Jurnal Dinamis (*Scientific Journal of Mechanical Engineering*)
Journal homepage: https://talenta.usu.ac.id/dinamis/

Effect of Indoor Temperature Setpoint on HVAC Energy Use and Thermal Comfort in Tropical Classrooms

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ARTICLE INFO

Article history:
Received May 20th 2026
Revised May 21th 2026
Accepted June 28th 2026
Available online June 30th 2026

E-ISSN: 2809-3410

How to cite:
Hotdian Sinambela, Pramio Garson Sembiring, Haksa Fadilman Sinambela, Mei Derman Hulu, Wilbert Wu, "Effect of Indoor Temperature Setpoint on HVAC Energy Use and Thermal Comfort in Tropical Classrooms", *Jurnal Dinamis (Scientific Journal of Mechanical Engineering)*, Vol. 14, No. 1, pp. 38-53, June 2026.

http://doi.org/10.32734/dinamis.v14i1.25664

ABSTRACT

Heating, Ventilation, and Air-Conditioning (HVAC) systems contribute significantly to electricity consumption in tropical educational buildings due to continuous cooling demand. This study evaluates the influence of indoor temperature setpoints on cooling energy consumption and thermal comfort in two university classrooms equipped with split air-conditioning systems in Medan, Indonesia, using EnergyPlus simulations. Six temperature setpoints ranging from 20°C to 25°C were analyzed under identical operational and climatic conditions. Thermal comfort performance was assessed using the Predicted Mean Vote (PMV) method based on ASHRAE Standard 55. To verify the representativeness of the climatic input data, the outdoor dry-bulb temperature obtained from the EPW weather file was compared with observed outdoor temperature data collected on 30 May 2026, resulting in a relative error of 2.26%. The results show that increasing the setpoint temperature reduced annual cooling electricity consumption from 5,515 kWh to 3,607 kWh in Room J20.301 and from 5,284 kWh to 3,581 kWh in Room J20.302, corresponding to energy savings of 34.6% and 32.2%, respectively. However, thermal comfort performance decreased as the setpoint increased. At 25°C, PMV values reached 0.71 and 0.73, exceeding the ASHRAE comfort limit and reducing annual comfort compliance to below 1% in both rooms. The 23°C setpoint provided the most balanced performance, with annual energy consumption of 4,379 kWh and 4,292 kWh while maintaining PMV values within the acceptable comfort range at 0.35 and 0.32. Annual comfort compliance at this condition reached 87.6% and 96.1% for Rooms J20.301 and J20.302, respectively.

Keyword: *HVAC, setpoint temperature, energy consumption, thermal comfort, tropical climate*

ABSTRAK

Sistem *Heating, Ventilation, and Air-Conditioning* (HVAC) memberikan kontribusi signifikan terhadap konsumsi listrik pada bangunan pendidikan di wilayah beriklim tropis akibat tingginya kebutuhan pendinginan sepanjang tahun. Penelitian ini bertujuan untuk mengevaluasi pengaruh temperatur *setpoint* ruang terhadap konsumsi energi pendinginan dan kenyamanan termal pada dua ruang kelas universitas yang menggunakan sistem pendingin udara tipe *split* di Kota Medan, Indonesia, melalui simulasi EnergyPlus. Variasi temperatur *setpoint* yang dianalisis meliputi 20°C hingga 25°C dengan kondisi operasional dan iklim yang identik. Evaluasi kenyamanan termal dilakukan menggunakan metode *Predicted Mean Vote* (PMV) berdasarkan standar ASHRAE 55. Untuk memverifikasi keterwakilan data iklim yang digunakan dalam simulasi, temperatur *dry-bulb* udara luar dari berkas cuaca EPW dibandingkan dengan data temperatur udara luar hasil observasi pada tanggal 30 Mei 2026 dan menghasilkan galat relatif sebesar 2,26%. Hasil penelitian menunjukkan bahwa peningkatan temperatur *setpoint* mampu menurunkan konsumsi listrik pendinginan tahunan dari 5.515 kWh menjadi 3.607 kWh pada Ruang J20.301 dan dari 5.284 kWh menjadi 3.581 kWh pada Ruang J20.302, yang setara dengan penghematan energi masing-masing sebesar 34,6% dan 32,2%. Namun demikian, peningkatan temperatur *setpoint* juga menyebabkan penurunan kinerja kenyamanan termal. Pada temperatur 25°C, nilai PMV meningkat hingga 0,71 dan 0,73 sehingga melampaui batas kenyamanan ASHRAE dan menurunkan *comfort compliance* tahunan hingga kurang dari 1% pada kedua ruangan. Temperatur *setpoint* 23°C memberikan kinerja paling optimal dengan konsumsi energi tahunan sebesar 4.379 kWh dan 4.292 kWh serta nilai PMV sebesar 0,35 dan 0,32 yang masih berada dalam rentang kenyamanan termal yang dapat diterima. Tingkat *comfort compliance* tahunan pada kondisi ini mencapai 87,6% dan 96,1% masing-masing untuk Ruang J20.301 dan J20.302.

Kata Kunci: HVAC, temperatur setpoint, konsumsi energi, kenyamanan termal, iklim tropis.

1. Introduction

The building sector has become one of the largest contributors to global energy consumption, particularly in tropical regions where cooling demand persists throughout the year due to high ambient temperatures and humidity levels [1]. In developing countries such as Indonesia, rapid urbanization, expanding educational infrastructure, and increasing dependence on mechanical cooling systems have significantly intensified electricity consumption in commercial and institutional buildings [2]. Among various building service systems, Heating, Ventilation, and Air Conditioning (HVAC) systems represent the dominant source of operational energy use, accounting for a substantial proportion of total building electricity demand [3].

Educational buildings exhibit unique operational characteristics that distinguish them from other commercial building categories. Variations in occupancy density, intermittent classroom utilization, fluctuating internal heat gains, and extended operational schedules contribute to highly dynamic cooling load profiles [4]. In tropical climates, these conditions often lead to excessive HVAC operation and inefficient energy utilization, particularly when indoor temperature setpoints are maintained at unnecessarily low levels. Although lower temperature settings are frequently perceived as beneficial for improving thermal comfort, previous studies have demonstrated that excessively low setpoints can substantially increase cooling energy demand while providing only marginal improvements in occupants' thermal perception [5].

Beyond energy consumption, HVAC operational strategies also directly influence indoor environmental quality and occupant productivity. Thermal comfort conditions in educational spaces play a critical role in supporting learning effectiveness, cognitive performance, and occupant well-being [6], [7]. Consequently, the optimization of HVAC operational parameters must not only prioritize energy efficiency but also ensure acceptable indoor thermal comfort conditions in accordance with international standards such as ASHRAE. Achieving an appropriate balance between energy conservation and thermal comfort therefore remains a major challenge in tropical educational buildings.

Recent advances in building energy simulation technologies have enabled more comprehensive analyses of HVAC system performance under various operational scenarios. Simulation platforms such as EnergyPlus have been extensively utilized to evaluate building thermal behavior, cooling load characteristics, and HVAC energy performance with high computational reliability [8], [9]. Previous studies have reported that increasing indoor temperature setpoints may significantly reduce cooling energy consumption and operational costs while maintaining acceptable thermal comfort conditions within certain temperature ranges [10], [11]. Several researchers have also highlighted the economic potential of optimized HVAC setpoint strategies in reducing long-term building operational expenditures and improving energy management performance [5].

Nevertheless, despite the growing body of research on HVAC optimization, most previous investigations have predominantly focused on whole-building analyses or office-type buildings located in subtropical and temperate climates. Limited studies have specifically examined classroom-scale thermal behavior and split-type air-conditioning performance in tropical educational buildings, particularly under real operational characteristics commonly found in Indonesian universities.

