International Journal on Emerging Technologies 16(2): 90-101(2025)

ISSN No. (Print): 0975-8364
ISSN No. (Online): 2249-3255

Innovative Strategies for Optimizing Energy Efficiency and Thermal Comfort in Heritage Architecture: The Case of Lawang Sewu

Hassan Gbran[1]*, Siti Rukayah[2], Atik Suprapti[2] and Edward E. Pandelaki[3]
[1]Ph.D. Researcher, Architecture Department, UNDIP, Semarang, Indonesia.
[2]Professor, Architecture, UNDIP, Semarang, Indonesia.
[3]Lecturer, Architecture, UNDIP, Semarang, Indonesia.

(Corresponding author: Hassan Gbran)*
(Received 08 May 2025, Revised 26 June 2025, Accepted 16 July 2025)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Buildings of historical significance, which were traditionally, constructed using locally sourced materials and adapted to regional climates, offer unique opportunities for improving energy efficiency while maintaining cultural heritage. This research focuses on analyzing the indoor environmental performance of Lawang Sewu, a historic structure completed in 1904 during the Dutch colonial period. The protected historical site Lawang Sewu stands as a Semarang symbol in its red-brick structure with its neo-Gothic architectural design. Temperature and humidity measurements at Lawang Sewu took place over one year across four different spaces that experienced varying occupancy and usage patterns. Temperature distribution patterns in rooms were heavily affected by the active number of building occupants and also by when they used and inhabited the spaces. Researchers examined different retrofit modifications as means to minimize energy usage. The combination of advanced glazing systems with roof-based photovoltaic panels generated impressive energy savings worth 90.46% compared to original scenarios annually. The study demonstrates that seasonal variation together with occupant actions and usage patterns substantially impacts the interior climate conditions. The research underlines that architects need to maintain equal emphasis on energy efficiency alongside thermal comfort coupled with architectural preservation throughout building retrofit processes.

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

INTRODUCTION

Buildings are designed for long-term use, yet environmental factors gradually compromise the integrity of their envelope, leading to a decline in airtightness. Retrofitting presents a solution that not only improves energy efficiency but also ensures the maintenance or enhancement of thermal comfort. Due to the cultural significance of heritage buildings, their retrofit needs differ, necessitating tailored approaches (Al-Habaibeh *et al.*, 2022). These buildings require two primary types of retrofitting: structural enhancements to the envelope and modernized system infrastructure. 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 (Polo López and Frontini 2014). Modern retrofit solutions cannot always be implemented in heritage structures because this method needs to maintain both the architectural design principles and visual heritage values of cultural landmarks (Polo López and Frontini 2014; Karimi *et al.*, 2024a).

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 (Gbran and Ratih Sari 2024). The architectural status of this established cultural site brings forward complex conditions to execute energy-efficient modernization projects. The research examines Lawang Sewu's thermal performance using infrared thermography and blower-door testing to create conservation-friendly energy-saving retrofits (Polo López and Frontini 2014; Vázquez-Torres *et al.*, 2023). 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. 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 (Gbran and Sari 2023; Lidelöw *et al.*, 2019).

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.

A. Improving the Thermal Envelope Performance of Historic Buildings

Thermal envelope improvements stand as the most beneficial methods for improving energy efficiency in heritage properties. 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 Polo López and Frontini (2014), but maintains structural compatibility with the original design of the building.

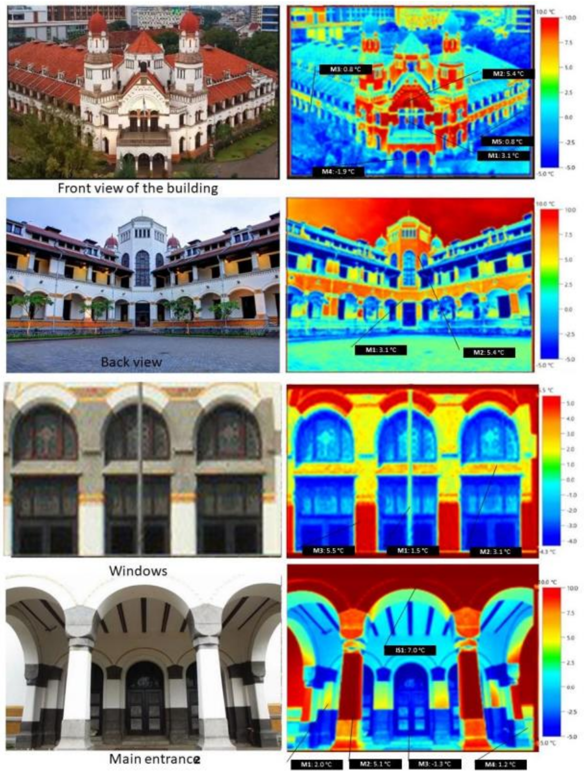


Fig. 1. Performance of Thermal Insulation in the Building Envelope.

