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Retrofit Strategies for Nearly Zero Energy Building Concept in Educational Building

Calista Priliana Ardini, Ova Candra Dewi*, Miktha Farid Alkadri, Kartika Rahmasari
Research Cluster of Architectural Science and Building Technology (ASBT), Department of Architecture, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI Depok, Indonesia
*Corresponding author: **ova.candewi@ui.ac.id**

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Abstract

Indonesia has set a roadmap to achieve energy-efficient buildings by 2050. This study explored potential energy demand reduction through building retrofit between 2024 and 2050, aligning with Indonesia's roadmap and Paris Agreement to promote Nearly-Zero Energy Buildings (NZEB) concept. This study examines the impact of combining insulation retrofitting and photovoltaic (PV) system integration on reducing energy demand in existing buildings in Indonesia, considering both the 2024 and 2050 climate conditions. Three insulating materials with a thickness of 50 mm were selected, based on their thermal properties and material cost. The selected materials were rockwool, polyisocyanurate (PIR), and aerogel board as an internal layer of the walls. In addition, an economic evaluation was conducted to compare the cost-effectiveness of the three insulation materials, assessing not only energy savings but also payback periods. The results were obtained through U-value calculation, energy simulation, Photovoltaic (PV) panels simulation and economic evaluation. From the three selected insulation materials, PIR showed the highest energy demand reduction with a reasonable payback period of 15 years. Based on the simulation, PIR potentially reduced Energy Use Intensity (EUI) by 22.5% and 29.9% in the 2024 and 2050 climate database, respectively. PV panels, particularly the 300 Wp system with a shorter payback, covered an average of 31.5% of the building's final energy demands after adding PIR as an insulation in the 2024 climate database. The combined retrofit strategy reduced the overall payback period to 8.3 years. These findings highlight the NZEB approach as a viable pathway to support Indonesia's energy-efficient building and renewable energy targets.

Keywords: building retrofit; energy demand reduction; energy use intensity; nearly-zero energy buildings; renewable energy.

Introduction

According to the Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment report (2021), the climate has already warmed 1.1°C since 1850-1900 and the global mean air temperature is expected to reach or exceed 1.5°C within the next few decades or even higher up to 5°C by the end of this century (IPCC, 2023). In dealing with the situation, the 21st UN Climate Conference (COP21) in December 2015 in Paris, France, aimed to limit the global temperature increase to 1.5°C (UNEP, 2024).

Heat waves are significant challenges for the future climate, with the potential to substantially impact indoor building conditions and its occupants' health, especially considering that humans spend 86.9% of their time indoors (Liyanage et al., 2024; Nelson et al., 1994). Heat waves are particularly noticeable in Indonesia that is located in tropical regions with a high mean temperature range of 28°C to 32°C (BMKG, 2024). A warmer climate will affect not only the durability of building materials but also indoor environments, creating an increased demand for cooling systems (IPCC, 2023). To address this issue, it is crucial to reduce heat transfer through the building envelope,

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including walls, roofs, and windows. One effective approach is to apply insulation to the walls, which represent the majority of the envelope's surface area. Walls are continuously exposed to solar radiation and tend to absorb and release external heat, especially when exposed to direct sunlight, making them critical targets for thermal retrofit strategies that aimed at minimizing heat gain and improving energy efficiency (Lechner & Andrasik, 2022).

Globally, energy consumption for cooling systems has tripled since 1990 (UNEP, 2024). With its hot and humid climate, the cooling systems of buildings in Indonesia show the highest proportion of energy consumption in buildings, about 60% (ESDM & Danish Energy Agency, 2022). On the other hand, buildings generate emissions during both the construction and operational phases, with the operational phase being a major source of carbon emissions and accounting for up to 37% of energy consumption (UNEP, 2024). The rising emissions have driven global initiatives, such as the Paris Agreement, to make a Nearly-zero Energy Buildings (NZEB) concept as a goal for reducing carbon emissions (EPA, 2023).

The term "nearly" in Nearly-zero Energy Building (NZEB) refers to a high energy performance, low-energy needs, and largely covered by onsite and nearby renewable energy sources (European Union 2018). Aligning with the NZEB concept, through Government Regulation No. 79/2014 on National Energy Policy, the Indonesian government has set a goal of achieving new and renewable energy to reach at least 23% in 2025, with a target of at least 31% in 2050 (ESDM & Danish Energy Agency, 2022).

The process of achieving Net Zero Energy Buildings (NZEB) can be divided into two main phases. the design phase and the operational phase (UN, 2023). The design phase focuses on reducing building energy demand by minimizing loads, improving energy efficiency, and integrating on-site renewable energy systems. Meanwhile, the operational phase focuses reducing building energy consumption mainly through energy retrofitting of existing buildings (Asdrubali et al., 2019). Retrofit is the process of making improvements or modifications to the existing buildings or systems to improve their energy efficiency, sustainability, and performance (Pacheco-Torgal, 2017). One of its goals is the improvement of the building envelope materials which has the greatest influence on energy demand (Elnabawi et al., 2024). One of the strategies is to focus on optimizing the building envelope to minimize energy demand, particularly cooling loads. The effectiveness of the building envelope in maintaining its indoor thermal condition is determining the amount of energy required by an active HVAC system to establish thermal comfort within the building (Papadopoulus et al., 2008). Tightening the thermal envelope by adding thermal insulation is an effective method to avoid heat and reduce energy demands, as the envelope acts as a barrier between the outdoor and indoor climates of the building (Lechner & Andrasik, 2022). Silveira et al. (2019) found that internal insulation is more suitable for tropical climates than external insulation due to condensation risks on cooler surface temperatures and related to the mold issues. According to the International Standards Organization (ISO) and the European Standardization Committee (CEN), materials classified as thermal insulation are materials with a thermal conductivity lower than 0.065 W/m.K which means the material has a low ability to conduct heat (Danaci & Akin, 2022).

Thermal insulation materials are generally categorized into three main groups, such as inorganic, organic, and advanced with the thermal conductivity ranging from 0.03 W/m.K to 0.07 W/m.K, 0.02 W/m.K to 0.055 W/m.K, and below 0.01 W/m.K, respectively (Pásztory, 2021). In addition to thermal conductivity, insulation materials suitable for hot and humid tropical climates should also have high moisture resistance to prevent water absorption, which can reduce their effectiveness (Lechner & Andrasik, 2022). Among the available options, Rockwool (inorganic) is the most cost-effective and widely used material (8.42 USD/m^2) for a thickness of 50 mm, Aerogel (advanced) offers the best insulation performance but is also the most expensive material (174.55 USD/m^2) for the same thickness, while Polyisocyanurate or PIR (organic) provides a balance between performance and cost (17.81 USD/m^2) for 50 mm thickness. These prices represent the average market rates in Indonesia and derived from products commonly available in the local market.

Based on a previous study, rockwool insulation on a building in tropical Malaysia decreased monthly power reduction by 16.67% (Muhieldeen et al., 2020). Meanwhile, in the hot and humid climatic conditions of UAE, 50 mm of PIR was added to a building and showed a 23% energy demand reduction (Rehman, 2017). Aerogel, which was applied as an advanced insulation for exterior walls in the hot-humid climate conditions of Turkey, achieved an 8% savings in energy demand compared to rockwool (Danaci & Akin, 2022).