Furthermore, previous studies have generally emphasized either energy consumption or thermal comfort independently, whereas the combined evaluation of annual cooling electricity consumption, operational cost savings, PMV-based thermal comfort, and annual comfort compliance hours at the classroom level remains limited, particularly in hot-humid tropical regions. The novelty of this study lies in the integrated evaluation of cooling energy consumption, electricity cost, PMV-based thermal comfort, and annual comfort compliance hours analysis for split-type air-conditioning systems operating in tropical university classrooms at Sumatera Utara under actual Indonesian occupancy schedules and internal heat gain conditions. Unlike previous EnergyPlus-based studies that predominantly focused on centralized HVAC systems or generalized building models, this research specifically investigates room-level thermal behavior and operational performance of split air-conditioning systems widely used in Indonesian educational buildings. Furthermore, this study provides a comparative analysis between two classrooms with different internal heat gain characteristics, enabling a more detailed understanding of how occupancy-related loads and equipment usage influence the trade-off between energy efficiency and thermal comfort in tropical educational environments.

2. Method

2.1. Building Design and Characteristic

The building model was developed based on the actual physical and operational conditions of the Master of Mechanical Engineering Building at Universitas Sumatera Utara. The modeling process incorporated several essential building parameters, including building geometry, room dimensions, building orientation, envelope characteristics, and thermal zoning configurations to ensure that the simulation accurately represented the real operational behavior of the building.

This study specifically focused on two classrooms located on the third floor of the building, namely Room J20.301 and Room J20.302, which were selected due to their comparable functional characteristics and operational schedules. Both classrooms are intensively utilized for academic activities, including lectures, group discussions, and classroom-based learning sessions during regular operational hours.

Each classroom has an identical floor area of approximately 72 m² with relatively similar spatial configurations. The rooms were designed with comparable interior layouts, occupancy patterns, and HVAC system specifications, thereby enabling a more reliable comparative assessment of the influence of indoor temperature setpoint variations on cooling energy consumption and thermal comfort performance. In addition, both classrooms are equipped with large glazed window areas positioned on one side of the exterior façade. The building orientation was modeled at approximately 352° relative to true north. Under the hot-humid tropical climatic conditions of Medan City, solar heat gain through the building envelope contributes significantly to the increase in indoor cooling loads and HVAC operational demand.

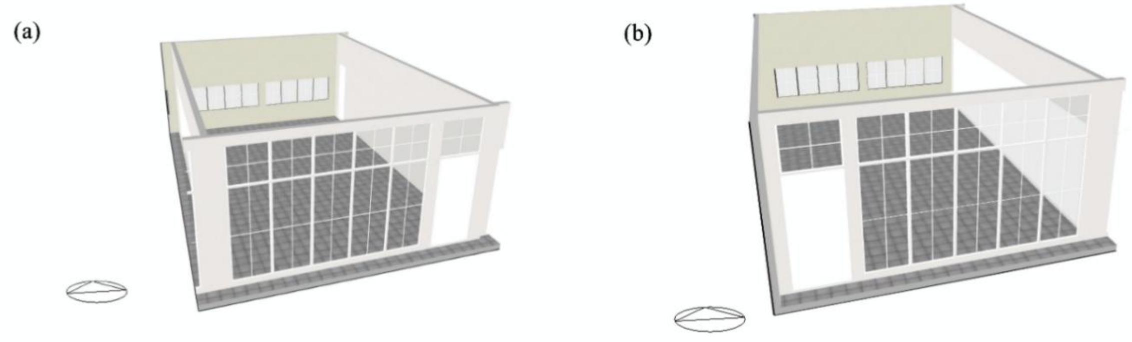

Figure 1. (a) J20.301 Room Model; (b) J20.302 Room Model.

Beyond occupancy-related parameters, the simulation model also incorporated the thermal properties of the building envelope materials, which strongly influence conductive and radiative heat transfer through the building structure. The wall, roof, floor, and glazing assemblies were modeled according to the actual construction conditions of the building to accurately represent the thermal response of the indoor environment. The specifications of the building envelope materials utilized in the simulation are summarized in Table 1.

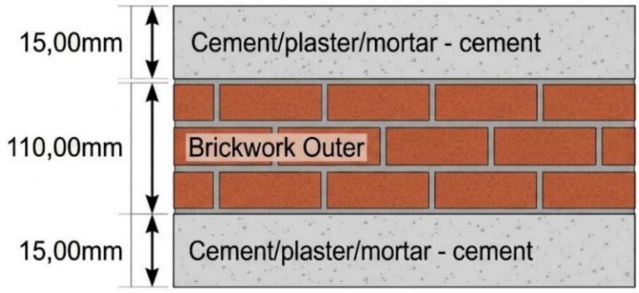

Figure 2. Wall Construction Model

Table 1. Building Material Spesification

No	Parameter	Construction Material
1	Wall Material	Cement plaster, Brickwork
2	Window Material	Clear Glass 3 mm
3	Roof Material	Gypsum ceiling, Air gap, Concrete
4	Floor Material	Ceramic tile, Cement, Concrete

The building and HVAC system data employed in this study were obtained directly from field observations and existing operational records of the Master of Mechanical Engineering Building at Universitas Sumatera Utara. The collected data included HVAC system specifications, room characteristics, internal heat gains, occupancy conditions, and operational schedules to ensure a high level of simulation reliability and representativeness. The thermal characteristics of the window system were incorporated into the EnergyPlus model to accurately represent solar heat gain and its influence on classroom cooling loads under tropical climatic conditions. Both analyzed classrooms were equipped with clear glass windows positioned on the exterior façade with a window-to-wall ratio of approximately 30%. The glazing configuration was modeled based on the actual building dimensions, including window height, sill height, and spacing between adjacent windows. These parameters significantly influence indoor thermal behavior because solar radiation transmitted through the glazing contributes directly to sensible cooling loads and increases HVAC operational demand during daytime classroom activities. The detailed window specifications utilized in the simulation model are presented in Table 2.

Table 2. Window Configuration Parameters

No	Parameter	Units	Value
1	Window-to-Wall	%	30
2	Window Height	m	1.1
3	Window Sill Height from Floor	m	0.8
4	Window Spacing	m	0.8

The technical specifications of the split-type air-conditioning systems used in this study are presented in Table 3. These specifications include cooling capacity, power input, and coefficient of performance (COP), which are critical parameters in evaluating the overall energy efficiency and operational cost implications of HVAC performance under different temperature setpoint scenarios.

Table 3. Split Air Conditioner Specification

No	Parameter	Units	Value
1	Cooling Capacity	kW	12.90
2	Power Input	kW	4.086
3	Coefficient of performance	-	3,16
4	Air Conditioner Horsepower	-	2

2.2. Simulation Variable and Model Configuration

The primary variable investigated in this study was the indoor temperature setpoint of the split-type air-conditioning system. The analyzed temperature setpoints consisted of 20°C, 21°C, 22°C, 23°C, 24°C, and 25°C. All simulation scenarios were conducted under identical environmental and operational conditions using climatic data for Medan City to ensure consistency and comparability among the investigated cases. The detailed simulation configuration parameters utilized in this study are summarized in Table 4.

Table 4. EnergyPlus Simulation Configuration Parameters

No	Parameter	Units	Value
1	Simulation Software	-	EnergyPlus
2	Weather File Source	-	Medan–Polonia EnergyPlusWeather
3	Simulation Period	-	January–December
4	Cooling Setpoint Range	°C	20–25
5	Cooling Setback Temperature	°C	28.5
6	Operational Schedule	-	09:00–16:00 WIB
7	Infiltration Rate	ACH	0.7
8	Fresh Air Ventilation	L/s-person	3.8
9	Mechanical Ventilation Rate	L/s-m²	0.3

10	HVAC System Type	-	Split-type Air Conditioner

The simulation model incorporated actual classroom operational characteristics, including occupancy schedules, ventilation rates, infiltration, internal heat gains, and HVAC operational control strategies. The classroom operational schedule was defined from 09:00 to 16:00 WIB during working days to represent active academic activities, while setback cooling conditions of 28.5°C were applied during unoccupied periods to reduce unnecessary cooling operation. In addition, holiday and non-holiday operational conditions were integrated into the annual simulation model to represent realistic building utilization patterns.