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 Polo López and Frontini (2014), 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 1923, displays its distinctive stone exterior. Materials chosen for application must be suitable with stone construction to prevent any destruction to the buildings' historical integrity together with its visual appearance (Polo López and Frontini 2014; Julayhe and Rahman 2020).

B. 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 Polo López and Frontini (2014), 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.

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.

C. 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 and Frontini (2014), 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 Michael *et al*. (2023), indicated that using electrochromic glazing can reduce thermal loads in the summer 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: For Lawang Sewu, thin-film solar panels (CIGS) can be installed on the roof or integrated into the windows using electrochromic glazing techniques. These solutions provide a sustainable energy source while preserving the building's historical character.

- Challenges in Improving Energy Efficiency in Historic Buildings.

Despite the significant benefits of improving energy efficiency, there are major challenges in implementing these technologies in heritage buildings. The main challenges are:

- Compliance with Laws and Regulations: Historic buildings in many countries are subject to strict regulations that prohibit modifications that may affect their original appearance.
- Impact on Air Quality and Humidity: Some insulation techniques can lead to problems with indoor ventilation, increasing the risk of mold formation.
- High Cost: Energy retrofit technologies are often expensive, posing a challenge for their widespread implementation.

Application to Lawang Sewu: In the case of Lawang Sewu, a comprehensive study should be conducted to evaluate the economic cost of the proposed retrofit technologies, focusing on achieving a balance between energy benefits and financial constraints. Local regulations concerning heritage buildings must also be considered to ensure compliance (Karimi *et al.*, 2024a).

- **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 and Frontini (2014) shows integrated solar energy systems decrease building energy consumption by 50%, while designers must consider the visual aesthetics of the structure.

Research conducted by Michael *et al.* (2023) ; Meena *et al.* (2024) proved electrochromic glazing lowers summer 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.

D. Challenges in Improving Energy Efficiency in Historic Buildings

These advanced technologies often face major implementation obstacles when used for heritage buildings, although they provide substantial energy efficiency advantages. The main challenges are Historic buildings around the world face strict legal requirements that prevent any modifications that might alter their historical form.

Some insulation solutions lead to poor ventilation, which creates moist air conditions that promote mold development inside buildings. The implementation of energy retrofit technologies faces barriers due to their high cost, which presents a challenge for scaling up adoption. Lawang Sewu requires a detailed economic analysis to determine the financial expenses of proposed retrofit approaches along with defining appropriate budgetary parameters that link energy advantages with practical limitations. Local regulations that deal with heritage buildings need attention to maintain compliance rules. The research shows that heritage buildings need an integrated method for energy performance enhancement that merges thermal insulation alongside ventilation systems and renewable technologies but maintains their historical integrity. Electrochromic windows, energy recovery systems, and insulation designed for historic buildings create promising solutions to attain energy efficiency while maintaining the architectural integrity of such buildings. Preserving heritage sites remains the key challenge alongside integrating modern technology in a sustainable approach that manages heritage preservation effectively.

The energy consumption reduction of 90.46% for the Lawang Sewu building can be achieved through electrochromic glazing coupled with solar energy systems while improving its thermal envelope, according to research findings.

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's existing condition as well as create sustainable conservation methods for sustaining its historical legacy.

A. 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 complied with ISO 9869 standards for the Heat Flow Meter method (Polo López and Frontini 2014). 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 m^3), 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.