In addition to the insulation strategy, the installation of photovoltaic (PV) panels on the rooftop maximize solar exposure in tropical climates for generating renewable energy on-site and subsequently reduce energy load (Balali et al., 2023; Shukla et al., 2023). PV panels were designed to cover at least 31% of the total energy demands of the building, aligning with Indonesia's National Energy Policy for 2050 based on Government Regulation of The Republic of Indonesia Number 79 of 2014 on National Energy Policy (ESDM, 2014).

Rising global temperatures due to climate change pose significant challenges, particularly energy demand increases in buildings. For instance, the Pusgiwa building at Universitas Indonesia was chosen as a case study. This study aimed to address the impact of climate change on energy demand in Pusgiwa UI through the development of comprehensive strategies by optimizing the building envelope with thermal insulation and integrating photovoltaic (PV) panels to generate on-site renewable energy to cover at least 31% of the building's energy demands. The goals were to reduce energy demand under the 2024 and 2050 climate database, considering the expected temperature rise. In addition to technical performance, an economic evaluation was conducted to assess the cost-effectiveness of the selected insulation materials. This evaluation considered installation costs, energy savings, payback periods, and long-term financial benefits, providing a practical framework for decision-makers to select insulation solutions that balance both energy efficiency and economic feasibility. It is hypothesized that if combined strategies were implemented in buildings, those strategies would reduce energy consumption and contribute to the broader global effort of mitigating climate change impacts while advancing sustainable building practices towards the NZEB concept.

Materials and Methods

Case study: Pusgiwa Building, Universitas Indonesia

Student Activity Center Building of Universitas Indonesia (Pusgiwa UI) is an educational building located on Jl. Prof. Dr. Fuad Hassan in Depok City, West Java. The Pusgiwa UI has an approximate area of 19,500 m^2 which is divided into 8 floors as shown in Fig. 1. The building is used as a student activity centre and offices, providing spaces for various academic activities, extracurricular, and administrative functions. Pusgiwa UI is implementing the concept of green building and has received Final EDGE Certification from Green Building Council Indonesia (GBCI) with 22% energy saving and 34% water saving (EDGE, 2023). Pusgiwa UI is well-positioned to adopt the NZEB approach which aims the energy demand to near zero by relying on renewable energy while Pusgiwa UI has already prioritized energy efficiency.

Fig. 1
Pusgiwa Building at Universitas Indonesia

Pusgiwa UI building consumed 350,453 kWh of energy annually or 17.97 kWh/ m^2/year according to the Energy Use Intensity (EUI) measurement in 2024. The energy consumption was distributed across various categories, with cooling load taking the majority at 73.3%, followed by electrical equipment at 16.2% and lighting at 10.5% as shown in **Fig. 2**. The data showed the significant role of cooling systems in the building's energy consumption, indicating potential areas for energy efficiency improvements and sustainability initiatives.

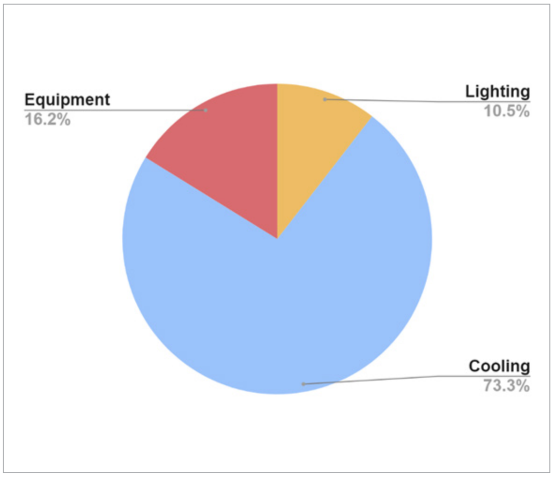


Fig. 2
Percentage of Pusgiwa's energy consumption by categories

Based on field measurement, the details of Pusgiwa UI specifications were floor area, number of floors, wall materials, energy consumption, EUI, cooling setpoint, occupant density, lighting load, equipment load, and weather data for Energy simulation as shown in **Table 1**. For occupant density, it was assumed by collecting data on Pusgiwa's users of for a month. Students were counted based on academic and extracurricular activities schedules in Pusgiwa (such activities still occurred infrequently), while office staffs were counted based on daily attendance.

Table 1
Pusgiwa Building specifications and energy simulation inputs

Type of Building	Specifications
Floor Area	± 19,500 m^2
Number of floors	8 floors
Wall Materials	Autoclaved Aerated Concrete (AAC), coverage: 6096 m^2
Energy Consumptions	350,453 kWh/year
EUI	17.97 kWh/m^2/year
Cooling setpoint	25°C
Occupant density	0.01 people/m^2
Lighting load	0.12 kWh/m^2
Equipment Load	1.99 kWh/m^2
Weather data	Energy Plus Weather File (EPW File) Jakarta-Soekarno-Hatta.Intl.AP JW IDN 967490 TMYx

Building Envelope Materials

This study focuses on the materials used in the walls of Pusgiwa UI, which are part of the building envelope. The Pusgiwa's walls were built by using Autoclaved Aerated Concrete (AAC), covering an area of approximately 6,096 m^2. AAC material has a thermal conductivity value of 0.042 W/m.K, a thickness of 100 mm and density of 115 kg/m^3 (Pagoni et al., 2024). The thermal conductivity of a material affects the U-value, which in turn affects heat transfer and thermal comfort (BSN, 2020).

The conditioned spaces of Pusgiwa, which were used as classrooms and offices, oriented to the north and south. The primary wall material was AAC blocks, with exposed clay brick used as an accent. In this study, the exposed clay brick areas were excluded.

Macroclimate

The macroclimate data was derived from the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG) and Weatherspark (2024), while the data for the simulation was obtained from the EnergyPlus Weather File (EPW File) for Soekarno-Hatta International Airport compiled as a Typical Meteorological Year (TMYx) dataset. For the 2050 climate scenario, the EPW file was morphed based on World Bank Group (WBG) and IPCC climate projections (WBG, 2021; IPCC, 2022). The macroclimate data provided insights for long-term climate planning in tropical regions.

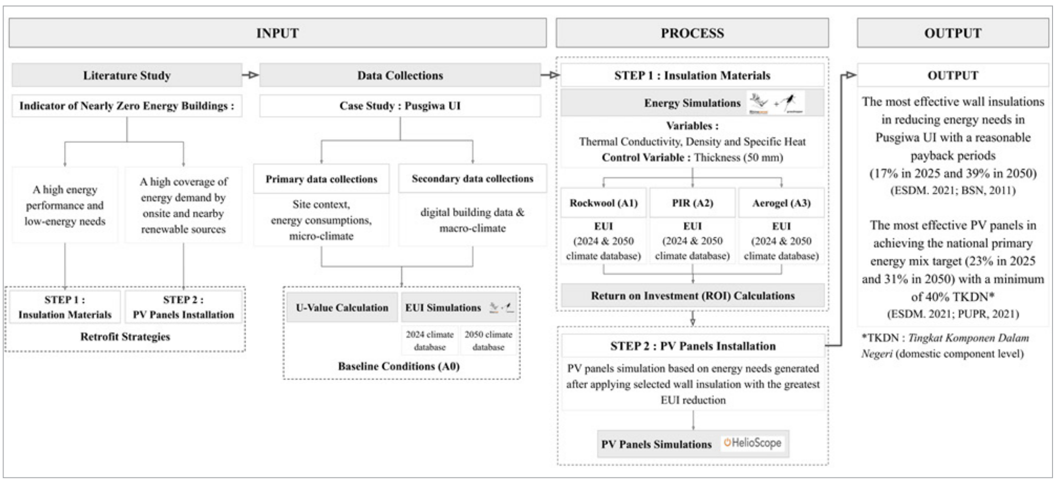
The temperature in Depok City, Indonesia has increased by 5.2°C since the year 2000. In 2024, the mean air temperature was 31.2°C, and it was projected to rise by 1.63°C across Indonesia by 2050, reaching an average of 33.83°C (BMKG, 2024; Weatherspark, 2024; WBG, 2021).