To improve the representativeness of the thermal model, several environmental and operational assumptions were incorporated into the EnergyPlus configuration. The analyzed classrooms utilized LED lighting systems with an installed lighting power of 130 W. In terms of office equipment configuration, Room J20.301 contained two operational laptops and one Smart TV unit, whereas Room J20.302 contained only two operational laptops. The additional electronic equipment in Room J20.301 contributed to higher sensible internal heat gains, which subsequently increased cooling demand and HVAC operational intensity compared with Room J20.302. The detailed lightning heat gain parameters employed in the simulation are presented in Table 5.

Table 5. Lightning Heat Gain Parameters

No	Parameter	Unit	Value
1	Lighting Type	-	LED
2	Lighting Power	W	130
3	Radiant Fraction	-	0.37
4	Visible Fraction	-	0.18
5	Luminaire Type	-	Reccesed

To assess the representativeness of the climatic input data used in the EnergyPlus simulations, the outdoor dry-bulb temperature obtained from the EPW weather file was compared with meteorological observations recorded on 30 May 2026. The observed temperature data were collected from a publicly available weather monitoring application that provides real-time outdoor weather information for Medan City. As presented in Figure 3, the simulated and observed temperatures exhibited good agreement, with only minor deviations in the daily minimum and maximum temperatures. The comparison yielded a relative error of 2.26%, indicating that the weather data used in the simulation adequately represented the actual outdoor climatic conditions during the observation period.

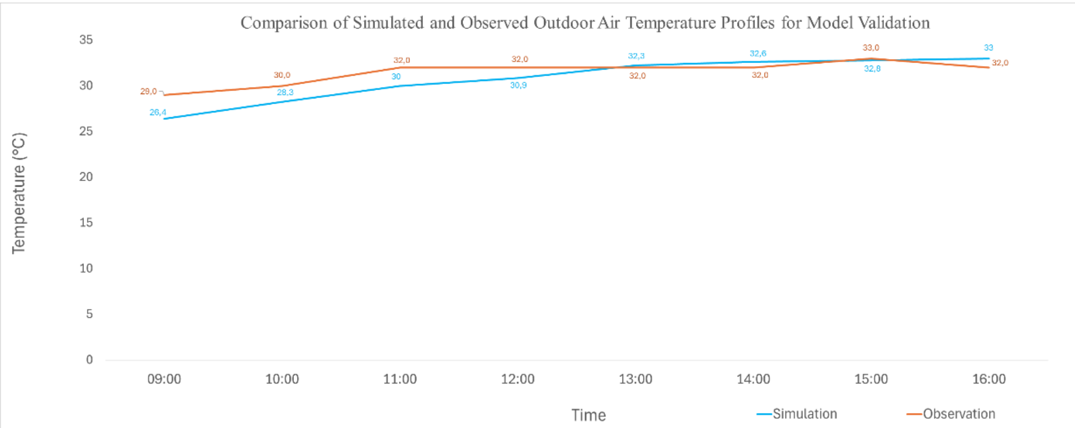

Figure 3. Comparison of Simulated and Observed Outdoor Air Temperature Profiles for Model Validation

Thermal comfort evaluation was conducted using the Predicted Mean Vote (PMV) model based on ASHRAE Standard 55. The PMV calculations considered several environmental and personal parameters, including air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation. The detailed PMV input assumptions utilized in this study are summarized in Table 6.

Table 6. Thermal Comfort Assumptions for PMV Calculation

No	Parameter	Unit	Value
1	Metabolic Rate	met	1.0
2	Metabolic Activity	-	Seated reading and writing

3	Clothing Insulation	clo	0.5
4	Air Velocity	m/s	0.15
5	Thermal Comfort Standard	-	ASHRAE Standard 55
6	Comfort Acceptance Range	PMV	-0.5 ≤ PMV ≤ +0.5
7	Occupancy density	People/m^2	31
8	Power Density Occupancy	W/m^2	0.043

2.3. Heat Balance Equations

The calculation of building energy performance in EnergyPlus is fundamentally based on the heat balance method. This approach evaluates heat transfer interactions through conduction, convection, and radiation while simultaneously accounting for internal thermal loads and HVAC system contributions within each thermal zone. The heat balance method is widely utilized in dynamic building energy simulations because it allows a comprehensive representation of transient thermal behavior under varying environmental and operational conditions:

$$Cz\frac{dTz}{dt} = \sum Q_{int} + \sum Q_{conv} + \sum Q_{inf} + \sum Q_{vent} + \sum Q_{sys} \quad (1)$$

Description:

C_z = heat capacity of the air within the thermal zone (J/K)
T_z = zone air temperature ($°C$)
$\sum Q_{int}$ = total internal heat gains generated by occupants, lighting systems, and electrical equipment (W)
$\sum Q_{conv}$ = total convective heat transfer within the thermal zone (W)
$\sum Q_{inf}$ = total heat gain caused by outdoor air infiltration (W)
$\sum Q_{vent}$ = total heat gain associated with air exchange between adjacent zones (W)
$\sum Q_{sys}$ = total thermal contribution of the HVAC system (W)

Within tropical climatic conditions, the cooling load experienced by educational buildings is strongly influenced by solar radiation intensity, outdoor air temperature, occupancy density, and internal heat gains from electronic equipment and lighting systems. Therefore, the heat balance method provides a robust analytical framework for evaluating the dynamic interaction between environmental conditions and HVAC operational performance. In EnergyPlus, these thermal interactions are solved iteratively throughout the simulation period, enabling accurate prediction of cooling demand and indoor thermal conditions under different operational scenarios.

2.4. Performance Evaluation

The performance of the HVAC system under each investigated temperature setpoint scenario was evaluated using several key performance indicators, including annual cooling energy consumption, electricity cost, and thermal comfort performance. The annual cooling energy consumption was obtained directly from the EnergyPlus simulation outputs for each analyzed classroom and temperature setpoint variation. The simulation provided the total annual cooling load required to maintain indoor thermal conditions throughout the operational period. Subsequently, the cooling load values were converted into electrical energy consumption using the Coefficient of Performance (COP) of the installed split-type air-conditioning system. The relationship between cooling energy demand and electrical energy consumption can be expressed as follows:

$$E = \frac{Q_{cooling}}{COP} \quad (2)$$

Description:

E = electrical energy consumption (kWh)
$Q_{cooling}$ = total cooling energy obtained from the simulation results (kWh)
COP = Coefficient of Performance of the Daikin split-type air-conditioning system

The COP value utilized in this study was based on the actual specification of the installed Daikin split-type air-conditioning unit. The incorporation of actual HVAC performance specifications enhances the reliability of the simulation outputs and ensures that the estimated energy consumption values closely represent real operational conditions within the analyzed building environment. To evaluate the economic implications of indoor temperature setpoint variations, the calculated electrical energy consumption values were further converted into annual electricity costs using the prevailing non-subsidized electricity tariff issued by PT PLN (Persero), amounting to IDR 1,699/kWh. The electricity cost analysis was conducted to estimate the operational expenditure associated with each temperature setpoint scenario and to quantify the potential economic benefits resulting from higher indoor temperature settings.