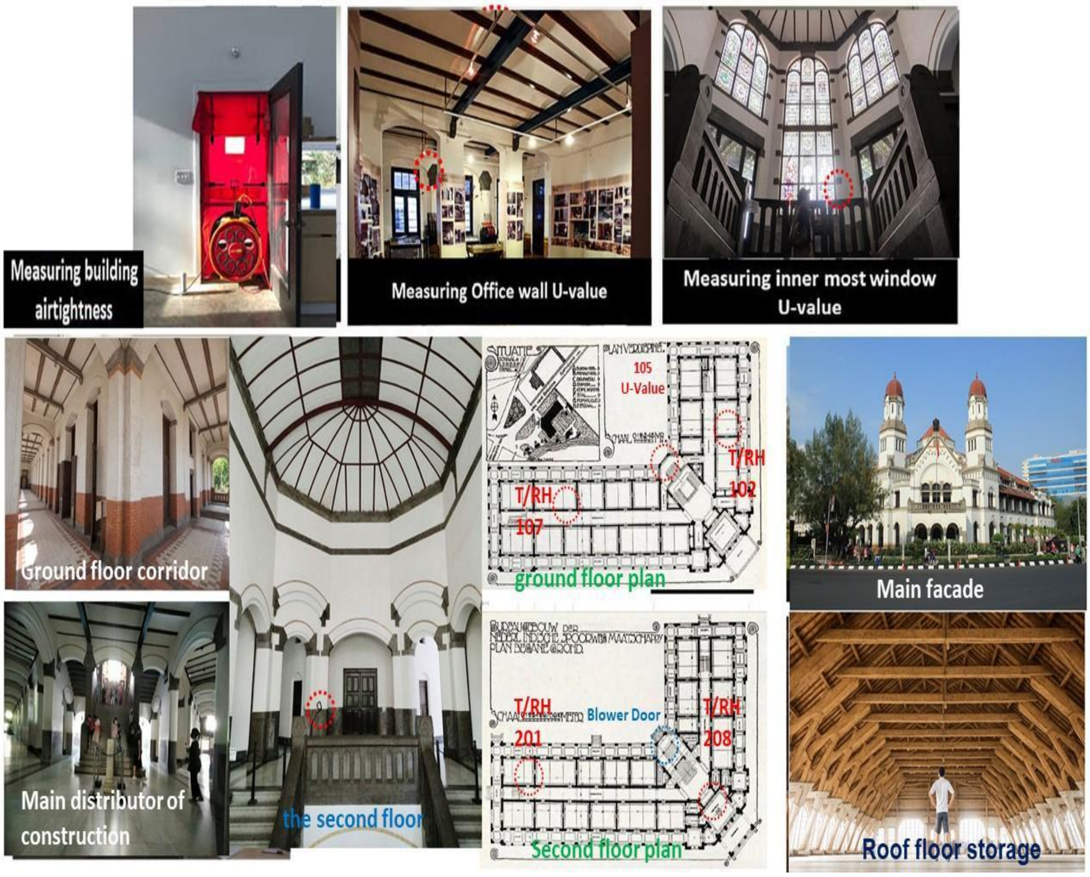


Fig. 2. Condition of the Building and Equipment for Measuring Thermal Transmittance. Source: Author; (Gbran and Sari 2023; Fanani and Syarif 2023; Cabeza *et al.*, 2018)**.**

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.

B. Simulation Analysis

Researchers utilized the building simulation tool EnergyPlus to evaluate different retrofitting approaches for Lawang Sewu while determining its energy efficiency outcomes. The simulation required detailed inputs about building envelope specifications alongside HVAC system parameters along with renewable energy technologies information. This reference model maintained the original building conditions consisting of stone and concrete walls and double-glazed windows supported by Spanish tile roofing. The simulation embodied occupant behavior patterns and lighting protocols while adopting the Fanger Equation (PMV index) as defined by ISO 7730 standards to assess thermal comfort standards. The inclusion of Copper Indium Gallium Selenide (CIGS) photovoltaic (PV) panels in the simulation allowed for an assessment of their efficiency in terms of energy utilization and the enhancement of indoor environmental comfort (Polo López and Frontini 2014).

C. 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.

D. 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 spring and autumn. Researchers attributed this variation to both the number of building occupants and their consumption patterns because occupants emit heat within the building (Al-Habaibeh *et al.*, 2022; Rukayah and Bharoto 2013).

The intense summer 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 (Polo López and Frontini 2014).

E. 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 (Polo López and Frontini 2014). 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 (Polo López and Frontini 2014).

F. 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 (Polo López and Frontini 2014). 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 (Gbran and Sari 2023). 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 (Polo López and Frontini 2014).

RESULTS

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.

A. 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 (Vázquez-Torres *et al.*, 2022; He and Isa 2024).

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

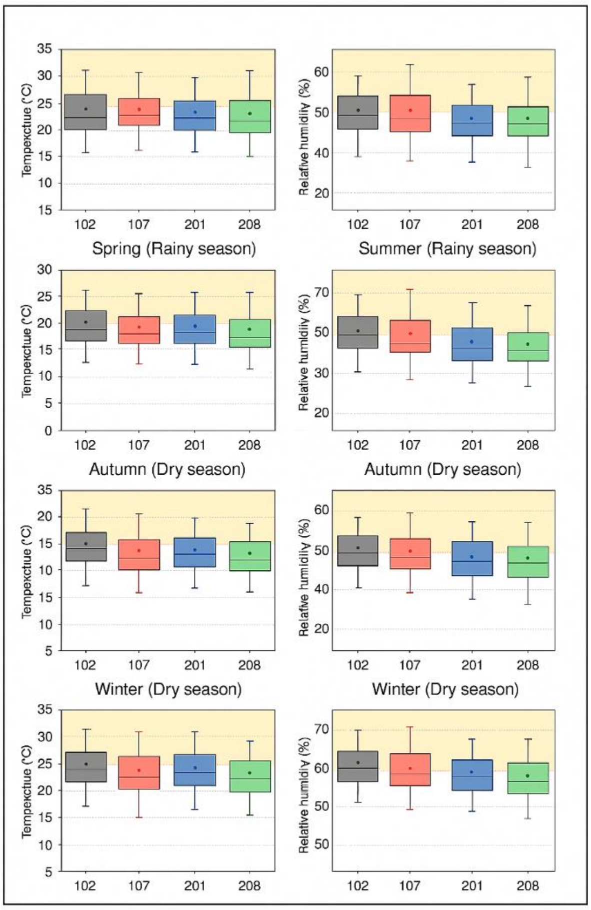


Fig. 3. (A+B) Changes in the internal environment of the offices (107, 201), the conference room (102) and the main entrance (208).