Methods

This research consisted of input, process, and output (Fig. 3). In terms of input, the literature study discussed the indicator of NZEB targets: a high energy performance, low-energy needs, and near-by renewable energy sources to cover the energy demand. To achieve NZEB targets, retrofits were implemented by applying thermal insulation and PV Panels. Data collection included both primary and secondary sources related to the selected case study: Pusgiwa UI, an educational building. The parameters used in this study were U-value, EUI, and mean air temperature to evaluate how thermal properties of materials affected the energy demand and indoor conditions.

Fig. 3

Research Framework



The process consisted of 2 steps of retrofit strategies: application of thermal insulation and PV Panel. The energy simulation of the existing Pusgiwa Building served as a baseline (A0) for Step 1. Step 1 involved application of insulation materials as an additional layer to the existing AAC interior surface wall on Pusgiwa UI and analyzed the reduction of EUI by comparing to the baseline in 2024 and 2050 climate database. These two climate databases were used to prepare the building for responding to the climate conditions not only in the present but also in the future.

This study focused on three selected insulation materials based on their thermal properties and material cost: rockwool (inorganic material), PIR (organic Material), and aerogel board (advanced material) which all had a thickness of 50 mm as shown in Table 2 (Rehman, 2017; Danaci & Akin, 2022). Aerogel as an advanced material has a thin thickness, thus in this study an aerogel board was used to achieve the same thickness of 50 mm as shown in Fig. 4 (Pagoni et al., 2024; AGITEC International AG, 2023). The independent variables used in the selection of insulation materials were thermal conductivity (W/m.K), density (kg/m^3), and specific heat (kJ/kg.K), with thickness (mm) as a control variable. Thermal conductivity reflects how well a material transfers heat, while specific heat indicates the amount of thermal energy a material can store per unit mass and temperature (Danaci & Akin, 2022; Harkness, 1970). The 50 mm thickness was chosen based on Rehman (2017) that evaluated 50 mm PIR in a UAE building and achieved a 23% energy demand reduction. Additionally, this thickness reflected practical considerations such as cost and local availability. These materials were highlighted for their thinner layer and their efficient thermal performance compared to other materials in reducing building load and space impact (Rehman, 2017). The most suitable insulation material in this study was determined based on the objective of achieving the lowest energy demand reduction (EUI reduction) combined with a reasonable return of investment (ROI) or payback periods. ROI represents the time required for the initial investment to be recovered through an annual energy cost saving. ROI calculated by dividing the total installation cost by the estimated annual electricity savings.

Table 2

Material Properties of Existing Pusgiwa Wall and Selected Insulation Material Scenarios

Scenario	Materials	Material Properties			
		Independent Variables		Control Variable	
		Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (kJ/kgK)	Thickness (mm)
A0	AAC (Baseline)	0.042 (Pagoni et al., 2024)	115 (Pagoni et al., 2024)	850 (Liu & McNabola, 2024)	100 (Pagoni et al., 2024)
A1	AAC + Rockwool	0.044 (Liu & McNabola, 2024)	100 (Liu & McNabola, 2024)	1470 (Liu & McNabola, 2024)	100 + 50 (Liu & McNabola, 2024)
A2	AAC + PIR	0.018 (Rehman, 2017)	30 (Rehman, 2017)	1500 (Rehman, 2017)	100 + 50 (Rehman, 2017)
A3	AAC + Aerogel board	0.016 (AGITEC International AG, 2023)	155 (AGITEC International AG, 2023)	1200 (Aegerter et al., 2023)	100 + 50 (AGITEC International AG, 2023)

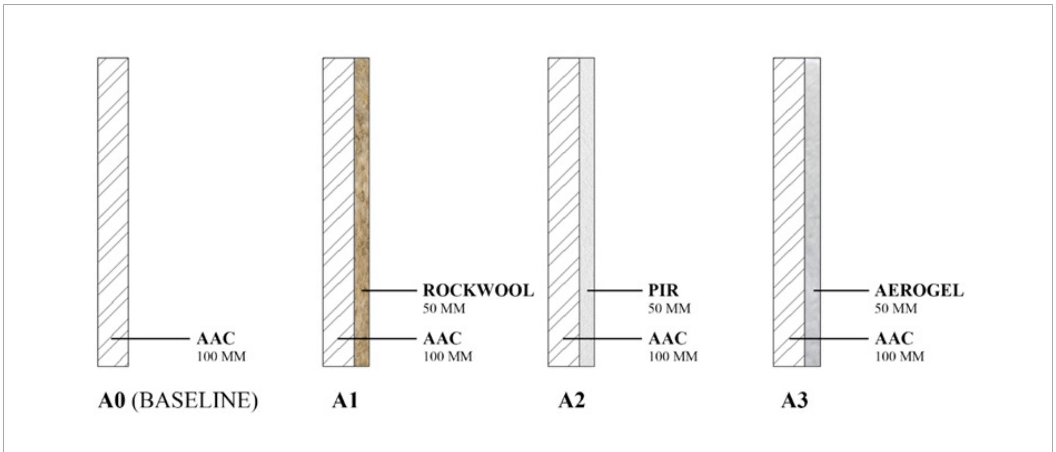


Fig. 4

Wall Configurations

Step 2 of the retrofit strategy was PV panel simulation by using a Helioscope to cover at least 31% of the building's post-intervention energy demands (the result from the energy demand reduction in Step 1: application of insulation material) as a substitution to conventional energy sources. The PV panel simulation input consisted of the surface area for PV panel installation, building location, type and specifications of the PV panels, and the tilt position of the panels. The selected PV panel specifications were referred to the minimum 40% domestic component level (TKDN) as required by the Regulation of the Minister of Public Works and Housing No. 21 of 2021 (PUPR, 2021).

The output of this study was to optimize the building envelope by applying insulation material to the walls to reduce energy demand at Pusgiwa UI and installing PV panels to cover the energy demand with onsite renewable energy sources. The result of this study was expected to allow Pusgiwa UI in achieving NZEB targets with near zero energy demand and relying on renewable energy.