From a building management and operational economics perspective, electricity expenditure associated with HVAC systems represents a major component of annual facility operating costs in educational buildings located in tropical climates. In addition to energy performance, indoor thermal comfort conditions were evaluated using the Predicted Mean Vote (PMV) index in accordance with ASHRAE thermal comfort standards. The PMV index is extensively used to predict occupants' thermal sensation based on environmental and physiological variables. In this study, the acceptable thermal comfort range was defined as $-0.5 \leq PMV \leq +0.5$ Conditions within this range were categorized as thermally comfortable according to ASHRAE standards. The PMV values obtained from the simulations were analyzed based on the average thermal conditions during classroom operational hours [12]. Furthermore, thermal comfort performance was also assessed through the calculation of annual comfort compliance hours and discomfort hours for each temperature setpoint scenario.

2.5. Research Design

To facilitate the systematic implementation of this study, a structured research methodology framework was developed in the form of a research flowchart:

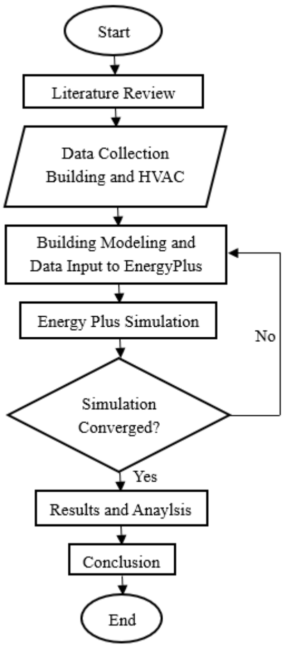

Figure 4. Flowchart

The research process commenced with preliminary data collection, including building geometry, HVAC specifications, occupancy characteristics, operational schedules, and climatic data for Medan City. Following the model development stage, simulation scenarios were established based on variations in indoor temperature setpoints ranging from 20°C to 25°C. The simulation outputs included annual cooling energy consumption, electricity cost estimation, PMV values, comfort compliance hours, and discomfort hours. The simulation results were subsequently analyzed to evaluate the influence of indoor temperature setpoint variations on HVAC energy efficiency and indoor thermal comfort performance.

3. Result and Discussion

3.1. Energy Consumption Analysis

The simulation results were obtained from EnergyPlus analyses conducted to evaluate the energy performance of split-type HVAC systems under various indoor temperature setpoint scenarios. Figures 5–7 illustrate the annual cumulative and weekly cooling energy consumption profiles for Rooms J20.301 and J20.302.