During weekdays from 9:00 AM to 6:00 PM, office rooms stayed in continuous use, yet they remained empty on the weekends. Temperatures within the building spaces measured from 16°C to 24°C because of heating systems engagement alongside occupants at the space. The temporary conference rooms achieved heating only during use, leading to a temperature range from 9°C up to 18°C. Outdoor temperatures constantly influenced the internal conditions during different seasons. The office, together with conference spaces, showed less temperature fluctuation throughout spring and autumn months as heating and cooling equipment remained inactive. The research team attributed temperature differences to the elevated number of office building occupants who produced internal heat (Polo López and Frontini 2014). During summer 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 (Polo López and Frontini 2014). Heated office areas experienced lower relative humidity levels than conference areas exposed to outdoor temperatures because high temperatures affect the behavior of vapor pressure (Polo López and Frontini 2014); (Verticchio *et al*., 2021).

B. 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; however, this strategy increased cooling energy usage by 11.19%. Including an electrochromic SHGC in the windows enabled enough sunlight to enter buildings during winter months to improve thermal energy efficiency (Polo López and Frontini 2014; Karimi *et al*. 2024b) .

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% (Polo López and Frontini 2014; Coelho and Henriques 2021). 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 (Polo López and Frontini 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 (Ilies *et al.*, 2023).

C. 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; Kamal, 2020).

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; Gao *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 (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 (Al-Habaibeh *et al*., 2022). However, the occupants' comfort in general office spaces registered a slight decrease. External canopy blinds were evaluated as a factor that only increased the thermal discomfort of residents (Michael *et al.*, 2023).

D. 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% (Polo López and Frontini 2014). 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 (Polo López and Frontini 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.

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 (Menteşe, 2022; Upasani *et al.*, 2024).

1. 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 (Polo López and Frontini 2014).
- Retrofitting strategies such as electrochromic glazing and AHU systems improved occupant comfort, particularly in spaces with high occupancy (Al-Habaibeh *et al.*, 2022).
- External awning blinds with CIGS panels posed challenges in terms of visual compatibility with the building's historic appearance (Ali *et al.*, 2025). The PAR_R package was identified as the most balanced solution, considering energy efficiency (Gbran, 2024b), thermal comfort, and preservation of architectural aesthetics (Jo *et al*., 2023). 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

(Cabeza *et al.*, 2018). 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 (Al-Habaibeh *et al.*, 2022). However, the occupants' comfort in general office spaces registered a slight decrease.

DISCUSSION

The research investigates how retrofit strategies affect Lawang Sewu's heritage building located in Semarang, Indonesia, regarding its energy consumption along with thermal comfort conveniences. These findings demonstrate how occupant activities, seasonal changes, and implemented retrofit methods work together to show sustainable methods that enable both historic preservation and functionality improvement in architectural heritage. This aligns with recent heritage retrofit analyses emphasizing the role of occupant behavior and climatic variability in post-intervention building performance (Panico *et al.*, 2024; Suprapti *et al.*, 2020).

A. Impact of Retrofit Package Composition on Energy Consumption

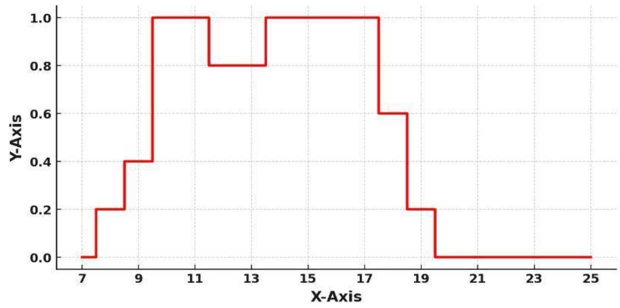
The researchers evaluated the Lawang Sewu energy needs for passive, active, and renewable energy packages as retrofit options. A stable indoor environment received priority status for the heritage building thanks to the package terminal heat pump (PTHP). An upgrade of the building envelope along with facility systems needed installation to minimize heating energy usage (Polo López and Frontini 2014). 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 (SHGC ≥ 0.77) decreased heating energy by 7.83% yet raised cooling energy by 11.19%.
2. ERV implementation led to a heating and cooling energy use rise of 26.62% and 13.55% relative to the non-retrofitted building operation. These increases mirror results from other retrofitted historical buildings where ERVs improved indoor air quality but increased load due to constant ventilation cycles (Tu *et al*., 2025).
3. Researchers studied the integration of CIGS photovoltaic panels made from copper indium gallium selenide materials, which were attached to roofs or installed as blinds, but achieved dissimilar results.