U-Value Calculation

Based on SNI 6389:2020, the definition of U-value or thermal transmittance is the amount of heat transfer from the air on one side of a material to the air on the other side (BSN, 2020). U-value is calculated by considering the thermal resistance of the air layers on both sides of the material. For walls or fenestration which consist of multiple building components, the U-value is calculated by using the following formula:

$$U = \frac{1}{Rtotal} = \frac{1}{Rul + Rk + Rru + Rup} \quad (1)$$

$$\mathrm{Rk} = \frac{t}{k} \quad (2)$$

U = Thermal transmittance (W/m2K)

Rtotal = The total thermal resistance of all wall layers, including the inner and outer air layers (m2K/W)

Rul = Outer surface air layer resistance (m^2K/W)

Rk = Thermal resistance of the material (m^2K/W)

t = Material thickness (m)

k = Thermal conductivity of the material (W/m.K)

Rru = Air cavity thermal resistance (m^2K/W)

Rup = Inner surface air layer resistance (m^2K/W)

Energy Consumption Simulation

This study used Rhino and Grasshopper to calculate the energy consumption in terms of energy use intensity (EUI) of the existing building. These tools modeled and analyzed building energy consumption in current condition by using EPW files that represented weather data for the entire year of 2024 and also predict the 2050 weather data scenarios by using morphed EPW files generated by the CCWorldWeatherGen tool. This tool converted current EPW files into climate change projections for 2050 using IPCC data and the 'morphing' methodology (Jentsch et al., 2013; IPCC, 2021). The morphing approach allowed for accurate simulations to assess and optimize building energy performance under the 2050 climate conditions.

The variables considered in the simulation process included the material properties of Pusgiwa UI's wall, occupant density (people/m^2), electrical and equipment energy load (kWh/m^2), and setpoint for the cooling system. Additionally, the accuracy of the 3D model and building orientation were used to ensure reliable simulation results as shown in **Fig. 5**.

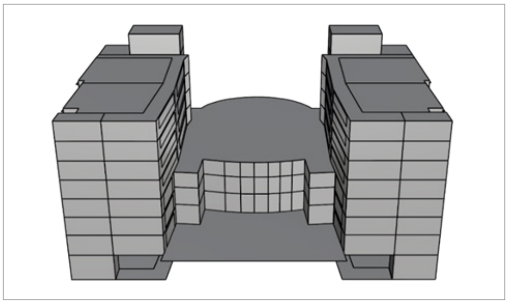


Fig. 5

Pusgiwa 3D Models for Energy Consumption Simulation

The simulation inputs for Energy Consumption were derived from field observations and measurements. The walls' material characteristics, which defined by their thickness (m), density (kg/m^3), specific heat (kJ/kg.K), and thermal conductivity (W/m.K), were included as inputs. The occupant density was set at 0.01 people/m^2, while the electrical energy load was 0.12 kWh/m^2, and the equipment energy load was 1.99 kWh/m^2. The cooling system setpoint was set at 25°C, and the building orientation was facing east. These variables were carefully considered to ensure the reliability and accuracy of the energy consumption simulation.

PV Panels Simulation for Renewable Energy

Photovoltaic (PV) panels were simulated by using Helioscope, a web-based PV design software. Helioscope was used to obtain the maximum energy capacity of PV modules by considering the available installation area, module type, and solar exposure on the Pusgiwa building. This study used Jakarta Soekarno Hatta climate data to gain the solar energy potential, aligned with the EPW file that was used in Energy Consumption Simulation. The PV module was selected by considering the domestic component level (TKDN) with the minimum of 40% as required by Regulation of the Minister of Public Works and Housing No. 21 of 2021 and the data availability in the Helioscope (PUPR, 2021; Kemenperin, 2024). The PV modules installed on the Pusgiwa rooftop as shown in **Fig. 6** were set up with a tilt angle 10° towards the north with an azimuth angle of 0° based on a previous study in Indonesia (Sugiono et al., 2022).

Fig. 6

PV module installation in Pusgiwa Rooftop (HelioScope Simulation, 2025)

Results and Discussion

Baseline Calculation and Simulation

The EUI baseline conditions of Pusgiwa UI used as a benchmark for analyzing intervention scenarios. The U-value of AAC in Pusgiwa's wall was 3.15 W/m^2.K. The simulation for the baseline condition of energy consumption was 17.99 kWh/m^2/year for 2024, showing a 0.11% deviation from Pusgiwa UI's actual EUI measurement (17.97 kWh/m^2/year). For 2050, based on morphed weather data, energy consumption was estimated at 23.06 kWh/m²/year, reflecting a 28.18% increase from the 2024 climate database. The increase in energy consumption highlighted the impact of climate change on building energy performance.

Step 1: Application of Insulation Materials

The first step of the retrofit strategy used in this study was adding insulation materials (scenario A1, A2, and A3) to the interior side of the existing wall material (baseline A0). The energy simulation was used to determine the most suitable insulation material that can improve the building's thermal performance, energy efficiency and prepared to face the 2050 climate conditions at Pusgiwa UI. The results showed that the simulations conducted under the 2024 and 2050 climate database revealed significant differences in EUI. These results implied that the selected insulation materials had an effect on reducing EUI, with the EUI results also influenced by the 2050 climate database.

By comparing the EUI from baseline scenario (A0) with various intervention scenarios (A1, A2, and A3), the data showed the effectiveness of different materials in improving energy efficiency (Table 3). AAC (A0) showed a U-value of 0.39 W/m²K and EUI of 17.99 kWh/m²/year. By adding Rockwool insulation (A1), U-value was reduced to 0.27 W/m²K, EUI was also reduced by 18.6%. PIR (A2) reduced the U-value to 0.19 W/m²K and achieved the best performance with a 22.5% EUI reduction, making it the most effective material for improving thermal performance. Meanwhile, the Aerogel board (A3) reduced the U-value to 0.18 W/m²K and EUI by 21.9%. The use of rockwool (18.6%) and Aerogel (21.9%) in Pusgiwa UI led to a more significant reduction in EUI compared to the previous study, which showed a 16.67% reduction for rockwool in a building in tropical Malaysia and an 8% reduction for aerogel in the hot-humid climate conditions of Turkey (Muhieldeen et al., 2020; Danaci & Akin, 2022). Meanwhile, the use of PIR in Pusgiwa UI showed a similar reduction of 22.5%, compared to the 23% reduction from the previous study in the hot and humid climatic conditions of the UAE (Rehman, 2017).

Table 3

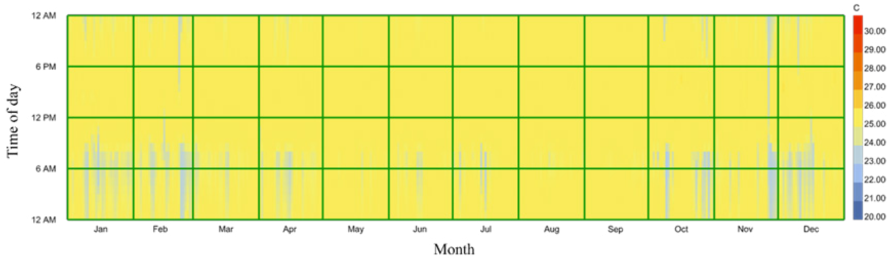
Intervention through Wall Insulation Under the 2024 and 2050 Climate Conditions

Wall Insulation						
Materials		U-Value (W/m²K)	2024 Climate Database		2050 Climate Database	
			EUI (kWh/m². year)	Energy Consumption (kWh/year)	EUI (kWh/m². year)	Energy Consumption (kWh/year)
A0	AAC (Baseline)	0.39	17.99	350,803.56	23.06	449,668.16
A1	AAC + Rockwool	0.27	14.60 (-18.6%)	284,698.83	16.96 (-26.5%)	330,718.64
A2	**AAC + PIR**	**0.19**	**13.94 (-22.5%)**	**271,828.88**	**16.16 (-29.9%)**	**315,118.71**
A3	AAC + Aerogel board	0.18	14.05 (-21.9%)	273,973.88	16.09 (-30.2%)	313,753.71

In the 2050 climate database, the baseline EUI (A0) was calculated to be 23.06 kWh/m²/year. With the application of Rockwool (A1), the EUI was reduced to 16.96 kWh/m²/year, showing a 26.5% reduction. PIR (A2) surpassed all insulation materials by reducing 29.9% EUI to 16.16 kWh/m²/year compared to the baseline. Aerogel board (A3) showed a smaller reduction, with an EUI of 16.07 kWh/m²/year, a 30.2% reduction in energy efficiency compared to the baseline. This result demonstrated the efficiency of PIR to reduce building energy consumption as global temperatures rise. In addition to its reduction in energy consumption, PIR (A2) also demonstrated the lowest mean air temperature (Table 4) and the shortest heat duration (Table 5) in both the 2024 and 2050 climate database.