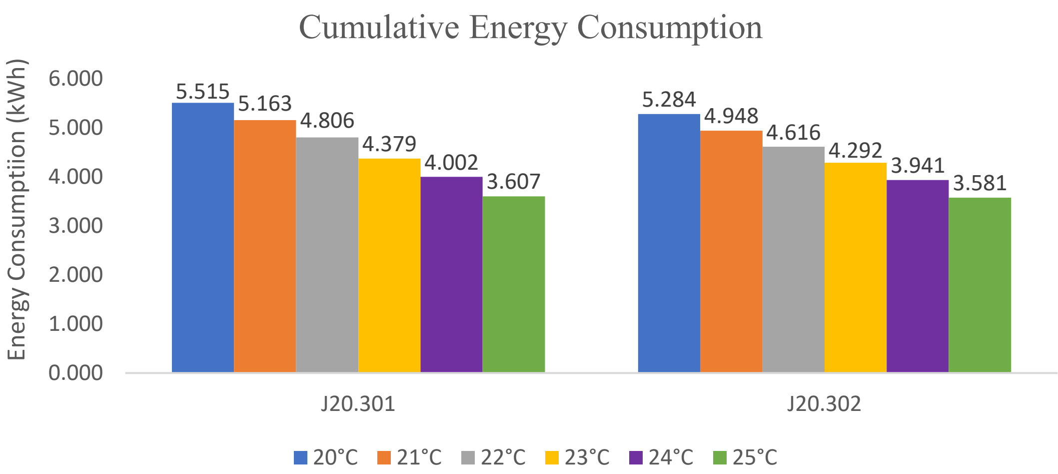

Figure 5. Comparison of Cumulative Energy Consumption Over One Year

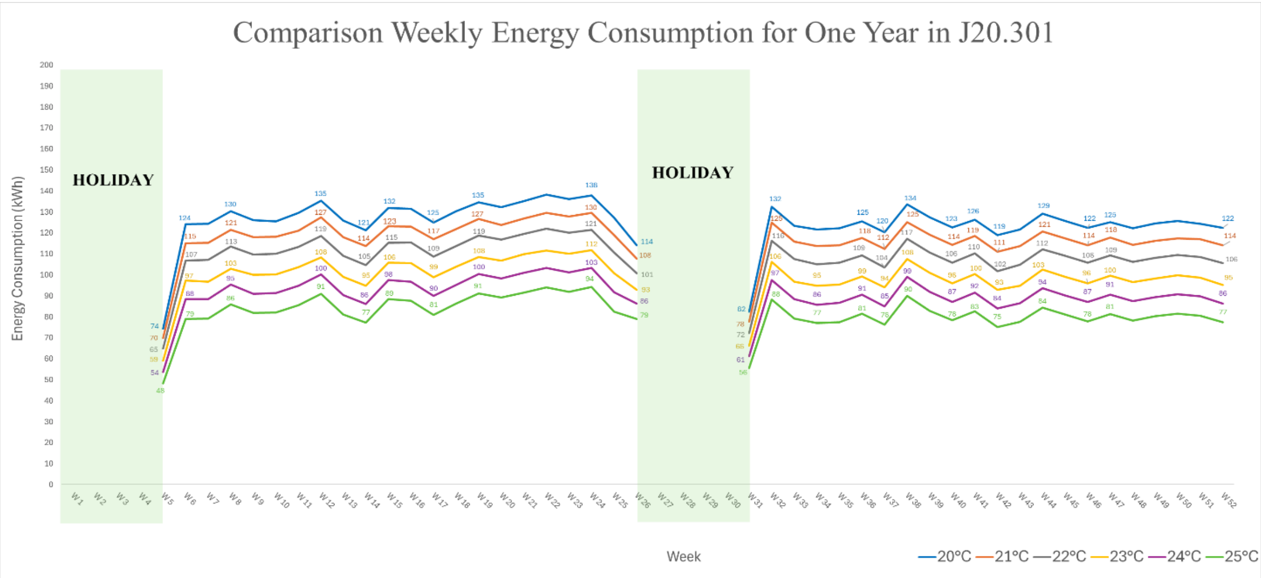

Figure 6. Comparison of Room Energy Consumption Over One Year in J20.301

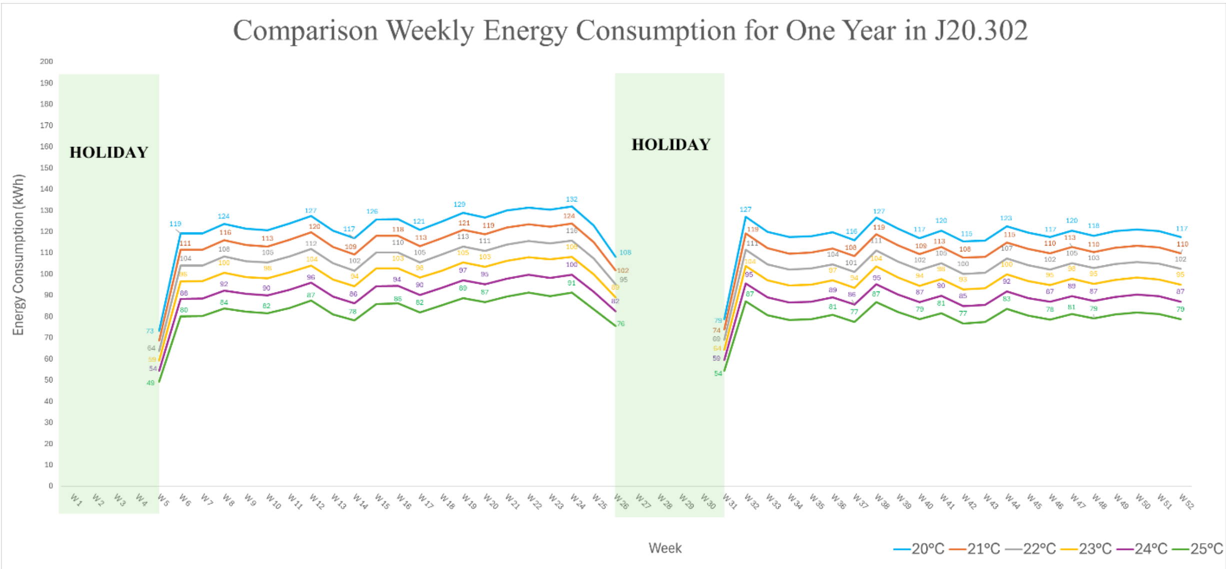

Figure 7. Comparison of Room Energy Consumption Over One Year in J20.302

The simulation results indicate that cooling electricity consumption was primarily governed by indoor-outdoor temperature differentials, occupancy-driven internal heat gains, and outdoor climatic conditions. Increasing the indoor temperature setpoint from 20°C to 25°C consistently reduced annual cooling electricity consumption by decreasing sensible cooling loads and compressor operating duration. This behavior reflects the strong dependence of split-type air-conditioning systems on the temperature gradient between indoor and outdoor environments [13]. A significant increase in cooling energy consumption was observed during the initial weeks following holiday periods, particularly during Weeks 6 and 32. During holidays, classroom occupancy remained minimal, resulting in limited operation of lighting systems, electronic equipment, and HVAC units. In addition, heat accumulation within the building envelope during prolonged inactive periods increased indoor thermal storage, requiring additional cooling energy when classroom activities resumed.

Throughout the simulation period, Room J20.301 consistently exhibited higher cooling energy consumption than Room J20.302. This difference was primarily attributed to the additional internal heat gain generated by the Smart TV unit, which increased sensible cooling loads within the conditioned space. Furthermore, solar heat gain transmitted through the glazing system contributed to greater thermal storage and cooling demand, particularly during daytime operation under tropical climatic conditions [14]. The simulation results further demonstrate that occupancy schedules and internal heat gains significantly affected cooling electricity demand because the HVAC system dynamically responded to variations in transient thermal loads within the conditioned zones.

Eriodic reductions in cooling electricity consumption were observed during Weeks 14, 37, and 42 despite continued classroom operation. These reductions coincided with more favorable outdoor climatic conditions, including lower ambient temperatures, increased rainfall intensity, and reduced solar radiation levels. Under tropical conditions, such climatic variations decrease heat transfer through the building envelope and reduce sensible cooling loads. The results indicate that outdoor weather conditions may exert a stronger influence on cooling demand than occupancy-related factors during certain periods of the year [15]. Furthermore, the reduction in energy consumption did not always follow a linear trend due to compressor cycling behavior and transient thermal load variations within the conditioned spaces [16]. Cooling energy reduction remained non-linear due to compressor cycling and transient thermal loads. At lower temperature setpoints, the compressor operated for longer continuous periods due to the larger indoor-outdoor temperature gradient.

During the operational transition after Week 4, cooling energy consumption increased considerably across all temperature setpoint scenarios. This increase reflected the growing cooling demand caused by higher occupancy levels, lighting operation, electronic equipment use, and longer HVAC operational durations. Throughout all investigated temperature scenarios, Room J20.301 consistently exhibited higher energy consumption than Room J20.302 because of the additional internal heat gain generated by the Smart TV unit in addition to two operational laptops. These additional electronic loads increased the room sensible heat gain, forcing the HVAC system to operate more intensively to maintain the designated indoor temperature conditions [17]. Peak cooling energy consumption observed during several specific weeks indicates that the HVAC systems were required to operate more intensively to sustain the designated indoor thermal conditions. In tropical buildings, elevated outdoor temperatures directly increase heat transfer through the building envelope and substantially intensify indoor cooling loads [18].

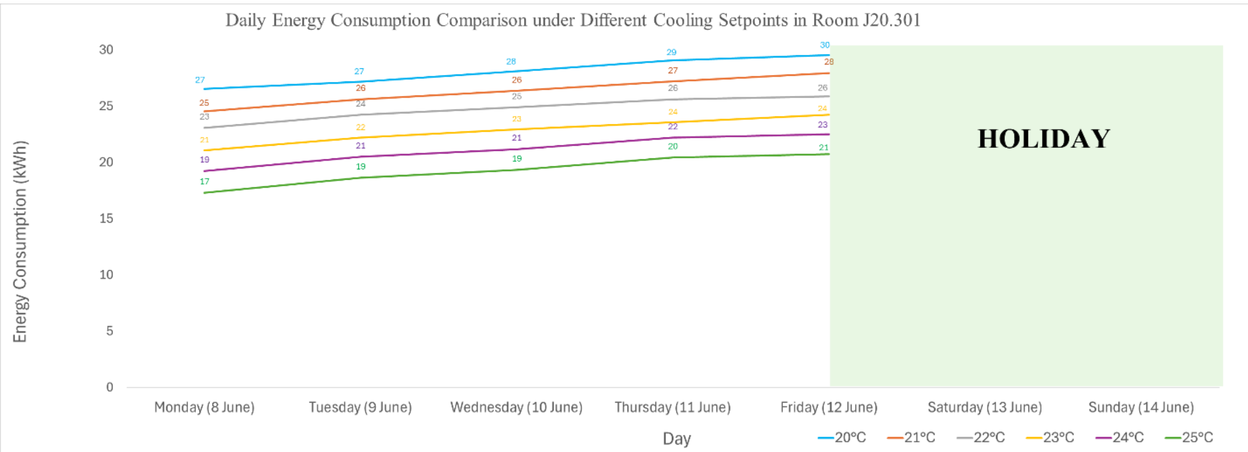

Figure 8. Comparison of Daily cooling energy consumption during Week 24 in J20.301

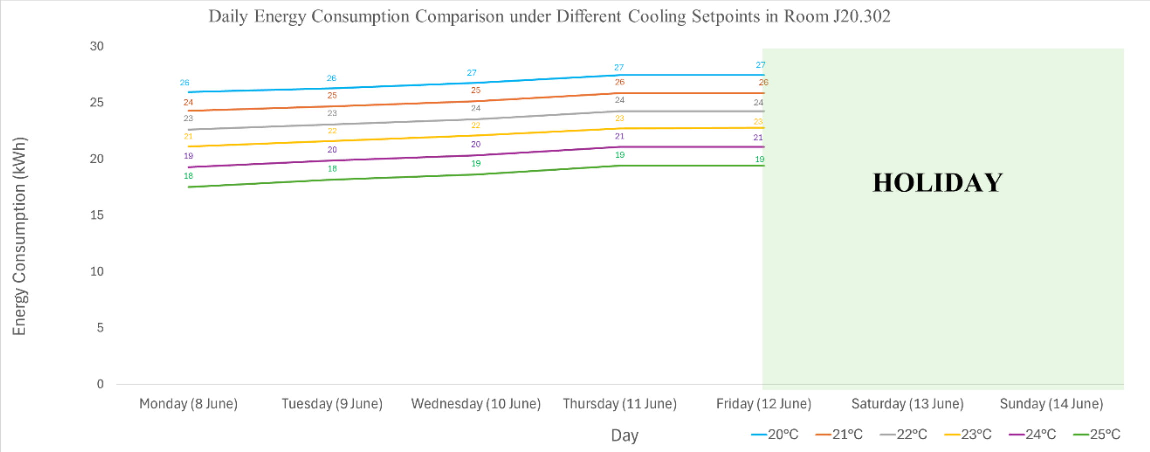

Figure 9. Comparison of Daily cooling energy consumption during Week 24 in J20.302

Figure 8 and Figure 9 present the daily cooling energy consumption profiles for Rooms J20.301 and J20.302 during Week 24 (8–14 June), which exhibited the highest cooling energy consumption among all simulated weeks. In both classrooms, cooling energy consumption gradually increased from Monday to Friday and dropped to zero during the holiday period due to the absence of classroom activities. For Room J20.301, daily cooling energy consumption ranged from approximately 17–21 kWh at the 25°C setpoint and 27–30 kWh at the 20°C setpoint. In Room J20.302, the corresponding values ranged from 18–19 kWh day and 26–27 kWh day, respectively.