• 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). This supports broader findings indicating that dynamic solar control via PV blinds can enhance passive cooling in hot seasons (Coelho and Henriques 2021).

Table 1: Simulation input parameters for evaluating energy performance and thermal comfort in Lawang Sewu.

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 (Gbran, 2024a).	- 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. - Solar energy gain factor (SHGC): 0.77.
Active system	Energy recovery ventilator (ERV)	- Heat transfer coefficient [W/mK]: 0.87, with an operational efficiency of 82%. Pmax=277 W,
Renewable system	CIGS PV roof CIGS PV blinds	Efficiency: 22% Efficiency: 82% Pmax=277 W, Efficiency: 22% Pmax=277 W, Efficiency: 22% 
Inhabitants	Hot Water Systems, Climate Control, and Artificial Lighting	07-00-19-00 Summer 06/Winter 1.2 03 (Light office work) 0.138 m/s 22.02 ACH.
seepage	PMV (Fanger equation)	-

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 (Reinhard *et al*., 2013; Jo *et al.*, 2023). This is consistent with findings from low-intrusion photovoltaic retrofits in heritage sites, where non-visible PV systems led to significant energy savings without affecting aesthetics (Lu *et al.*, 2025).

To provide a quantitative overview of the building systems and thermal characteristics used in the simulation process, Table 1 summarizes the input parameters applied in the energy and comfort modeling scenarios for Lawang Sewu. These parameters reflect the physical features of the building envelope, mechanical systems, and climate settings essential to evaluating retrofit performance accurately (Amla *et al.*, 2017; Gbran and Alzamil 2025).

To systematically evaluate the effectiveness of different retrofit strategies, Table 2 presents a structured classification of the applied packages into three main categories: Passive (PA), Active (AC), and Renewable (RN). Each category targets specific performance goahls in heritage buildings, thereby providing a comparative framework for assessing their impact on energy demand and thermal comfort.

Table 2: Characteristics of Retrofit Technologies for Heritage Buildings.

Category	Details	Target
PA	Smart Electrochromic Window Systems (EC)	Optimizing the building shell and minimizing energy demands for heating
AC	Ventilation System with Energy Recovery (ERV)	Ensuring superior thermal comfort levels for occupants
RN	Photovoltaic Blinds Integrated into Roof/Windows (CIGS)	Achieving significant reductions in yearly energy usage
PA_AC	EC + ERV	Combining envelope optimization with enhanced occupant comfort
PA_RN	EC + CIGS	Cutting annual energy consumption via advanced envelope design and renewable energy integration
AC_RN	ERV + CIGS	Elevating indoor environmental quality to support extended operational hours
PAR	EC + ERV + CIGS	A holistic retrofit solution addressing both conservation and functional adaptability

Table 2 provides a systematic classification of retrofit technologies used in the Lawang Sewu project, categorized into three main groups: Passive (PA), Active (AC), and Renewable (RN). This framework facilitates the evaluation of each technology’s role in improving energy performance while preserving the historical and architectural integrity of heritage buildings.

- **Passive Technologies (PA):** These include electrochromic glazing systems designed to reduce heat gains through solar control, thereby lowering the demand for mechanical heating. Such systems are ideal for heritage buildings because they are minimally invasive and do not alter the external appearance, making them highly compatible with conservation guidelines.
- **Active Technologies (AC):** Represented by energy recovery ventilator (ERV) systems, this category enhances indoor air quality and stabilizes thermal comfort. However, these systems may lead to increased energy consumption due to continuous ventilation cycles. Despite this drawback, they are essential for mitigating humidity-related issues such as mold growth, especially in humid tropical climates.
- **Renewable Technologies (RN):** These include CIGS photovoltaic systems installed on rooftops or integrated into blinds and windows. Their primary function is to generate renewable energy and significantly reduce the building’s dependency on conventional energy sources. While highly effective in energy savings (up to 90.46%), their integration must be carefully designed to avoid visual incompatibility with historical facades.
- **Hybrid Configurations (e.g., PA_AC, PA_RN, PAR):** The combinations of passive, active, and renewable technologies offer comprehensive solutions that balance energy performance, user comfort, and heritage conservation. For example, the PAR package (PA + AC + RN) represents a holistic retrofit solution that addresses all key objectives—thermal efficiency, indoor environmental quality, and visual integrity.

This classification serves not only as a decision-making tool but also as a guideline for practitioners aiming to retrofit heritage buildings. It supports the selection of context-sensitive strategies that align with conservation ethics while achieving measurable sustainability outcomes.

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 (Reinhard *et al*., 2013).

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 (Polo López and Frontini 2014).