Table 4

Average Indoor Air Temperature Results for Wall Insulation Simulation Scenarios

<table>
<tr><th colspan="3">Wall Insulation - 2024 and 2050 Climate Database</th></tr>
<tr><th></th><th>Year</th><th>Average Indoor Air Temperature (°C)</th></tr>
<tr><td rowspan="2">A0</td><td>2024</td><td>
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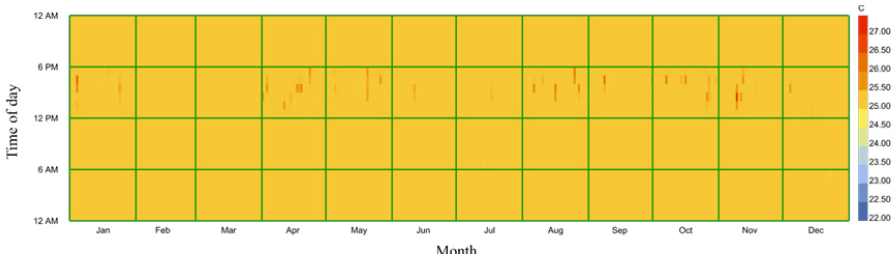
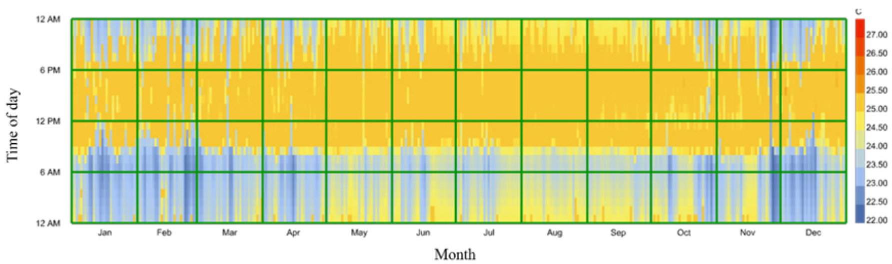
<tr><td>2050</td><td>
</td></tr>
<tr><td rowspan="2">A1</td><td>2024</td><td>
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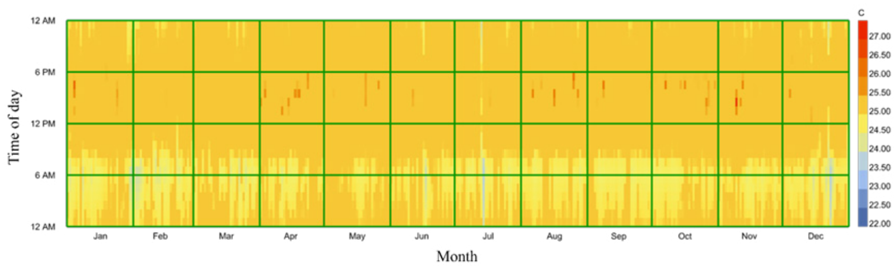
<tr><td>2050</td><td>
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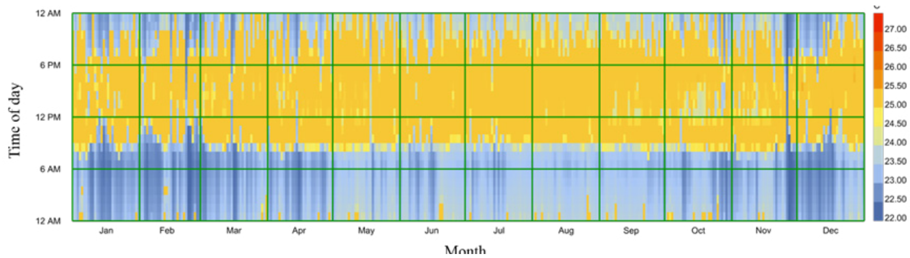
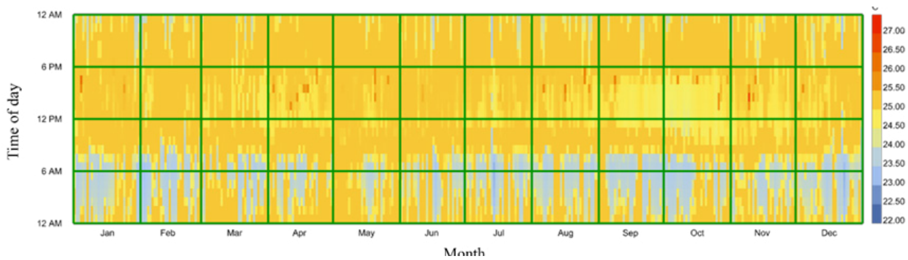
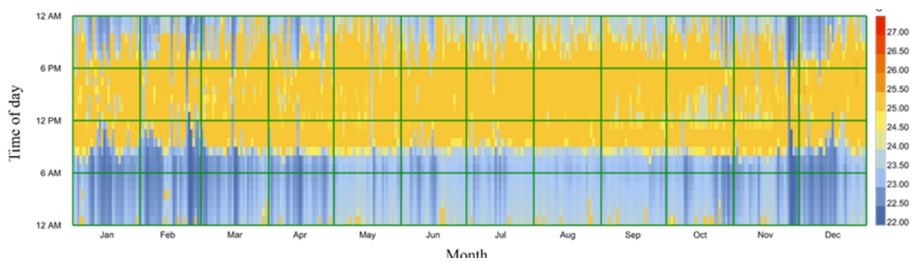
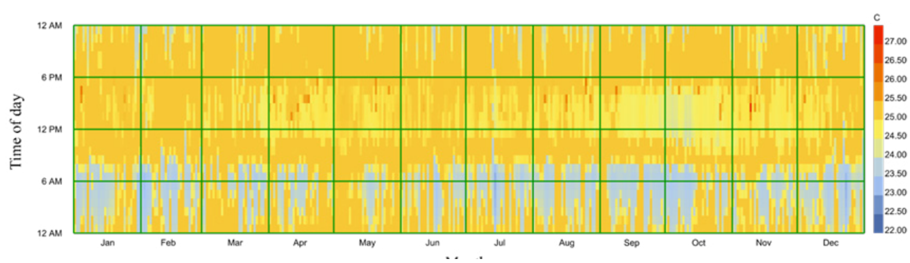
Wall Insulation - 2024 and 2050 Climate Database		
	Year	Average Indoor Air Temperature (°C)
A2	2024	
	2050	
A3	2024	
	2050	