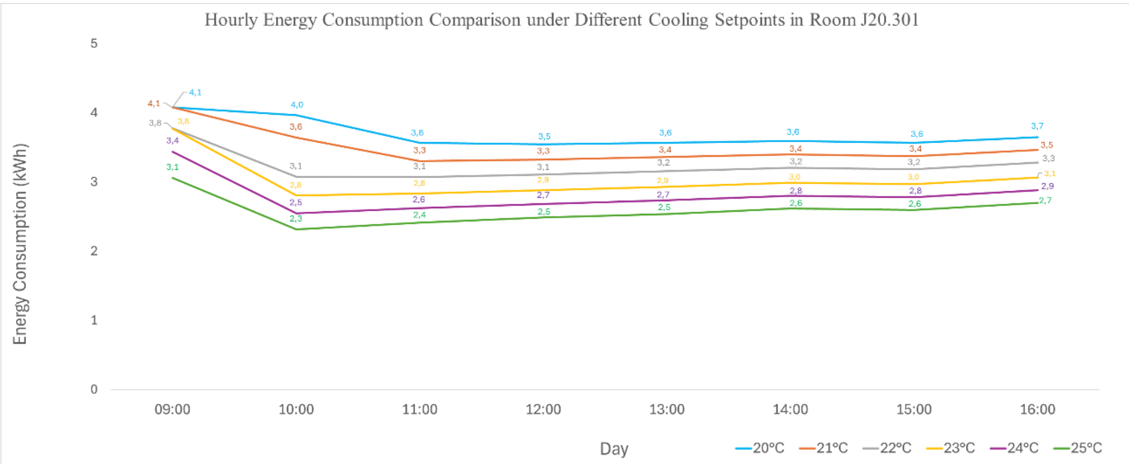

Figure 10. Comparison of Hourly cooling energy consumption at 12 June in J20.301

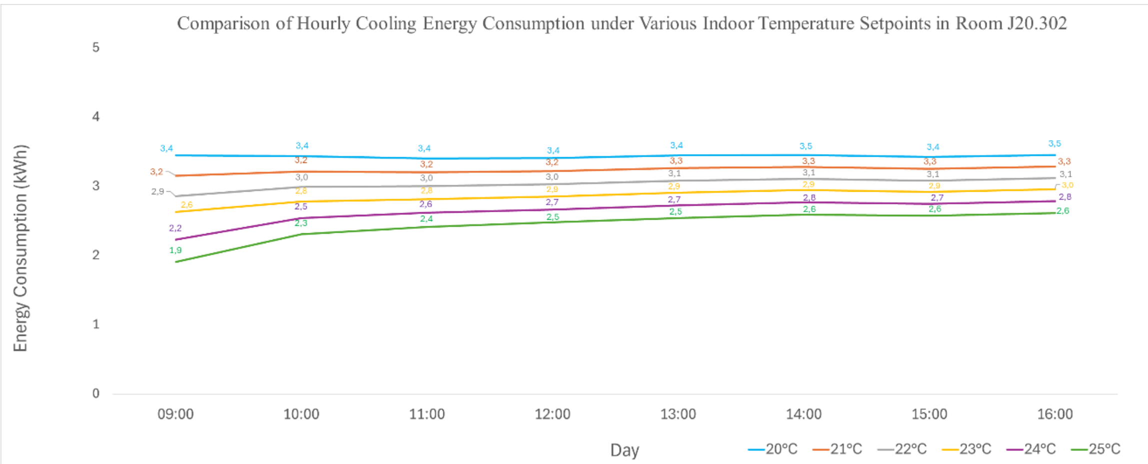

Figure 11. Comparison of Hourly cooling energy consumption at 12 June in J20.302

Figures 10 and 11 present the hourly cooling energy consumption profiles for Rooms J20.301 and J20.302 on 13 June, which recorded the highest daily cooling energy consumption during Week 24. This day was therefore selected to provide a detailed assessment of HVAC performance under peak cooling demand conditions. As shown in Figure 10, Room J20.301 exhibited a pronounced cooling energy peak during the first operational hour across all temperature setpoints. For example, energy consumption at the 25°C setpoint decreased from 3.1 kWh at 09:00 to 2.3 kWh at 10:00 before stabilizing throughout the remaining operating period. This behavior indicates a pull-down cooling load, where the HVAC system removed heat accumulated within the room during non-operational hours. In contrast, Figure 11 shows a more stable hourly energy profile in Room J20.302, suggesting lower thermal storage and internal heat gains.

igures 10 and 11 further demonstrate that Room J20.301 consistently consumed more cooling energy than Room J20.302 across all investigated temperature setpoints. Besides the additional internal heat gains generated by the Smart TV unit, this difference can be attributed to greater thermal storage within the building envelope and solar heat gain transmitted through the glazing system. As the indoor temperature approached the thermostat setpoint, cooling demand gradually decreased and energy consumption stabilized. A slight increase toward 16:00 was also observed, which may be associated with continued solar heat gains and the delayed release of heat stored within the building envelope [19]. These findings indicate that short-term cooling demand is governed not only by internal heat gains but also by the dynamic interaction between thermal mass, solar radiation, and HVAC operational characteristics.

3.2. Thermal Comfort Analysis

Thermal comfort performance was evaluated using the Predicted Mean Vote (PMV) index in accordance with ASHRAE thermal comfort standards. The simulation results for each investigated indoor temperature setpoint are presented in Tables 7 and 8.

Table 7. PMV-Based Thermal Comfort Evaluation for Room J20.301

No	Room Temperature	ASHRAE Comfort Range (PMV)	Average PMV	Comfort Status
1	20°C	-0.5 ≤ PMV ≤ +0.5	-0.17	Comfortable
2	21°C	-0.5 ≤ PMV ≤ +0.5	0.004	Comfortable
3	22°C	-0.5 ≤ PMV ≤ +0.5	0.18	Comfortable
4	23°C	-0.5 ≤ PMV ≤ +0.5	0.35	Comfortable
5	24°C	-0.5 ≤ PMV ≤ +0.5	0.55	Uncomfortable
6	25°C	-0.5 ≤ PMV ≤ +0.5	0.71	Uncomfortable

Table 8. PMV-Based Thermal Comfort Evaluation for Room J20.302

No	Room Temperature	ASHRAE Comfort Range (PMV)	Average PMV	Comfort Status
1	20°C	-0.5 ≤ PMV ≤ +0.5	-0.28	Comfortable
2	21°C	-0.5 ≤ PMV ≤ +0.5	-0.08	Comfortable
3	22°C	-0.5 ≤ PMV ≤ +0.5	0.12	Comfortable
4	23°C	-0.5 ≤ PMV ≤ +0.5	0.32	Comfortable
5	24°C	-0.5 ≤ PMV ≤ +0.5	0.52	Uncomfortable
6	25°C	-0.5 ≤ PMV ≤ +0.5	0.73	Uncomfortable

The results indicate that increasing indoor temperature setpoints consistently increased PMV values in both analyzed classrooms. Higher setpoint temperatures increased sensible heat accumulation and reduced latent cooling performance. Under tropical humidity conditions, elevated indoor air temperature significantly intensified occupants' warm thermal sensation despite relatively small increases in setpoint temperature. In Room J20.301, the average PMV increased from -0.17 at 20°C to 0.71 at 25°C. Similarly, in Room J20.302, the PMV increased from -0.28 to 0.73 within the same temperature range.