B. 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 (Polo López and 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. Recent studies have emphasized the importance of localized surface treatments in historic buildings to balance thermal gradients while avoiding condensation risks (Piscitelli *et al.*, 2024). 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 Mohammed *et al.* (2022) showed external awning blinds led to a higher likelihood of occupants feeling cold since shadows were created by the blinds during application. This finding is in line with occupant surveys from other cultural heritage buildings that experienced similar discomfort due to static shading systems (Koh *et al.*, 2018).

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 (Polo López and Frontini 2014).

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. Such discomfort has been reported in multiple post-retrofit evaluations where visual and thermal sensations were not synchronized (Gao *et al.*, 2015).

The implementation of these refined technologies included integration with renewable energy solutions, which were employed across multiple dimensions. The study conducted analysis through two separate groups. Different user thermal comfort levels were assessed in winter based on whether CIGS material was added to the roof only or to the roof and blinds at the same time. The best thermal comfort condition emerged from applying PA and AC together with CIGS on the roof and blinds in Room 107 and the corridor. Retrofitted CIGS insulation was applied to both the roof and external blinds while the subsequent thermal comfort ratings followed the sequence of PA_AC, then PA, followed by PA_RN_R+B. The use of external awnings during retrofitting changes the overall results, showing that variable outcomes might appear in climates different from the analyzed one (Polo López and Frontini 2014). The differences in occupant thermal comfort across retrofit packages were quantified using the PMV scale. Table 3 compares the PMV range under each configuration, distinguishing how roof-only versus roof + blind PV systems affect thermal neutrality and perceived comfort in heritage interiors (Arya *et al.*, 2024).

Table 3: PMV-based evaluation of occupant thermal comfort across different retrofit configurations in Lawang Sewu.

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)

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).

C. 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 (Akyol and Avcı 2023). 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 Fisk *et al.* (2020).

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.

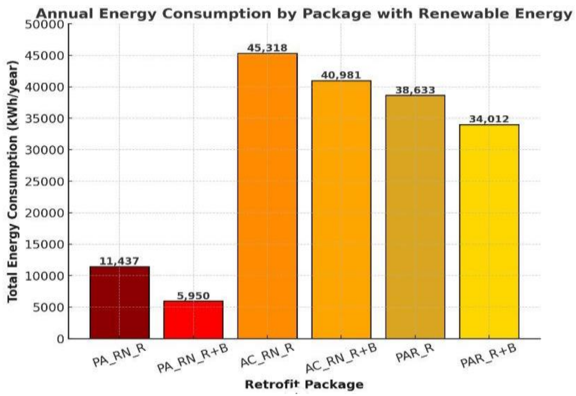


Fig. 4. Energy consumption patterns on an annual basis, classified by package, reflecting the impact of implementing new and renewable energy sources.

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.

CONCLUSIONS

This study presents a comprehensive evaluation of innovative retrofit strategies aimed at improving energy efficiency and thermal comfort in heritage buildings, with Lawang Sewu in Semarang, Indonesia, serving as a representative case. By integrating passive, active, and renewable energy interventions, the research demonstrated that energy demand and occupant comfort can be optimized without compromising the architectural and cultural integrity of historical structures. The implementation of electrochromic glazing, energy recovery ventilation (ERV), and CIGS photovoltaic systems yielded a measurable improvement in both annual energy performance and thermal comfort indices.

Among all configurations tested, the combined passive and renewable strategy (PA_RN) achieved the highest energy savings—reaching up to 90.46% annually—while maintaining indoor comfort within acceptable PMV thresholds. Moreover, the application of these strategies validated the potential of low-impact technologies to retrofit heritage buildings in tropical climates where temperature and humidity fluctuations are significant. The study also confirms that data-driven simulation tools are essential for predicting the thermal behavior of historical structures and guiding retrofit decisions that respect conservation ethics.

Ultimately, this research contributes to the evolving discourse on sustainable heritage preservation by offering a replicable and adaptable framework that balances environmental performance with cultural value. The methodological integration of environmental data, simulation modeling, and heritage-sensitive technologies provides a pathway for future retrofitting efforts in similar contexts globally. It is hoped that these findings will inform policy, practice, and design strategies that prioritize both sustainability and heritage conservation in the built environment.

FUTURE SCOPE

The present study provides a foundational framework for integrating passive, active, and renewable retrofit strategies in heritage buildings under tropical climatic conditions. Future research may expand this work by applying the proposed simulation models to other heritage typologies across varied climate zones, such as arid or temperate regions. In addition, further investigation into user-centered design parameters, including behavioral adaptation and occupancy patterns, could enhance the personalization and responsiveness of retrofit solutions. Integrating Internet of Things (IoT)-based real-time monitoring systems and adaptive control algorithms can also offer deeper insights into the dynamic thermal performance of retrofitted historical buildings. A longitudinal study involving post-occupancy evaluation (POE) would significantly strengthen empirical validation and policy translation.

