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Capacity-Limited Cooling Explains Simultaneous Energy Waste and Thermal Discomfort in Two University Buildings in the Southern Philippines

Fejaycris O. Pillodar[1], Dioniela Mae C. Ellos[1], Jiza Gay P. Jarabe[1], John Russel A. Dalogdog[1], Monaliza Joy Z. Magsayo[1,2], Charlene Mae Z. Gaab[1], Manuel Anthony P. Jondonero[1,3], Melgie A. Alas[4], Rovick Pelos P. Tarife[5], Noel R. Estoperez[5], Mark June L. Aporador[4], Napoleon A. Enteria[6], Kim Emissary C. Magarin[7], Ryan Lloyd R. Carpentero[7], Hernando P. Bacosa[1]*, and Peter D. Suson[1,7]

[1]Department of Environmental Science, School of Interdisciplinary Studies, Mindanao State University-Iligan Institute of Technology, Andres Bonifacio Avenue, Tibanga, Iligan City, Lanao del Norte 9200, Philippines
[2]Environmental Science Department, College of Agriculture and Environmental Studies, Northwestern Mindanao State College of Science and Technology, Labuyo, Tangub City, Misamis Occidental 7214, Philippines
[3]Natural Sciences Department, College of Arts and Sciences, Bukidnon State University, Fortich Street, Malaybalay City, Bukidnon 8700, Philippines
[4]Office of Monitoring and Evaluation, Office of the Vice Chancellor for Strategic Initiatives, Mindanao State University-Iligan Institute of Technology, Andres Bonifacio Avenue, Tibanga, Iligan City, Lanao del Norte 9200, Philippines
[5]Department of Electrical Engineering, College of Engineering, Mindanao State University-Iligan Institute of Technology, Andres Bonifacio Avenue, Tibanga, Iligan City, Lanao del Norte 9200, Philippines
[6]Department of Mechanical and Engineering Science, College of Engineering, Mindanao State University-Iligan Institute of Technology, Andres Bonifacio Avenue, Tibanga, Iligan City, Lanao del Norte 9200, Philippines
[7]MSU-IIT Centre for Resiliency, Office of the Vice Chancellor for Strategic Initiatives, Mindanao State University-Iligan Institute of Technology, Andres Bonifacio Avenue, Tibanga, Iligan City, Lanao del Norte 9200, Philippines

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E-mail addresses:
fejaycris.pillodar@g.msuiit.edu.ph (Fejaycris O. Pillodar)
dionielamae.ellos@g.msuiit.edu.ph (Dionela Mae C. Ellos)
jizagay.jarabe@g.msuiit.edu.ph (Jiza Gay P. Jarabe)
johnrussel.dalogdog@g.msuiit.edu.ph (John Russel A. Dalogdog)
monalizajoy.zaragoza@g.msuiit.edu.ph (Monaliza Joy Z. Magsayo)
charleenmae.gaab@g.msuiit.edu.ph (Charlene Mae Z. Gaab)
manuelanthony.jondonero@g.msuiit.edu.ph (Manuel Anthony P. Jondonero)
melgie.alas@g.msuiit.edu.ph (Melgie A. Alas)
rovick.tarife@g.msuiit.edu.ph (Rovick Pelos P. Tarife)
noel.estoperez@g.msuiit.edu.ph (Noel R. Estoperez)
markjune.aporador@g.msuiit.edu.ph (Mark June L. Aporador)
napoleon.enteria@g.msuiit.edu.ph (Napoleon A. Enteria)
kimemissary.magarin@g.msuiit.edu.ph (Kim Emissary C. Magarin)
ryanlloyd.carpentero@g.msuiit.edu.ph (Ryan Lloyd R. Carpentero)
hernando.bacosa@g.msuiit.edu.ph (Hernando P. Bacosa)
peter.suson@g.msuiit.edu.ph (Peter D. Suson)
* Corresponding author

ABSTRACT

Institutional buildings in the humid tropics are commonly assumed to waste energy because occupants set thermostats to low setpoints. This study tested that assumption in the two largest academic buildings at the Mindanao State University-Iligan Institute of Technology (MSU-IIT), combining 2,491 equipment records, 642 temperature and humidity observations, illuminance in 212 rooms, and a survey of 175 occupants. Room-level records were analysed using Welch t-tests, Mann-Whitney U tests, Hedges' g, chi-square tests, and ordinary least squares regression at a significance level of

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0.05. Combined annual use was 1,151 MWh, costing PHP 13.81 million and emitting 639.5 t CO_2, with air conditioning taking 47.2% and 56.3% of demand. Set-points averaged 20.11 °C and fell below the 24 °C national guideline in 70.9% of observations, yet were attained in only 2.0%, and delivered temperature was almost insensitive to set-point (slope 0.097, 95% CI 0.053 to 0.140). Air conditioning held rooms only 1.75 °C below free-running rooms, indicating capacity-limited rather than control-limited operation, and self-reported set-points corroborated the measured values to within 0.5 °C. Separately, 87.3% of rooms fell below 300 lx, despite an average lighting power density of only 2.9 W m^{-2}, a provision deficit. These findings invert the conventional retrofit hierarchy, because thermostat policy cannot save energy while units remain capacity-limited, so cooling capacity and the building envelope must be restored first. Sequenced this way, five measures deliver 21.6% of baseline consumption at a 3.3-year payback, twice the reduction required of state universities. Testing set-point attainment before prescribing behavioural measures is a transferable diagnostic for tropical institutional estates.

Keywords: Building energy audit, canopy cover, energy conservation measures, greenhouse gas emissions, illuminance, indoor environmental quality, lighting power density, set-point attainment

INTRODUCTION

Energy underpins socio-economic development, yet its production and consumption carry a large environmental footprint through greenhouse gas (GHG) emissions (Masoso & Grobler, 2010). In 2019, the Philippines emitted 237 million t of CO_2 equivalent, a 3.2% increase over 2018, ranking 38th globally and accounting for 0.49% of global emissions (United Nations Development Programme, 2026). Power generation is the largest domestic source of GHG emissions, accounting for 56.2% of national emissions (Department of Energy Philippines, 2024), and the Philippine Energy Plan 2023-2050 identifies the commercial and institutional sectors as among the largest consumers.