Table 5

Average Cooling Energy Results for Wall Insulation Simulation Scenarios

<table>
<tr><th colspan="3">Wall Insulation - 2024 and 2050 Climate Database</th></tr>
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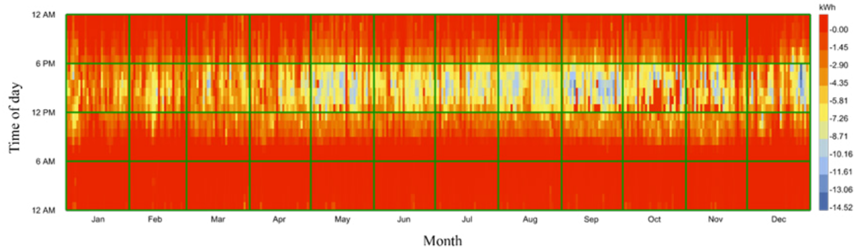
<tr><td rowspan="2">A0</td><td>2024</td><td>
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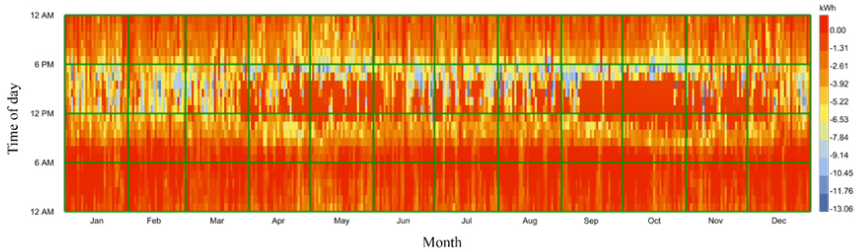
<tr><td>2050</td><td>
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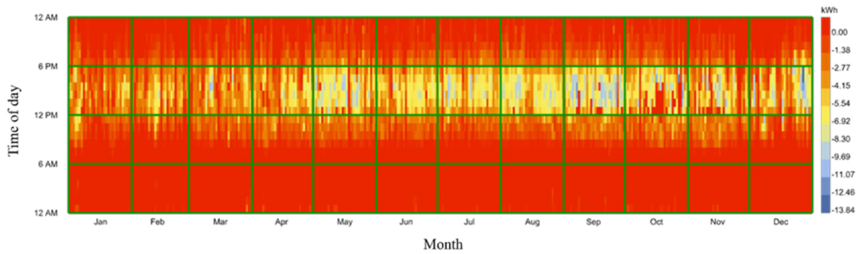
<tr><td rowspan="2">A1</td><td>2024</td><td>
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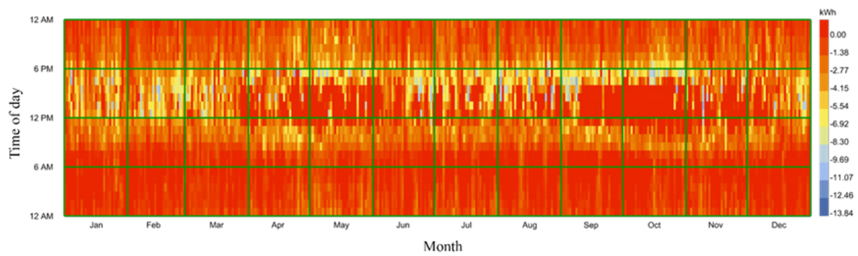
<tr><td>2050</td><td>
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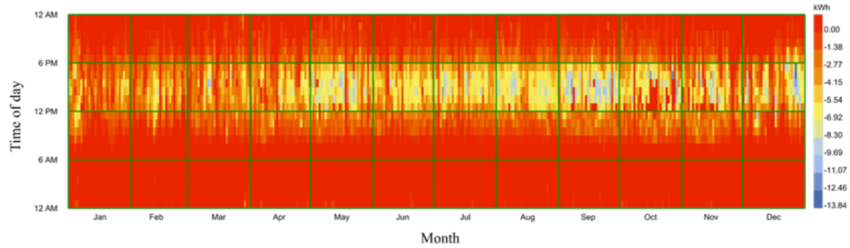

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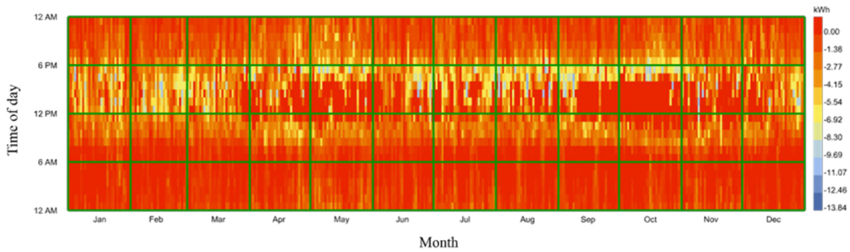

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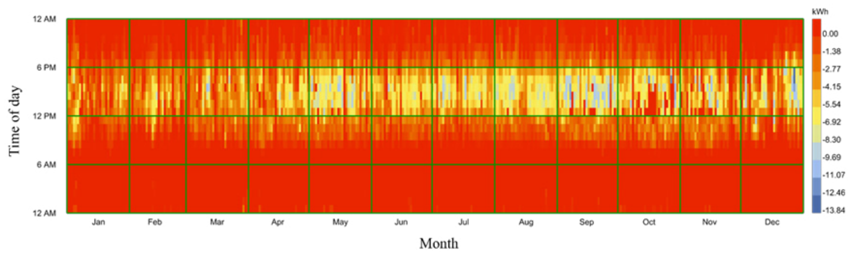

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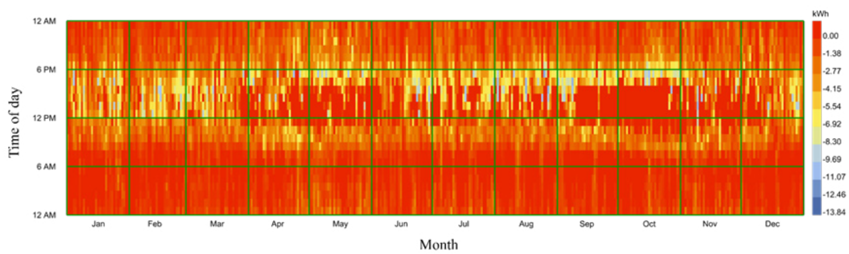

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Step 2: Application of PV Panels

For the second step of the study, the integration of 200 modules of Monocrystalline Photovoltaic (PV) Panels was simulated to evaluate the renewable energy potential to meet the energy demand of the Pusgiwa UI. Two types of PV Panels listed in the Helioscope modules library and compliant with Indonesia's domestic component level requirement (TKDN above 40%) were selected for the simulation The selected PV Panels were local manufactured modules with power capacities of 300 Wp and 455 Wp which have a TKDN level of 47.5% (Kemenperin, 2024; HelioScope, 2025).

The PV Panels were installed on the building's roof with a fixed tilt of 10° to the north to optimize the energy capture based on the building's location and orientation (Abd Malek et al. 2018). Based on the Annual Production Report from HelioScope simulation, the 300 Wp system generated an annual output of 130,253.5 kWh, while the 455 Wp system generated 85,652.2 kWh annually (**Fig. 7**). These outputs are equivalent to cover 31.5% of the building's annual energy demand when using the 300 Wp system and 47.9% when using the 455 Wp system, based on the final Pusgiwa building's energy needs (271,828.88 kWh/year) that had already been reduced by 22.5% from the result of the application of insulation material by using the 2024 climate database. The overall reduction in energy use and the combination with the PV system's contribution supports Indonesia's national target, as outlined in Government Regulation No. 79/2014, to achieve 31% renewable energy in buildings by 2050.