These results demonstrate that indoor thermal sensation gradually shifted from neutral conditions toward warmer thermal sensations as indoor temperatures increased. Within the temperature range of 20°C to 23°C, both classrooms remained within the ASHRAE thermal comfort limits. Under these conditions, occupants were expected to experience thermally acceptable indoor environments. However, at the 24°C setpoint, PMV values slightly exceeded the ASHRAE comfort threshold, reaching 0.55 in Room J20.301 and 0.52 in Room J20.302. These conditions indicate a slightly warm thermal sensation but had not yet reached severe thermal discomfort levels. Therefore, in this study, the 24°C setpoint was categorized as "near comfortable" because it still maintained a relatively acceptable comfort tolerance for educational buildings operating under tropical climatic conditions. At the 25°C setpoint, PMV values increased substantially to 0.71 in Room J20.301 and 0.73 in Room J20.302. These conditions indicate that indoor thermal sensation shifted toward the warm category and exceeded the ASHRAE thermal comfort limits. Such conditions imply that occupants may experience considerable thermal discomfort during certain operational periods, particularly under peak occupancy conditions when internal heat gains increased significantly [20].

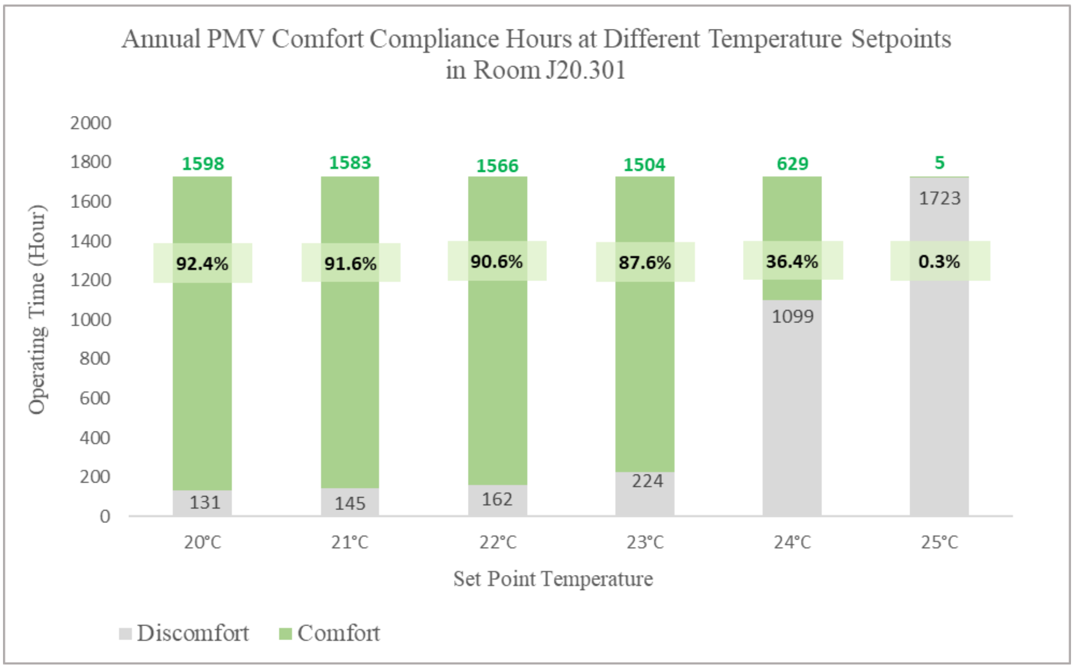

Figure 12. Comparison of Annual Comfort and Discomfort Operating Time in Room J20.301

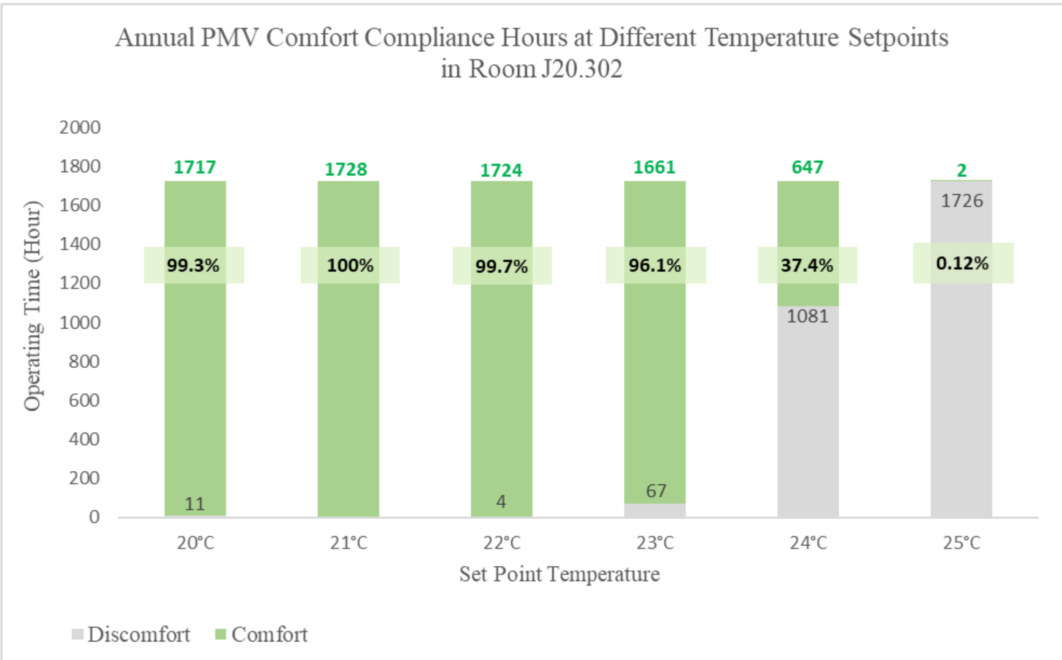

Figure 13. Comparison of Annual Comfort and Discomfort Operating Time in Room J20.302

Figures 12 and 13 further demonstrate substantial variations in annual comfort compliance hours and discomfort hours across different temperature setpoints. In Room J20.301, the 20°C setpoint produced approximately 1,598 annual comfort hours, equivalent to 92.4% of the total operational period. Although thermal comfort performance remained very high under this condition, several operational hours experienced PMV values below -0.5; indicating excessively cold indoor conditions. This phenomenon occurred because the cooling system operated excessively under relatively low cooling loads, causing temporary indoor overcooling conditions. When the indoor setpoint temperature increased to 21°C, thermal comfort performance remained relatively stable with a comfort compliance rate of approximately 91.6%. At 22°C and 23°C, the comfort percentage gradually decreased to 90.6% and 87.6%, respectively. These findings indicate that higher temperature setpoints gradually reduced the capability of the HVAC system to consistently maintain neutral thermal conditions throughout operational hours.

The most substantial decline in thermal comfort performance occurred when the setpoint increased from 23°C to 24°C. The sharp reduction in comfort compliance observed during the transition from 23°C to 24°C indicates the existence of a critical thermal threshold under tropical classroom conditions. Once the indoor setpoint exceeded 23°C, the combined effects of occupant metabolic heat, electronic equipment loads, solar heat gain, and indoor humidity accumulation caused PMV values to rapidly exceed the ASHRAE comfort boundary. Under this condition, annual comfort hours sharply declined from 1.504 hours to only 629 hours, representing approximately 36.4% of the annual operational period. This dramatic reduction indicates that the thermal comfort threshold began to be exceeded when the split-type HVAC system operated at 24°C. Under these conditions, elevated indoor temperatures caused PMV values to shift toward warmer thermal sensations, resulting in a substantial increase in discomfort hours. Under hot-humid climatic conditions, higher indoor temperatures reduced the latent heat removal effectiveness of the split-type air-conditioning system, resulting in greater indoor moisture accumulation and warmer perceived thermal sensation [21]. Simultaneously, sensible heat generated by occupants, lighting systems, and electronic equipment accumulated more rapidly within the conditioned space, intensifying occupants' warm thermal perception despite only a 1°C increase in setpoint temperature.