Depletion of the Malampaya gas field increases reliance on imported liquefied natural gas (Department of Energy Philippines, 2022), exposing the country to global price volatility (International Energy Agency, 2020) and to geopolitical disruption of alternative domestic supply (Abinales & Amoroso, 2017), so demand-side efficiency is not merely an environmental preference but a measure of energy resilience. Republic Act 11285, the Energy Efficiency and Conservation Act of 2019, places state universities and colleges under the Government Energy Management Program (Republic of the Philippines, 2019), which targets a reduction of at least 10% in electricity and fuel consumption in government facilities and requires each agency to maintain an energy management program, define conservation measures, target savings, and designate an energy conservation officer.

University energy audits in the tropics constitute a substantial body of literature, but most of it stops at accounting. They report end-use disaggregation, benchmark energy use

intensity (EUI), and conclude with generic recommendations that are rarely tested against the building's measured performance (Chan et al., 2020; Ferrer-Balas et al., 2010; Leal Filho et al., 2019; Lopez et al., 2017). Three consequences follow. Energy audits and indoor environmental quality (IEQ) surveys are usually conducted separately, so it cannot be asked whether the energy consumed is for purchasing comfort. Where high cooling energy is observed, it is attributed either to inefficient equipment or to low thermostat setpoints, without a measurement that can distinguish between them. Recommended measures are seldom quantified, so institutions receive priorities that are not ranked by savings, cost, or abatement.

The distinction between control-limited and capacity-limited operation has not been tested in a Philippine institutional setting. In a control-limited system, the plant has sufficient capacity, cycles under thermostat control, and the set-point governs both delivered temperature and energy consumed, so the set-point policy is the correct intervention. In a capacity-limited system, the plant runs continuously without reaching its set-point because capacity, refrigerant charge, or envelope and infiltration losses constrain it; thus, the set-point governs neither comfort nor consumption, and behavioural policy will fail. The regimes are separable because the elasticity of delivered temperature with respect to set-point approaches unity in the first case and zero in the second, a test that requires recording set-point and room temperature together, which routine audits rarely do.

This study integrates an equipment-level energy audit with concurrent thermal, hygric and luminous measurements in the same rooms of two large academic buildings and uses the combined dataset to diagnose mechanisms before prescribing measures. The objectives were to quantify energy use, cost and GHG emissions by end use per unit floor area, to decompose the difference in cooling energy into installed capacity, technology mix and operating schedule, to test whether the cooling systems are control-limited or capacity-limited by estimating set-point attainment and the set-point elasticity of delivered temperature, to assess thermal, hygric and luminous compliance against ASHRAE and national criteria using psychrometric analysis that separates real moisture removal from temperature-driven changes in relative humidity (RH), to determine whether under-lighting reflects inefficient luminaires or insufficient installed lighting power, to examine how site geometry and afternoon solar exposure relate to the diurnal structure of the indoor difference, and to appraise a prioritized package of conservation measures by annual saving, avoided emissions, capital cost and simple payback. The study introduces a diagnostic test that distinguishes capacity from control limitation using data that an ordinary audit can collect, shows that the intervention hierarchy conventionally recommended for tropical institutional buildings is inverted in these buildings, and delivers a quantified retrofit package for a state university subject to a statutory savings target.

MATERIALS AND METHODS

Study Buildings and Audit Period

The audit covered the two largest academic buildings of Mindanao State University-Iligan Institute of Technology (MSU-IIT) in Iligan City, Philippines, at 8.24° N, 124.24° E, in a tropical rainforest climate under the Köppen classification (Af). The College of Engineering (COE) has a gross floor area of 4,987.27 m² across five stories and presents its principal glazed façade to the west, toward Iligan Bay, with no intervening obstruction. The College of Science and Mathematics (CSM) has 5,507.31 m² across the main and annex blocks, three storeys high, and lies immediately east of COE, bounded on its western side by tall, mature trees. Both operate on a five-day academic week. Data were collected from September to November 2024 during the first semester under normal occupancy, as shown in Figure 1.

The buildings were selected because institutional electricity is metered at the feeder level rather than at the building level, and prior estimates ranked these two colleges highest in connected load and gross floor area. Establishing building-level baselines was therefore itself an objective, since no energy audit had previously been conducted at MSU-IIT.

Equipment Inventory and Energy Estimation

Every electrical device in every accessible room was enumerated, recording the device type, brand, quantity, nameplate power, functional status, and daily operating hours, the