Acknowledgements. This research was supported by a doctoral scholarship grant from Diponegoro University, Indonesia. The author express his sincere gratitude to the university president for awarding the Excellence Scholarship that made this study possible. Special thanks are extended to the International Office for International Students and to the Faculty of Engineering leadership. The author are particularly grateful to Professor Siti Rukayah, Professor Atik Suprapti and for their continued academic supervision, to for departmental support, and to Dr. Edward Pandelaki for his critical guidance and technical insights throughout the research.

REFERENCES

Akyol, G. & Avcı, A. B. (2023). AI applications in cultural heritage preservation: technologcal advancements for the conservation. *Baskent International Conference on Multidisciplinary Studies*, *August*, 94–101.

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.

Ali, A. O., Elgohr, A. T., El-Mahdy, M. H., Zohir, H. M., Emam, A. Z., Mostafa, M. G., Al-Razgan, M., Kasem, H. M. & Elhadidy, M. S. (2025). Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects. *Energy Conversion and Management: X*, *26*, 100952.

Amla, A., Anoop, A. & Sharma, K. (2017). Development and Environment Interactions-Need for Climate Responsive Campuses: Study and Proposals. *International Journal on Emerging Technologies*, *8*(1), 243–250.

Arya, N., Saraswat, S., Lal, S. P., Management, C. R. & Science, C. (2024). *AgriBio Innovations*. *1*(1), 62–66.

Cabeza, L. F., de Gracia, A., and Pisello, A. L. (2018). Integration of renewable technologies in historical and heritage buildings: A review. *Energy and Buildings*, *177*, 96–111.

Coelho, G. B. A. & Henriques, F. M. A. (2021). Performance of passive retrofit measures for historic buildings that house artefacts viable for future conditions. *Sustainable Cities and Society*, *71*, 102982.

Fanani, A. Z. & Syarif, A. M. (2023). Historical Building 3D Reconstruction for a Virtual Reality-based Documentation. *International Journal of Advanced Computer Science and Applications*, *14*(9), 811–818.

Fisk, W. J., Singer, B. C. & Chan, W. R. (2020). Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. *Building and Environment*, *180*, 107067.

Gao, J., Wang, Y. & Wargocki, P. (2015). Comparative analysis of modified PMV models and SET models to predict human thermal sensation in naturally ventilated buildings. *Building and Environment*, *92*, 200–208.

Gbran, H. (2024a). From Physical Models to Innovations: Technology Advances in Architectural and Civil Engineering. *ARSITEKTURA*, *22*(1), 91.

Gbran, H. (2024b). *Preserving History in a Modern Setting "An Adaptive Redesign of Lawang Sewu for Sustainable Development and Architectural Heritage Conservation." Vol. 07, N.*

Gbran, H. & Alzamil, K. W. (2025). Integrated Waste Management in Smart Cities: A Case Study of Circular Economy Solutions in Msheireb Downtown Doha. *International Journal on Emerging Technologies*, *16*(1), 14–29.

Gbran, H. & Ratih Sari, S. (2024). Studying the visual impact of modern construction on historic cityscapes: a case study of Lawang Sewu building, Indonesia. *Contexto*, *18*(28), 15–34.

Gbran, H. & Sari, S. R. (2023). The Visual Impact of Modern Constructions on the Old Cities in Indonesia: The Lawang Sewu Building in Semarang. *ISVS E-Journal*, *10*(2), 71–90.

He, D. & Isa, M. H. M. (2024). Investigation of indoor thermal comfort of heritage buildings in hot summer and cold winter zone of China: A case study. *Case Studies in Thermal Engineering*, *53*, 103820.

Ilies, D. C., Herman, G. V., Safarov, B., Ilies, A., Blaga, L., Caciora, T., Peres, A. C., Grama, V., Bambang, S. W., Brou, T., Taglioni, F., Hassan, T. H. & Hossain, M. A. (2023). Indoor Air Quality Perception in Built Cultural Heritage in Times of Climate Change. *Sustainability*, *15*(10), 8284.

Jo, H. H., Yuk, H., Kang, Y. & Kim, S. (2023). Conservation of architectural heritage: Innovative approaches to enhance thermal comfort and promote sustainable usage in historic buildings. *Case Studies in Thermal Engineering*, *51*, 103500.

Julayhe, N. H. & Rahman, M. M. (2020). Greening Existing Buildings for Energy Efficiency: A review. *International Journal on Emerging Technologies*, *11*(5), 366–380.

Kamal, M. A. (2020). *Passive Techniques for Achieving Thermal Comfort in the Vernacular Dwellings*. *8*(January 2017), 1–6.

Karimi, H., Adibhesami, M. A., Hoseinzadeh, S., Movafagh, S., Estalkhsari, B. M. & Garcia, D. A. (2024a). Solar energy integration in heritage buildings: A case study of St. Nicholas Church. *Energy Reports*, *11*(March), 4177–4191.