A similar trend was also observed in Room J20.302, although thermal comfort performance remained slightly better than that of Room J20.301. Between 20°C and 23°C, the comfort compliance rate remained exceptionally high, ranging from 96.1% to nearly 100%. At the 21°C setpoint, Room J20.302 maintained thermally comfortable conditions for almost the entire annual operational period. Similar to Room J20.301, a limited number of operational hours at 20°C produced PMV values below -0.5, indicating slightly overcooled conditions; however, the occurrence remained relatively insignificant compared with the total operational hours. The most substantial reduction in thermal comfort performance in Room J20.302 also occurred during the transition from 23°C to 24°C. Under this condition, annual comfort hours declined sharply from 1,661 hours to approximately 647 hours, representing only 37.4% of the annual operational period. This finding suggests that 24°C represents the critical threshold at which discomfort hours increase significantly in both analyzed classrooms. At 25°C, annual comfort hours declined to only approximately 2 hours or 0.12% of the annual operational period, indicating that nearly all operational conditions exceeded the ASHRAE thermal comfort range.

The increase in discomfort hours at 24°C and 25°C was further intensified by elevated internal heat gains during peak operational periods. During active classroom activities with maximum occupancy levels, metabolic heat generated by occupants, electronic equipment operation, and lighting systems significantly increased both sensible and latent cooling loads within the conditioned spaces [17]. In addition, the high humidity levels characteristic of tropical climates caused the split-type air-conditioning systems to require longer periods to remove indoor heat and moisture at higher temperature setpoints. As a result, indoor temperatures became more susceptible to thermal drift during high-occupancy periods. Nevertheless, occupants living in tropical regions such as Indonesia generally exhibit higher adaptive tolerance toward warmer indoor temperatures. Such adaptive thermal behavior is influenced by daily climatic exposure, clothing patterns, and habitual air-conditioning usage. Several previous studies have reported that indoor temperatures ranging from 24°C to 25°C may still be considered acceptable for tropical building occupants despite slightly exceeding theoretical ASHRAE comfort limits [22].

3.3. Energy Consumption Price Analysis

To evaluate the economic implications of indoor temperature setpoint variations, the annual cooling energy consumption obtained from the EnergyPlus simulations was converted into electricity costs using the prevailing non-subsidized electricity tariff issued by PT PLN (Persero), amounting to IDR 1,699/kWh. The estimated annual operational costs for each investigated temperature setpoint scenario are summarized in Tables 9 and 10.

Table 9. Total Operating Cost of the Air Conditioning System in Room J20.301 based on Setpoint Temperature

No	Setpoint Temperature	Operating Cost (IDR/Year)	Cost Savings from 20°C (IDR/Year)
1	20°C	9,207,522	0
2	21°C	8,620,606	586,916
3	22°C	8,024,687	1,182,835
4	23°C	7,307,867	1,899,655
5	24°C	6,679,740	2,527,782
6	25°C	6,020,149	3,187,373

Table 10. Total Operating Cost of the Air Conditioning System in Room J20.302 based on Setpoint Temperature

No	Setpoint Temperature	Operating Cost (IDR/Year)	Cost Savings from 20°C (IDR/Year)
1	20°C	8,821,797	0
2	21°C	8,260,834	560,963
3	22°C	7,706,550	1,115,247
4	23°C	7,164,947	1,656,850
5	24°C	6,578,922	2,242,875
6	25°C	5,978,117	2,843,680

The results clearly demonstrate that increasing the indoor temperature setpoint consistently reduced annual HVAC operating costs in both analyzed classrooms. In Room J20.301, the annual electricity expenditure decreased from approximately IDR 9,207,522 at the 20°C setpoint to approximately IDR 6,020,149 at the 25°C setpoint. A comparable trend was also observed in Room J20.302, where annual operational costs declined significantly as indoor setpoint temperatures increased.

From an operational and economic perspective, the reduction in electricity expenditure is directly associated with the decrease in cooling energy demand at higher temperature setpoints. This reduction occurred because higher indoor setpoint temperatures lowered the sensible cooling load and reduced compressor operating duration throughout the annual operational period. As the indoor-outdoor temperature differential became smaller, the split-type air-conditioning system required less cooling capacity to maintain indoor thermal conditions, thereby decreasing electricity consumption. When the indoor temperature setpoint increases, the HVAC system experiences a lower sensible cooling load, thereby reducing compressor operating duration and overall electricity consumption [23]. Consequently, the lifecycle operational burden of the split-type air-conditioning system becomes substantially lower at higher indoor temperature settings.

The findings further indicate that the 25°C setpoint achieved the lowest annual operating cost among all investigated scenarios, making it the most energy-efficient option purely from a financial standpoint. However, despite the substantial operational cost savings, this condition also generated the highest PMV values and the greatest number of discomfort hours. Therefore, selecting HVAC operating setpoints solely based on energy cost reduction may compromise occupant thermal satisfaction and indoor environmental quality.

From a techno-economic perspective, the 23°C setpoint provides a more balanced operational strategy because it simultaneously achieves considerable reductions in annual electricity expenditure while maintaining acceptable thermal comfort performance within ASHRAE standards during most operational periods. This balance is particularly important for educational buildings, where occupant productivity, concentration, and learning performance remain highly dependent on stable indoor thermal conditions. Although higher setpoint temperatures improved energy efficiency and reduced electricity expenditure, excessive increases in indoor temperature significantly degraded thermal comfort performance. This finding highlights the non-linear trade-off between cooling energy reduction and occupant thermal satisfaction under hot-humid tropical conditions.

4. Conclusion

This study evaluated the influence of indoor temperature setpoint variations on cooling energy consumption, electricity cost, and thermal comfort performance of split-type air-conditioning systems in two tropical university classrooms using EnergyPlus simulations. The simulation results demonstrated that increasing the indoor temperature setpoint consistently reduced cooling energy demand and annual electricity expenditure in both analyzed classrooms. Within the investigated temperature range of 20°C to 23°C, cooling energy consumption decreased by approximately 20.6% in Room J20.301 and 18.8% in Room J20.302. However, increasing the setpoint temperature also reduced thermal comfort performance. At 25°C, PMV values increased to 0.71 and 0.73, exceeding the ASHRAE comfort limit and reducing annual comfort compliance to below 1% in both classrooms. Among all investigated scenarios, the 23°C setpoint provided the best balance between energy efficiency and thermal comfort. At this condition, annual electricity consumption reached 4,379 kWh and 4,292 kWh for Rooms J20.301 and J20.302, respectively, while PMV values remained within the ASHRAE comfort range at 0.35 and 0.32. In addition, annual comfort compliance reached 87.6% and 96.1%, indicating that the 23°C setpoint can serve as an effective HVAC operational strategy for tropical educational buildings. Future studies should investigate the performance of inverter-based split air-conditioning systems using measured operational data to further evaluate the potential for energy savings and thermal comfort improvement under tropical classroom conditions. Such investigations would provide a more comprehensive assessment of HVAC optimization strategies in educational buildings.

Acknowledgement

The authors would like to express their sincere appreciation to Universitas Sumatera Utara, particularly the Department of Mechanical Engineering, for the institutional support, research facilities, and academic environment that significantly contributed to the successful completion of this study. The authors also gratefully acknowledge all parties who provided technical assistance, operational data, and valuable support throughout the research and simulation processes.

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