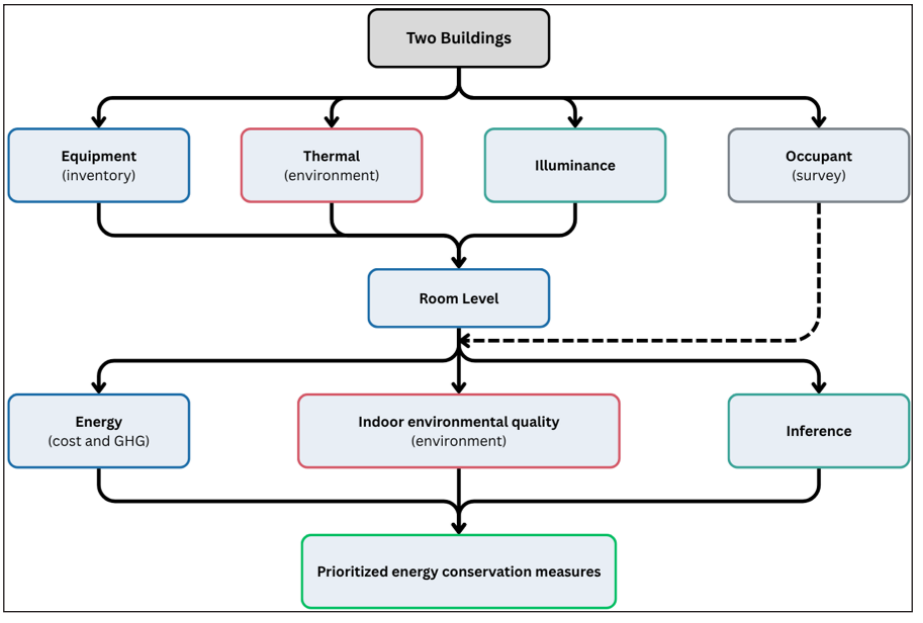

Figure 1. Design of the study, showing the five data streams, their sampling design and sample sizes, the room-level harmonisation step and the analysis branches leading to the prioritised conservation measures

latter of which was established through interviews with the room custodian and direct observation. The inventory yielded 2,491 records, 1,309 at COE and 1,182 at CSM, in five end-use categories (Table 1).

The daily energy consumption for each record was estimated using Equation 1, where P is the nameplate power in kW, N is the quantity, and h is the daily operating hours. Annual consumption was calculated using Equation 2, where D is the effective operating days, taken as 168 to match the academic calendar, excluding weekends, semestral breaks, and holidays, or 365 for continuously operating equipment. Energy cost was computed using Equation 3 at the prevailing Iligan Light and Power, Inc. tariff of PHP 12 per kWh, and emissions using Equation 4 with the Mindanao grid-weighted factor of 0.5555 kg CO_2 per kWh.

$$E_{\text{daily}} = P \times N \times h \quad [1]$$

$$E_{\text{annual}} = E_{\text{daily}} \times D \quad [2]$$

$$C = E \times 12 \quad [3]$$

$$G = E \times 0.5555 \quad [4]$$

All quantities were normalised by gross floor area to give energy use intensity in kWh m^{-2} y^{-1}, cost intensity in PHP m^{-2} y^{-1}, and emission intensity in kg CO_2 m^{-2} y^{-1}. This approach estimates consumption from rated power and reported schedules rather than measurement. Nameplate power is a rated maximum, so variable-load devices draw less on average, and the method tends to overestimate; reported hours are also subject to recall bias. Part-load efficiency, compressor cycling, and simultaneity are not represented, and standby power is not captured, which biases in the opposite direction. Non-functional equipment, 178 records at COE and 92 at CSM, was excluded from consumption but retained in the asset inventory. The estimates are therefore a consistent relative baseline rather than a substitute for metered consumption, and because both buildings were audited by the same team using the same protocol in the same period, systematic bias should be largely common to both.

Thermal Environment Measurement

Air temperature and RH were measured using a handheld thermo-hygrometer with an accuracy of ±1 °C and ±3% RH, respectively. Five stations were used in each room: the four corners and the centre, at approximately 1.1 m above floor level, corresponding to the seated occupant head height specified in ASHRAE Standard 55 (ASHRAE, 2020). The

instrument was allowed to stabilise at each station, and the five readings were averaged to give the room value.

Each room was surveyed at approximately 08:00, 12:00 and 17:00, spanning the occupied period. Outdoor temperature and RH were recorded concurrently immediately outside the envelope, and, for air-conditioned rooms, the thermostat setpoint displayed on the unit was logged. Rooms were measured under normal occupancy and normal air-conditioning operation as found. The campaign yielded 642 room-period observations, 276 at COE and 366 at CSM, across 206 physical rooms, of which 443 were air-conditioned and 199 free-running.

Two derived quantities were used. The set-point gap is the difference between the measured room temperature and the thermostat set-point, so a system meeting its set-point yields a gap of zero or less. The humidity ratio W, in g kg^{-1} of dry air, was computed from the dry-bulb temperature and RH at standard atmospheric pressure using the Magnus formulation and is reported because RH alone conflates moisture content with temperature. Compliance thresholds follow ASHRAE Standard 55 (ASHRAE, 2020) and the Guidelines on Energy Conserving Design of Buildings (Department of Energy Philippines, 2021), namely a comfort band of 23 to 27 °C, an RH ceiling of 60% and a recommended set-point of 24 °C.

Illuminance and Lighting Power Measurement

Task-plane illuminance was measured with a digital lux meter with an accuracy of ±2%. Readings were taken on a grid ranging from 8 to 40 points per room, depending on room dimensions, at a desk height of approximately 0.75 m, following the grid-averaging procedure in the IESNA lighting handbook (Rea, 2000). Measurements were taken during daytime occupied hours with the installed luminaires switched on and blinds or curtains in their normal in-use position, so the recorded values represent the combined artificial and daylight conditions experienced by occupants. Room dimensions were measured to derive floor area, and total connected luminaire wattage was recorded, giving the installed lighting power density (LPD) in W m^{-2} and installed system efficacy in lx m^2 W^{-1}. Rooms were classified against the 300-lx minimum for general classroom and office tasks as under-lit below 300 lx, acceptable from 300 to 500 lx and over-lit above 500 lx. Complete records were obtained for 212 rooms, 93 at COE and 119 at CSM.

Site Geometry and Canopy Cover Estimation

Site geometry was characterised from a georeferenced satellite image of the campus, which recorded the orientation of each building and the disposition of surrounding obstructions, and an indicative estimate of canopy cover in plan was derived from the same image. Vegetation pixels were classified using the excess green index, defined as

twice the normalised green channel minus the normalised red and blue channels, with a threshold of 0.02 and the additional requirement that the green channel exceed both the blue channel and 95% of the red channel. Canopy fraction was computed within circular buffers of 30, 50, 75, and 100 m around each building centroid. Because the centroids are 59 m apart, only the 30 m buffers are effectively non-overlapping, and this radius is the primary comparison. Sensitivity was tested by displacing each centroid by up to 20 pixels, about 7 m. The estimate is a plan-view screening measure that does not resolve canopy height or the azimuth of obstruction.

