., Al-Kayiem, H. H., & Kurnia, J. C. (2018). Thermal Comfort Assessment of an Office Building in Tropical Climate Condition. *MATEC Web of Conferences*, *225*, 1–6. https://doi.org/10.1051/matecconf/201822501003

Lidelöw, S., Örn, T., Luciani, A., & Rizzo, A. (2019). Energy-efficiency measures for heritage buildings: A literature review. *Sustainable Cities and Society*, *45*, 231–242. https://doi.org/10.1016/j.scs.2018.09.029

Loli, A., & Bertolin, C. (2018). Towards zero-emission refurbishment of historic buildings: A literature review. *Buildings*, *8*(2). https://doi.org/10.3390/buildings8020022

Mainini, A. G., Bonato, D., Poli, T., & Speroni, A. (2015). Lean strategies for window retrofit of Italian office buildings: Impact on energy use, thermal and visual comfort. *Energy Procedia*, *70*, 719–728. https://doi.org/10.1016/j.egypro.2015.02.181

Menteşe, S. (2022). *8 - Airborne bacteria and sick building syndrome (SBS)*. https://doi.org/10.1016/B978-0-323-85206-7.00007-1

Organization, I., & Standardization, F. (2014). *Thermal Insulation: Building Elements: In-situ Measurement of Thermal Resistance and Thermal Transmittance. Part 1: Heat Flow Meter Method*.

Park, J. H., Jeon, J., Lee, J., Wi, S., Yun, B. Y., & Sumin Kim. (2019). *Comparative analysis of the PCM application according to the building type as retrofit system*. https://doi.org/10.1016/j.buildenv.2019.01.048

Polo López, C. S., & Frontini, F. (2014). Energy efficiency and renewable solar energy integration in heritage historic buildings. *Energy Procedia*, *48*(0), 1493–1502. https://doi.org/10.1016/j.egypro.2014.02.169

Rahmaniya, L. I., & Dwiyanto, A. (2024). Experimental Study on Design of External Shading Devices in Dental Unit Room. *Journal of Architectural Design and Urbanism*, *6*(2), 74–81. https://doi.org/10.14710/jadu.v6i2.21858

Rebec, K. M., Deanovič, B., & Oostwegel, L. (2022). Old buildings need new ideas: Holistic integration of conservation-restoration process data using Heritage Building Information Modelling. *Journal of Cultural Heritage*, *55*, 30–42. https://doi.org/10.1016/j.culher.2022.02.005

Tagliabue, L. C., Leonforte, F., & Compostella, J. (2012). Renovation of an UNESCO heritage settlement in southern Italy: ASHP and BIPV for a “Spread Hotel” project. *Energy Procedia*, *30*, 1060–1068. https://doi.org/10.1016/j.egypro.2012.11.119

Valagussa, A., Frattini, P., Crosta, G., Spizzichino, D., Leoni, G., & Margottini, C. (2021). Multi-risk analysis on European cultural and natural UNESCO heritage sites. *Natural Hazards*, *105*(3), 2659–2676. https://doi.org/10.1007/s11069-020-04417-7

Walker, R., & Pavía, S. (2015). *Thermal performance of a selection of insulation materials suitable for historic buildings*. https://doi.org/10.1016/j.buildenv.2015.07.033

Wi, S., Chang, S. J., & Sumin Kim. (2020). *Improvement of thermal inertia effect in buildings using shape stabilized PCM wallboard based on the enthalpy-temperature function*. https://doi.org/10.1016/j.scs.2020.102067