Karimi, H., Adibhesami, M. A., Hoseinzadeh, S., Movafagh, S., Estalkhsari, B. M. & Garcia, D. A. (2024b). Solar energy integration in heritage buildings: A case study of St. Nicholas Church. *Energy Reports*, *11*, 4177–4191.

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.

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.

Lu, F., Kwon, M. & Jang, J. (2025). Application of Copper Indium Gallium Selenide Thin-Film Solar Technology in Green Retrofitting of Aging Residential Buildings. *Buildings*, *15*(10), 1633.

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.

Meena, L. K., Singh, R., V, P. K. K., Meena, D. & Sharma, N. (2024). Impact of Binder Materials on the Mechanical and Thermal Properties of Biofuel Briquettes. *Biological Forum-An International Journal (BFIJ)*, *16*(9), 178–184.

Menteşe, S. (2022). *8 - Airborne bacteria and sick building syndrome (SBS)*.

Michael, M., Favoino, F., Jin, Q., Luna-Navarro, A. & Overend, M. (2023). A Systematic Review and Classification of Glazing Technologies for Building

Façades. *Energies*, *16*(14), 5357.
Mohammed, A., Tariq, M. A. U. R., Ng, A. W. M., Zaheer, Z., Sadeq, S., Mohammed, M. & Mehdizadeh-Rad, H. (2022). Reducing the Cooling Loads of Buildings Using Shading Devices: A Case Study in Darwin. *Sustainability*, *14*(7), 3775.
Panico, S., Larcher, M., Herrera-Avellanosa, D., Cennamo, D. & Troi, A. (2024). Long-term monitoring data of hygrothermal conditions of a retrofitted historic building in Settequerce, South Tyrol (Italy). *Data in Brief*, *53*, 110137.
Piscitelli, P., Miani, A., Mecca, S. & Hodgton, R. (2024). Optimizing the Indoor Air Quality in Historical Buildings: Strategies for Environmental Improvement and Public Health Enhancement. *International Journal of Environmental Research and Public Health*, *21*(3).
Polo López, C. S. & Frontini, F. (2014). Energy efficiency and renewable solar energy integration in heritage historic buildings. *Energy Procedia*, *48*(0), 1493–1502.
Park, J. H., Jeon, J., Lee, J., Wi, S., Yun, B. Y. & Kim, S. (2019). Comparative analysis of the PCM application according to the building type as retrofit system. *Building and Environment*, *151*, 291-302.
Reinhard, P., Chirila, A., Blosch, P., Pianezzi, F., Nishiwaki, S., Buecheler, S. & Tiwari, A. N. (2013). Review of Progress Toward 20% Efficiency Flexible CIGS Solar Cells and Manufacturing Issues of Solar Modules. *IEEE Journal of Photovoltaics*, *3*(1), 572–580.
Rukayah, R. S. & Bharoto (2013). Bazaar in Urban Open Space as Contain and Container Case study: Alun-alun Lama and Simpang Lima Semarang, Central Java, Indonesia. *Procedia - Social and Behavioral Sciences*, *50*, 741–755.
Suprapti, A., Sejati, A. W., Sardjono, A. B., Pandelaki, E. E., Malik, A. & Huwaida, N. M. (2020). Toward Sustainable Preservation of Cultural Heritage Buildings: A Combination of Digital Mapping and Architectural mapping for Omah Pencu in the Historic Area of Kudus Kulon. *Teknik*, *41*(3), 201–211.
Tu, A., Zhao, X., Liu, S. & Zhu, D. (2025). An Analysis of the Energy Efficiency and Control Strategy of ERVs with Energy Recovery in Different Typical Regions Throughout the Year. *Energies*, *18*(5), 1112.
Upasani, N., Guerra-Santin, O. & Mohammadi, M. (2024). Developing building-specific, occupant-centric thermal comfort models: A methodological approach. *Journal of Building Engineering*, *95*, 110281.
Vázquez-Torres, C. E., Beizaee, A. & Bienvenido-Huertas, D. (2022). The impact of human occupancy in thermal performance of a historic religious building in sub-humid temperate climate. *Energy and Buildings*, *259*, 111912.
Vázquez-Torres, C. E., Bienvenido-Huertas, D., Beizaee, A., Bassam, A. & Torres, M. J. (2023). Thermal performance of historic buildings in Mexico: An analysis of passive systems under the influence of climate change. *Energy for Sustainable Development*, *72*, 100–113.
Verticchio, E., Frasca, F., Bertolin, C. & Siani, A. M. (2021). Climate-induced risk for the preservation of paper collections: Comparative study among three historic libraries in Italy. *Building and Environment*, *206*, 108394.

How to cite this article: Hassan Gbran, Siti Rukayah, Atik Suprapti and Edward E. Pandelaki (2025). Innovative Strategies for Optimizing Energy Efficiency and Thermal Comfort in Heritage Architecture: The Case of Lawang Sewu. *International Journal on Emerging Technologies, 16*(2): 90–101.