Occupant Survey

A structured questionnaire was administered during the audit period to provide an independent check on the operating conditions recorded at the units, covering thermal adjustment method, the conditions under which air conditioning is operated, the temperature at which units are set, daily operating duration, and agreement with candidate conservation policies scored on five-point scales. It returned 175 valid responses, 114 from COE and 61 from CSM, all from undergraduate students, since the staff and faculty branch returned none. Survey findings are therefore treated as the perspective of student occupants and used only for corroboration, not as primary evidence. Responses were not room-linked or entered into the room-level models, and self-reported set points outside the plausible range of 15 to 30 °C were excluded, removing 5 responses. Participation was voluntary and anonymous, and respondents were informed of the purpose of the study beforehand.

Data Harmonization

The three technical datasets were harmonised on a common room key derived from room numbers or labels, with combined spaces retained as merged units. They covered 207 rooms in the audit, 212 in the illuminance survey, and 206 in the thermal survey, and 138 rooms carried complete records across all three, forming the matched dataset used for correlation and regression. Building-level aggregates use the full datasets, and raw source files were not modified.

Statistical Analysis

Analyses were performed in Python 3.12 using NumPy 2.4, SciPy 1.17, and pandas 3.0, with a significance level of 0.05 throughout, and figures were produced with Matplotlib 3.10. Continuous variables are summarised as mean ± standard deviation with 95% confidence intervals (CI), median, and interquartile range. Normality was assessed with the Shapiro-Wilk test and homogeneity of variance with the median-centred Levene test. Because most distributions departed from normality at $p < 0.05$, even with large sample sizes, two-group

comparisons are reported using the Welch unequal-variance t-test as the primary test and the Mann-Whitney U test as a distribution-free confirmation; the two agreed in direction and significance for every comparison. Effect sizes are reported as Hedges' g with 95% CI and mean differences with 95% CI, so that both practical and statistical significance can be assessed. Comparisons across the three times of day used one-way analysis of variance with the Kruskal-Wallis test as a check, and categorical compliance outcomes were compared with the Pearson chi-square test.

Associations among room-level variables were assessed using Pearson correlation. Two ordinary least squares (OLS) models were estimated on the matched dataset of air-conditioned rooms, for which $n = 92$. The first regressed air-conditioning energy intensity on installed input power density, set-point, daily operating hours, window-type capacity share, and building; the second regressed the set-point gap on the same predictors, excluding operating hours. The set-point elasticity of delivered temperature was estimated by simple linear regression of measured room temperature on set-point, and internal consistency of the survey constructs was assessed with Cronbach's alpha.

Appraisal of Energy Conservation Measures

Five energy conservation measures (ECMs) were appraised, covering the replacement of window-type units with inverter split systems, set-point control at 24 °C, LED relighting to 300 lx, plug-load and standby control, and envelope sealing with solar-control glazing. Annual savings were estimated by applying measure-specific savings fractions to the relevant audited end-use baseline, and the fractions, their justification and the unit bases of the capital costs are stated in the note to Table 5. Set-point governance was credited only after the replacement measure because set-point changes cannot save energy while units remain capacity-limited. Simple payback is the capital cost divided by the annual cost savings, assuming PHP 12 per kWh, and excludes discounting, escalation, and maintenance. The package is benchmarked against the target under Republic Act 11285, with at least a 10% reduction in consumption.

RESULT AND DISCUSSIONS

Inventory of Electrical Equipment

The inventory assigned 2,491 records to five categories (Table 1). Cooling and ventilation equipment dominated in both buildings. COE carried more operations equipment, consistent with its computer laboratories, while CSM carried more electrical appliances. Laboratory equipment was numerous in both, but it contributed modestly to energy use because it operates intermittently. A total of 178 records at COE and 92 at CSM were non-functional yet remained installed, an asset-management finding.

Table 1
Equipment categories, representative equipment and inventory counts

Category	Examples	COE records	CSM records	COE units	CSM units
HVAC	Air conditioner, ceiling fan, wall fan, stand fan, exhaust fan, humidifier	133	178	156	207
Electrical appliances	Refrigerator, rice cooker, microwave, oven	70	84	70	93
Laboratory equipment	Microscope, oscilloscope, digital analytical balance, spectrophotometer	132	155	295	252
Lighting	Fluorescent, bulb, pin light	199	178	1,490	1,405
Operations	Monitor, keyboard, mouse, CPU, speaker, projectors	775	587	1,241	940
Total		1,309	1,182		

Energy Consumption, Cost and Greenhouse Gas Emissions

Combined annual electricity consumption was 1,151 MWh, costing PHP 13.81 million and emitting 639.5 t of CO_2 (Table 2, Figure 2). Building EUI values were closely matched at 107.2 kWh m^{-2} y^{-1} for COE and 112.0 kWh m^{-2} y^{-1} for CSM, placing both at the lower end of the range reported for tropical university buildings, which is unsurprising given single-split cooling, the absence of central plant and daytime-only occupancy.

The end-use composition differed materially. Cooling and ventilation accounted for 47.2% of COE and 56.3% of CSM electricity, and were dominant in both, consistent with the literature on cooling-dominated institutional buildings (Pérez-Lombard et al., 2008; Ryu & Yoo, 2025; Santamouris, 2016). The second-largest end use diverged sharply, with operations equipment taking 29.3% at COE against 16.2% at CSM, reflecting COE's computer laboratories, whereas CSM's appliance load at 11.8% exceeded COE's at 7.8%.