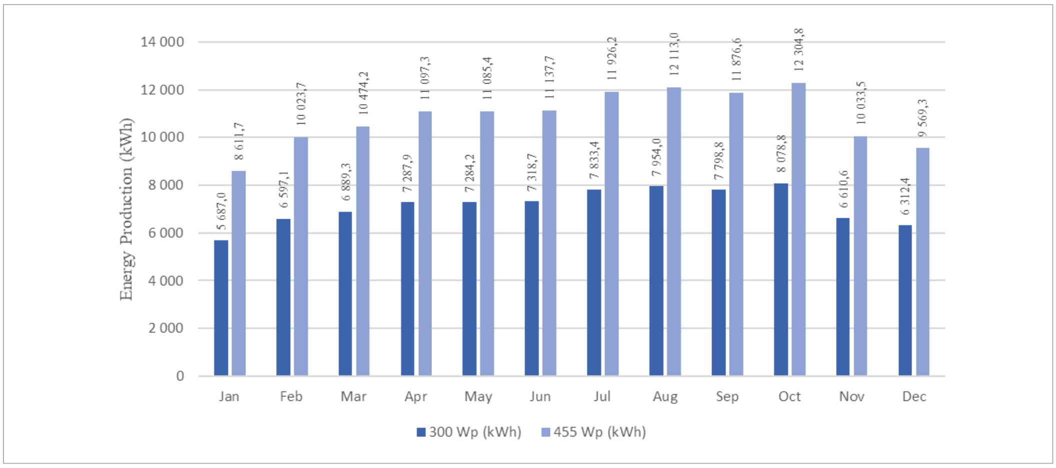

Fig. 7

Monthly Average of PV Power Production (HelioScope Simulation, 2025)

Economics Evaluation

The application of insulation materials such as Rockwool, PIR, and Aerogel has showed a various energy demand reduction in tropical climates. In this study, an economic evaluation was conducted to compare the cost-effectiveness of the three insulations for a total building envelope coverage area of 6,096 m^2. In local markets, Rockwool is the most cost-effective option at approximately 8.42 USD/m^2, followed by PIR at 21.37 USD/m^2, and Aerogel at 174.55 USD/m^2. When applied to the total coverage area, the total material costs are 51,313.13 USD for Rockwool, 108,546.11USD for PIR, and 1,064,029.09 USD for Aerogel. Based on the local electricity rate of 1,500 IDR/kWh (≈ 0.09 USD/kWh), the return of investment (ROI) was calculated based in the EUI reduction for 2024 climate database. The results showed that Rockwool achieved a payback period of approximately 9 years, PIR around 15 years, and Aerogel a significantly longer payback of 152 years. Although PIR insulation has a longer payback period compared to Rockwool, its thermal performance made it a strategic choice for long-term energy efficiency with 22.5% EUI reduction. Therefore, PIR with a return on investment within 15 years is still considered acceptable, especially when aligned with national energy transition goals set for 2050.

To further improve efficiency, a rooftop PV panels by using 200 modules of two locally available options, such as 300 Wp panels (164 USD/module) and 455 Wp panels (248 USD/module). The 455 Wp system generated 130,254 kWh annually, resulting in electricity savings of 11,841.23 USD/year and an ROI of 4.1 years. Meanwhile the 300 Wp system produced 85,652 kWh/year, saving 7,786.54 USD annually with an ROI of 4.2 years.

When combined the PV panels with PIR insulation, the integrated systems significantly improve overall payback. The combination of PIR insulation with the 455 Wp PV system yields a total ROI of 9.4 years, while the combination with the 300 Wp system offers an even shorter ROI of 8.3 years. These results highlight the effectiveness of combining passive and active energy-saving strategies to achieve both energy efficiency and financial feasibility, in line with sustainable development and national policy targets.

Conclusion

This study, based on the case study of Pusgiwa Building at Universitas Indonesia, showed how retrofit strategies were effectively used to improve thermal performance and energy efficiency in both 2024 and 2050 climate databases. The results were obtained through U-value calculation, energy simulation, and Photovoltaic (PV) panels simulation. The most effective material for improving thermal performance was the addition of polyisocyanurate insulation (PIR) to the building envelope which showed the best performance with a 22.5% EUI reduction from 17.99 kWh/m^2/year to 13.94 kWh/m^2/year by using the 2024 climate database. Furthermore, by using the 2050 climate database, the EUI decreased by 29.9% from 23.06 kWh/m^2/year to 16.16 kWh/m^2/year as a result of applying PIR insulation. The economic evaluation showed that PIR insulation, with a total installation cost of 108,546.11 USD, achieved a Return on investment (ROI) of approximately 15 years.

To further enhance energy performance, the integration of rooftop PV panels was also evaluated. Between the two available options (300 Wp and 455 Wp modules), the 300 Wp system was selected due to its shorter payback period. This system generated 85,652 kWh annually, resulting in electricity savings of 7,786.54 USD per year and a payback period of 4.2 years. When combined with PIR insulation, the integrated system reduced the overall payback period to just 8.3 years, demonstrating a highly cost-effective solution.

As a whole, these tactics showed promises for achieving notable energy savings, meeting Indonesia's national energy goals, and assisting international efforts to slow down the climate change. The combination of insulation retrofitting by using PIR and integrating a PV system can reduce energy demand in tropical buildings. This study was limited to one educational building, specifically Pusgiwa UI and should be further explored to other types of buildings in tropical regions, considering the local factors.

Acknowledgment

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References

Abd Malek, N. A. A., Chew, J. M., Naamandadin, N. A., Zainol, N. Z., & Muhammad, K. (2018). A study on association between tilt angle, solar insolation exposure and output of solar PV panel using BIM 3D modelling. In MATEC Web of Conferences (Vol. 195, p. 06009). EDP Sciences. https://doi.org/10.1051/matecconf/201819506009

Aegerter, M. A., Leventis, N., Koebel, M., & Steiner Iii, S. A. (Eds.). (2023). Springer Handbook of Aerogels. Springer International Publishing. https://doi.org/10.1007/978-3-030-27322-4

AGITEC International AG. (2023). Technical data sheet: Pureflex roll insulation. https://www.agitec.ch

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., & Guattari, C. (2019). Energy and environmental payback times for an NZEB retrofit. Building and Environment, 147, 461-472. https://doi.org/10.1016/j.buildenv.2018.10.047

Balali, A., Yunusa-Kaltungo, A., & Edwards, R. (2023). A systematic review of passive energy consumption optimisation strategy selection for buildings through multiple criteria decision-making techniques. Renewable and Sustainable Energy Reviews, 171, 113013. https://doi.org/10.1016/j.rser.2022.113013

Badan Meteorologi, Klimatologi, dan Geofisika (BMKG). (2024). Indonesia's climate and temperature range. Badan Meteorologi, Klimatologi, dan Geofisika. https://www.bmkg.go.id

Badan Standardisasi Nasional (BSN). (2020). SNI 03-6389-2020: Energy conservation of building envelopes in buildings (SNI 03-6389-2020). National Standardization Agency of Indonesia.