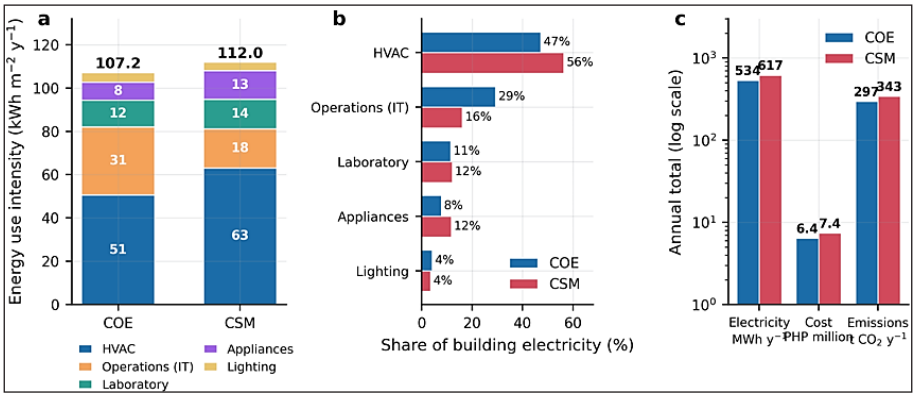

Figure 2. Energy, cost and emissions. (a) End-use energy intensity by building. (b) End-use composition as a share of building electricity. (c) Building-level annual totals for electricity, cost and emissions on a logarithmic scale

Table 2
Annual energy, cost and emission intensity by end use

Type of equipment	COE kWh m^{-2}	CSM kWh m^{-2}	COE PHP m^{-2}	CSM PHP m^{-2}	COE kg CO_2 m^{-2}	CSM kg CO_2 m^{-2}
HVAC	50.56	63.09	606.7	757.1	28.08	35.05
Electrical appliances	8.36	13.25	100.3	159.0	4.64	7.36
Laboratory equipment	12.30	13.57	147.6	162.9	6.83	7.54
Lighting	8.36	13.25	100.3	159.0	4.64	7.36
Operations	31.45	18.10	377.4	217.2	17.47	10.06
Total	107.16	111.98	1,285.8	1,343.8	59.51	62.21

Lighting was the smallest end use in both at 4.2% and 3.5% because the illuminance deficit cannot be remedied by cutting lighting energy and there is ample headroom to increase it.

Determinants of the Difference in Cooling Energy

CSM used 12.5 kWh m^{-2} y^{-1} more cooling energy than COE. Such differences are often attributed to equipment age, which is not a measurable quantity in an audit of this kind, so the difference was instead decomposed into its physical components (Figure 3), as in multi-dimensional analyses of air-conditioning energy use in university teaching buildings (Li et al., 2020).

The two buildings differ fundamentally in technology. Of the 147 units at CSM, 120 (81.6%) are window-type or portable, whereas of the 104 units at COE, 93 (89.4%) are split systems. This matters thermodynamically because window units house the compressor, condenser, and evaporator in a single casing, so condenser heat rejection is compromised by the small coil face area and by short-circuiting of the discharge air. Their seasonal efficiency is typically well below that of split systems, which is why labelling schemes

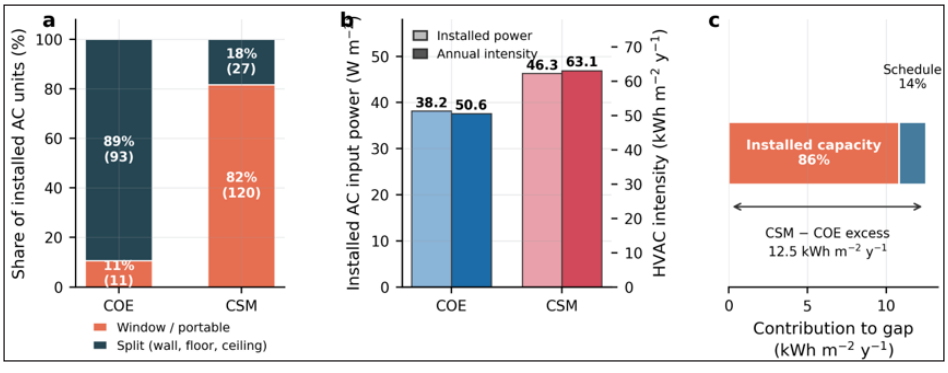

Figure 3. Origin of the difference in cooling energy. (a) Composition of the installed air-conditioning fleet by technology, with unit counts in parentheses. (b) Installed input power density on the left axis against annual cooling energy intensity on the right axis. (c) Logarithmic decomposition of the difference between CSM and COE into installed capacity and operating schedule

such as the Department of Energy's Cooling Seasonal Performance Factor rating distinguish between the classes.

The consequence appears in installed capacity. Air-conditioning input power density was 46.3 W m^{-2} at CSM against 38.2 W m^{-2} at COE, so CSM installs 21% more electrical input to condition a comparable area, while capacity-weighted operating hours were nearly identical at 8.05 and 7.80 h per day. A logarithmic decomposition attributes 86% of the gap to installed capacity and 14% to schedule, and the model in Table 4 confirms the mechanism, since cooling energy intensity is explained almost entirely by installed input power density and operating hours, with no independent building effect once these are controlled ($p = 0.743$). CSM therefore has more and less efficient installed cooling power for the same task, a more actionable diagnosis than equipment age, because it identifies the 120 window units as the intervention target.

Set-Point Attainment and the Capacity Limitation of Cooling

Set points were low, averaging 20.11 ± 3.72 °C, and 70.9% of observations fell below the 24 °C national guideline, the pattern conventionally read as wasteful occupant behaviour (Figure 4). Measured room temperatures in the same rooms averaged 26.79 ± 1.76 °C. The set-point was attained in only 9 of 443 observations, or 2.0%, and the mean gap was 6.68 °C with a 95% CI of 6.33 to 7.03, being 6.02 ± 3.36 °C at COE and 7.17 ± 3.99 °C at CSM (Welch $t = -3.29$, $p = 0.001$, $g = -0.31$).

Regressing delivered temperature on set-point yields a slope of 0.097 with a 95% CI of 0.053 to 0.140 and an R^2 of 0.042, whereas a control-limited system would approach 1.0. A slope near zero means that lowering the thermostat by 10 °C buys roughly 1 °C

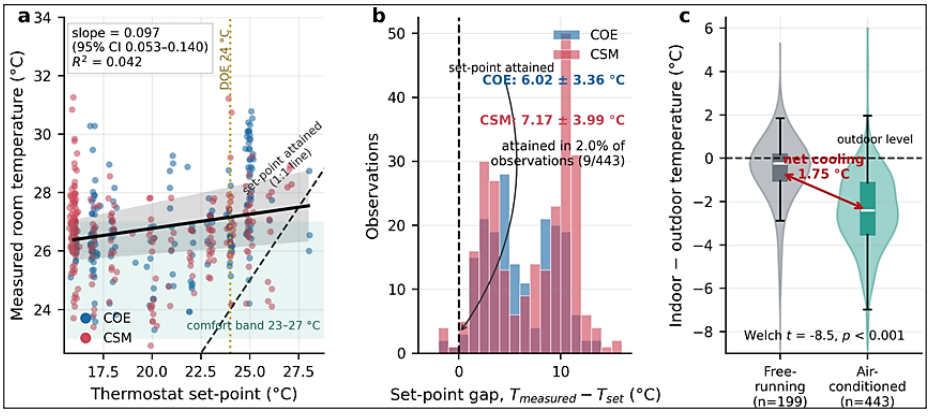

Figure 4. Set-point attainment. (a) Measured room temperature against thermostat set-point for all air-conditioned observations, with the 1:1 attainment line shown dashed, the fitted regression shown solid with its 95% confidence band, the comfort band of 23 to 27 °C and the national guideline of 24 °C. (b) Distribution of the set-point gap by building. (c) Indoor-outdoor temperature difference for free-running and air-conditioned rooms, where the difference between group means represents, the net cooling delivered

of delivered cooling, so the rooms are not over-cooled but barely cooled at all. Installed capacity density did not predict the gap ($r = 0.027$, $p = 0.802$), and in the second model of Table 4, the set-point coefficient on the gap was −1.007 with a 95% CI of −1.075 to −0.939, indistinguishable from −1.0, the signature of a delivered temperature invariant to the set-point. An independent measure confirms the magnitude: air-conditioned rooms sat 2.40 °C below outdoor air, while free-running rooms sat 0.65 °C below, so the net cooling attributable to air conditioning is only 1.75 °C (Welch $t = -8.52$, $p < 0.001$). For roughly half of the electricity these buildings consume, the thermal return is very small.

The occupant survey corroborates this account independently. Respondents reported setting or preferring a mean air-conditioning temperature of 19.65 ± 3.02 °C against the 20.11 ± 3.72 °C recorded at the units, and reported operating durations consistent with the audited schedule, so two measurements sharing no common source of error agree to within 0.5 °C. The low set-points are real and settled, rather than artefacts of logging, while occupant practice is otherwise unremarkable. Several mechanisms are consistent with the shortfall and are not mutually exclusive. Envelope and infiltration losses are likely dominant, because rooms are entered and left continuously between classes, many have jalousie or awning windows and undercut doors, and no room has a vestibule. Degraded capacity is also implicated, since window units predominate at CSM, the refrigerant charge is not on a maintenance schedule, and the condenser coils show visible fouling, while under-sizing relative to internal gains is plausible in the computer laboratories at COE. The data nonetheless exclude one candidate because the set point demonstrably does not govern the outcome. The behavioural corollary is a feedback loop: a room that fails to cool invites the occupant to lower the thermostat further, which cannot improve comfort in a saturated system but does keep the compressor at full load, a pattern consistent with evidence that occupant interaction with air-conditioner controls is shaped by the response of the equipment itself (Winkler et al., 2018; Zhang et al., 2018).

Thermal Environment and Comfort Compliance

Given the preceding result, the two buildings should differ little in delivered thermal conditions, and they do not (Figure 5, Table 3). COE averaged 27.79 ± 2.08 °C and CSM 27.36 ± 1.98 °C, a difference of 0.43 °C with a 95% CI of 0.11 to 0.75 (Welch $t = 2.64$, $p = 0.009$; Mann-Whitney $p = 0.024$). The effect size is small ($g = 0.21$), so the magnitude of the difference alone is not evidence of superior thermal performance at CSM; its structure across the day is the more informative feature.

Compliance is the more meaningful comparison and is poor in both buildings, since 59.1% of COE and 50.3% of CSM observations exceeded 27 °C, with only 40.9% and 48.9% inside the 23 to 27 °C band, a range in which classroom temperature has been linked to measurable differences in student thermal comfort and cognitive performance (Jiang et

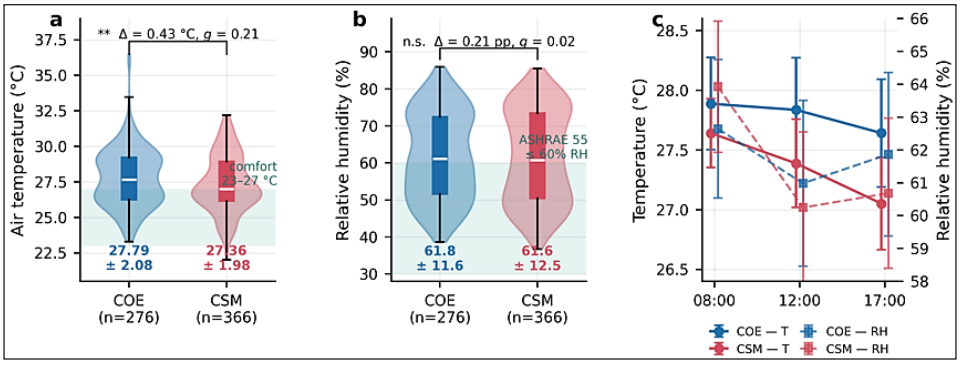

Figure 5. Indoor thermal and hygric environment. (a) Air temperature and (b) relative humidity by building, shown as violin plots with embedded box plots, where shaded bands mark the comfort criteria. (c) Diurnal pattern of temperature shown solid and relative humidity shown dashed, as mean with 95% confidence interval