Danaci, H. M., & Akin, N. (2022). Thermal insulation materials in architecture: a comparative test study with aerogel and rock wool. Environmental Science and Pollution Research, 29(48), 72979-72990. https://doi.org/10.1007/s11356-022-20927-2

EDGE Building. (2023). Pusgiwa UI. Accessed from https://edgebuildings.com/project-studies/

Elnabawi, M. H., Saber, E., & Bande, L. (2024). Passive building energy saving: Building envelope retrofitting measures to reduce cooling requirements for a residential building in an arid climate. Sustainability, 16(2), 626. https://doi.org/10.3390/su16020626

Environmental Protection Agency (EPA). (2023). Net zero resources. Accessed from https://www.epa.gov/

European Union. (2018). Nearly-zero energy and zero-emission buildings. Retrieved from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-and-zero-emission-buildings_en

Kementerian Energi dan Sumber Daya Mineral (ESDM). (2014). Government Regulation of the Republic of Indonesia Number 79 of 2014 on National Energy Policy. Ministry of Energy and Mineral Resources. https://jdih.esdm.go.id/dokumen/view?id=1777

Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR). (2021). Regulation No. 21 of 2021 on the performance assessment of green buildings

Harkness, D. D. (1970). Artificial carbon-14, a tracer for carbon in the atmosphere and biosphere. University of Glasgow (United Kingdom).

Intergovernmental Panel on Climate Change (IPCC). (2021). Summary for policymakers. In Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://climateknowledgeportal.worldbank.org/

Intergovernmental Panel on Climate Change (IPCC). (2022). History of the IPCC Data Distribution Centre. https://www.ipcc.ch/data/

Intergovernmental Panel on Climate Change (IPCC). (2023). Climate change 2023: Synthesis report - Summary for policymakers. Intergovernmental Panel on Climate Change. https://www.ipcc.ch

Jentsch, M. F., James, P. A. B., Bourikas, L., & Bahaj, A. S. (2013). Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. Renewable Energy, 55, 514-524. https://doi.org/10.1016/j.renene.2012.12.049

Kementerian Perindustrian Indonesia (Kemenperin). (2024). Peningkatan Penggunaan Produk dalam Negeri. Daftar Inventarisasi Barang/Jasa Produksi dalam Negeri. https://tkdn.kemenperin.go.id/search.php?where=produk&what=modul%20surya&hal=YBSkfmOOVYlx7YS_0ga1yxOlwp0UM52EqEfIxApKuws

Kementerian Energi dan Sumber Daya Mineral (ESDM) & Danish Energy Agency. (2022). Roadmap for an Energy Efficient, Low-Carbon Buildings and Construction Sector in Indonesia. Danish Energy Agency.

Lechner, N., & Andrasik, P. (2022). Heating, cooling, lighting: Sustainable design strategies towards net zero architecture (5th ed.). John Wiley & Sons, Inc.

Liu, Y., Considine, B., & McNabola, A. (2024). Assessment of hygrothermal performance and mould growth risk in roofs of post-retrofitted non-dormer and dormer attic rooms with reduced ventilation. Building and Environment, 250, 111172. https://doi.org/10.1016/j.buildenv.2024.111172

Liyanage, D. R., Hewage, K., Hussain, S. A., Razi, F., & Sadiq, R. (2024). Climate adaptation of existing buildings: A critical review on planning energy retrofit strategies for future climate. Renewable and Sustainable Energy Reviews, 199, 114476. https://doi.org/10.1016/j.rser.2024.114476

Muhieldeen, M. W., Wong, Q. Y., Abd Rahman, U. Z., & Tey, W. Y. (2020). Energy saving by applying different wall thermal insulations on a room at malaysian institution. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 65(1), 130-139.

Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., ... & Engelmann, W. H. (1994). The National Human Activity Pattern Survey (NHAPS).

Pacheco-Torgal, F. (2017). Introduction to cost-effective energy-efficient building retrofitting. In Cost-Effective Energy Efficient Building Retrofitting (pp. 1-20).

Woodhead Publishing. https://doi.org/10.1016/B978-0-08-101128-7.00001-0

Pagoni, P., Møller, E. B., Peuhkuri, R. H., & Jensen, N. F. (2024). Robustness of internal insulation systems in practice-Role of installation, physical impact, paint types, and surface covering. Journal of Building Engineering, 98, 111177. https://doi.org/10.1016/j.jobe.2024.111177

Papadopoulos, A. M., Avgelis, A., & Anastaselos, D. (2008). Low energy cooling of the White Tower, functioning as a contemporary museum. Energy and buildings, 40(8), 1377-1386. https://doi.org/10.1016/j.enbuild.2007.12.008

Pásztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. Journal of Building Engineering, 44, 102604. https://doi.org/10.1016/j.jobe.2021.102604

Rehman, H. U. (2017). Experimental performance evaluation of solid concrete and dry insulation materials for passive buildings in hot and humid climatic conditions. Applied Energy, 185, 1585-1594. https://doi.org/10.1016/j.apenergy.2016.01.026

Silveira, V. D. C., Pinto, M. M., & Westphal, F. S. (2019). Influence of environmental factors favorable to the development and proliferation of mold in residential buildings in tropical climates. Building and Environment, 166, 106421. https://doi.org/10.1016/j.buildenv.2019.106421

Shukla, A. K., Yadav, A. K., & Prakash, R. (2023). Active and passive methods for cooling load reduction in a tropical building: A case study. Energy Conversion and Management, 293, 117490. https://doi.org/10.1016/j.enconman.2023.117490

Sugiono, F. A. F., Larasati, P. D., & Karuniawan, E. A. (2022). Pengaruh sudut kemiringan panel surya terhadap potensi pemanfaatan plts rooftop di bengkel teknik mesin, Politeknik Negeri Semarang. Jurnal Rekayasa Energi, 1(1), 1-8. https://doi.org/10.31884/jre.v1i1.5

United Nations Environment Programme. (2024). Global status report for buildings and construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector. Global Alliance for Buildings and Construction (GlobalABC). https://www.unep.org

Weatherspark. (2024). Iklim dan Cuaca Rata-Rata Sepanjang Tahun di Kota Depok. https://id.weatherspark.com/y/116856/Cuaca-Rata-rata-pada-bulan-in-Kota-Depok-Indonesia-Sepanjang-Tahun

World Bank Group (2021). What is Climate Change?: Understanding The Big Picture. https://climateknowledgeportal.worldbank.org/

About the authors

CALISTA PRILIANA ARDINI

Master Student

Department of Architecture, Faculty of Engineering

Main research area

Energy, Sustainable Built Environment

Address

Kampus Baru UI Depok
E-Mail: clstpriliana@gmail.com

OVA CANDRA DEWI

Lecturer, Thesis supervisor

Department of Architecture, Faculty of Engineering

Main research area

Sustainable Built Environment, Low Carbon Cities

Address

Kampus Baru UI Depok
E-Mail: ova.candewi@ui.ac.id

MIKTHA FARID ALKADRI

Lecturer

Department of Architecture, Faculty of Engineering

Main research area

Building performance simulation, Remote sensing, Digital fabrication

Address

Kampus Baru UI Depok
E-Mail: miktha@ui.ac.id

KARTIKA RAHMASARI

Researcher

Department of Architecture, Faculty of Engineering

Main research area

Energy, Architecture and built environment

Address

Kampus Baru UI Depok
E-Mail: kartikarsari@gmail.com