Table 3
Descriptive statistics and between-group comparisons for indoor environmental variables

Variables	Groups	Group 1 (n, M ± SD)	Group 2 (n, M ± SD)	Difference (95% CI)	t (df)	p (W/ MW)	g (95% CI)
Temperature (°C)	COE, CSM	276, 27.79 ± 2.08	366, 27.36 ± 1.98	0.43 (0.11 to 0.75)	2.64 (578)	0.009 / 0.024	0.21 (0.06 to 0.37)
Relative humidity (%)	COE, CSM	276, 61.83 ± 11.63	366, 61.62 ± 12.47	0.21 (−1.66 to 2.09)	0.22 (612)	0.823 / 0.845	0.02 (−0.14 to 0.17)
Temperature (°C)	AC, free-run	443, 26.79 ± 1.76	199, 29.23 ± 1.52	−2.45 (−2.71 to −2.18)	−17.95 (439)	<0.001 / <0.001	−1.45 (−1.63 to −1.26)
Relative humidity (%)	AC, free-run	443, 56.42 ± 9.35	199, 73.49 ± 8.78	−17.07 (−18.58 to −15.57)	−22.33 (404)	<0.001 / <0.001	−1.86 (−2.05 to −1.66)
Humidity ratio (g kg^{-1})	AC, free-run	443, 12.58 ± 3.03	199, 19.00 ± 3.10	−6.42 (−6.94 to −5.90)	−24.45 (374)	<0.001 / <0.001	−2.10 (−2.31 to −1.90)
Set-point gap (°C)	COE, CSM	188, 6.02 ± 3.36	255, 7.17 ± 3.99	−1.15 (−1.84 to −0.46)	−3.29 (433)	0.001 / 0.001	−0.31 (−0.50 to −0.12)
Illuminance (lx)	COE, CSM	93, 166.5 ± 105.0	119, 158.0 ± 115.1	8.5 (−21.4 to 38.4)	0.56 (205)	0.576 / 0.355	0.08 (−0.19 to 0.35)
RH, laboratories (%)	COE, CSM labs	123, 59.16 ± 11.41	168, 62.62 ± 12.66	−3.47 (−6.26 to −0.68)	−2.45 (277)	0.015 / 0.015	−0.29 (−0.52 to −0.05)
Outdoor temperature (°C)	COE, CSM site	276, 29.36 ± 2.30	366, 29.44 ± 1.25	−0.08 (−0.38 to 0.22)	−0.52 (396)	0.607 / 0.274	−0.04 (−0.20 to 0.11)

al., 2025; Li et al., 2025). Upper storeys were consistently warmer, the third floor of COE averaging 29.18 ± 2.64 °C against 27.28 ± 1.42 °C on the first, and the third floor of the CSM annex 28.35 ± 1.95 °C against 26.73 ± 2.03 °C on the second floor of the main block, a documented consequence of roof solar gain and stack effect in the tropics (Rajapaksha,

2019). Both buildings peaked in the morning and declined slightly throughout the day ($F = 2.59$, $p = 0.076$; Kruskal-Wallis $p = 0.013$), a diurnal pattern in which morning temperature and humidity covary (Zhmakin, 2023), consistent with thermal mass charging overnight and with cooling systems that, once started, run continuously without recovering to set point.

Site Geometry, Shading and the Diurnal Divergence

The two buildings sit 59 m apart in the same dense low-rise urban fabric, and their outdoor air temperatures were indistinguishable at every time of day, differing by 0.09 °C in the morning, −0.15 °C at noon, and −0.18 °C in the afternoon, nonsignificant. Ambient conditions, therefore, cannot account for the indoor difference, and attention turns to solar exposure.

The exposures differ in geometry rather than in the quantity of surrounding vegetation. COE presents its principal glazed façade to the west, where the ground falls away toward Iligan Bay, so the façade receives direct low-angle radiation through the afternoon without obstruction, whereas CSM lies east of COE and is screened in the afternoon both by tall, mature trees along its western boundary and by the mass of COE itself. Plan-view canopy cover does not capture this asymmetry, and estimated cover within the non-overlapping 30 m buffer was, in fact, higher around COE, at 11.8% versus 8.6%, and remained higher at 50, 75, and 100 m (Figure 6). A planar fraction is insensitive to canopy height and to the azimuth of obstruction, and those are precisely the properties that determine afternoon shading, so canopy fraction describes the site rather than testing the hypothesis.

The diurnal structure of the indoor data is consistent with the geometry. Expressed relative to outdoor air, so that ambient variation is removed, COE sat 1.14 °C below outdoor

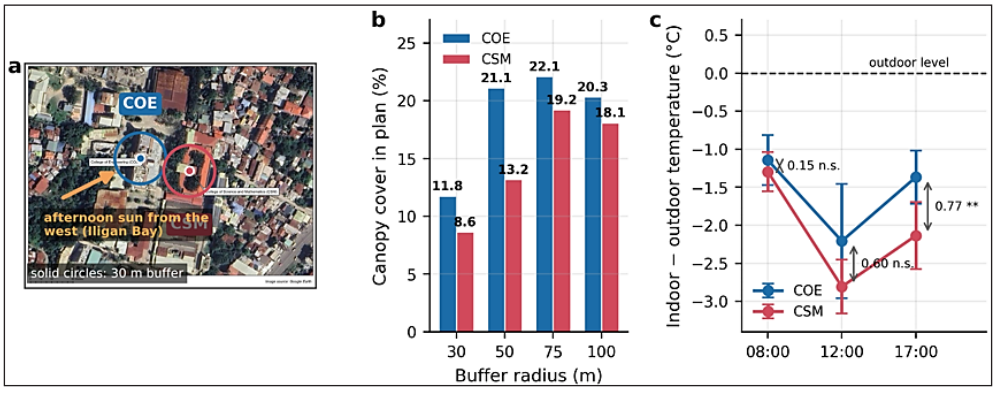

Figure 6. Site geometry, canopy cover and the diurnal divergence. (a) Satellite view of the two buildings with 30 m buffers showing COE's unobstructed western exposure toward Iligan Bay. (b) Estimated canopy cover in plan within buffers of 30 to 100 m, a measure insensitive to canopy height and to the azimuth of obstruction. (c) Indoor minus outdoor temperature by time of day, as mean with 95% confidence interval, with the difference between buildings annotated

in the morning, against 1.30 °C at CSM, a difference of 0.15 °C, widening to 0.60 °C at noon and 0.77 °C in the afternoon ($p = 0.008$). The same monotonic widening appears in air-conditioned rooms, from 0.28 °C in the morning to 0.62 °C at noon ($p = 0.043$) and 0.80 °C in the afternoon ($p = 0.012$). Between morning and afternoon, indoor temperature at CSM fell by 0.59 °C while its outdoor temperature rose by 0.25 °C, whereas at COE, indoor temperature fell by only 0.25 °C against a flat outdoor trend. CSM decouples from ambient conditions as the afternoon progresses, and COE does not; the signature expected of a building shielded from afternoon solar gain, as opposed to one that is not.

This is an inference from indoor thermal behaviour and site geometry rather than a measurement of the mechanism, since façade irradiance, external surface temperatures, and canopy geometry were not measured, and the divergence is absent in the small subset of free-running rooms, which are predominantly corridors of uncertain orientation. The data support the conclusion that the thermal difference is associated with afternoon solar exposure rather than with the amount of vegetation per se, even though green space can moderate humid heat where canopy cover is extensive (Yang et al., 2024), so the appropriate intervention at COE is solar control on the western façade, which is included in the appraisal as part of ECM-5.

Relative Humidity and Psychrometric Performance

Between buildings, RH was effectively identical at 61.83 ± 11.63% for COE and 61.62 ± 12.47% for CSM, a difference of 0.21 percentage points with a 95% CI of −1.66 to 2.09 ($p = 0.823$, $g = 0.02$), so no difference in relative humidity between the buildings can be claimed.

The substantive hygric finding concerns what air conditioning does, and psychrometric analysis is required to see it (Figure 7). Air-conditioned rooms averaged 56.42 ± 9.35% RH against 73.49 ± 8.78% in free-running rooms ($g = −1.86$). Because RH falls when air is merely warmed, this alone would not establish dehumidification, but converting to humidity ratio removes the ambiguity. Air-conditioned rooms held 12.58 ± 3.03 g kg^{-1} against 19.00 ± 3.10 g kg^{-1}, a reduction of 6.42 g kg^{-1} with a 95% CI of 5.90 to 6.94 and $g = −2.10$, the largest effect in the study. The coils are performing genuine latent-load removal, indicating that sensible capacity, rather than the refrigeration cycle, is the binding constraint. Only 35.4% of observations fell inside the combined comfort zone of 23 to 27 °C and 30 to 60% RH, and free-running rooms clustered almost entirely outside it at high humidity ratios, consistent with the role of humidity as a governing comfort parameter in warm and humid climates (Amaripadath et al., 2023; Jing et al., 2013), confirming that natural ventilation alone cannot deliver comfort in this climate.

Laboratories carry equipment-protection requirements and merit separate comment. Those at CSM averaged 62.62 ± 12.66% RH, compared with 59.16 ± 11.41% at COE (p =

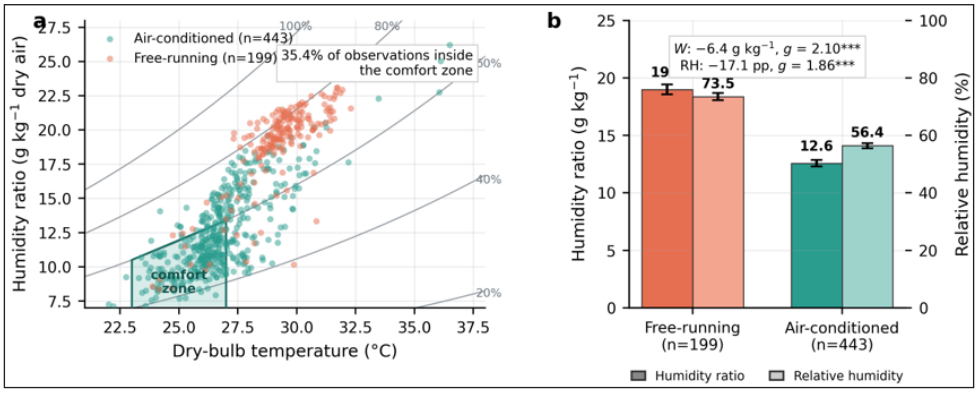

Figure 7. Psychrometric performance. (a) All observations plotted on temperature and humidity-ratio axes with constant-relative-humidity curves and the comfort zone of 23 to 27 °C and 30 to 60% relative humidity. (b) Humidity ratio and relative humidity for free-running and air-conditioned rooms, as mean with 95% confidence interval, where the humidity-ratio difference demonstrates real moisture removal rather than a temperature artefact

0.015, g = −0.29). Within CSM, they were more humid than non-laboratories ($p = 0.025$), whereas within COE, they were indistinguishable ($p = 0.974$). A plausible explanation, consistent with the inventory, is the different character of the wet work, since the chemistry and biology laboratories at CSM operate water baths, autoclaves, distillation apparatus, and sinks that release latent load directly into the space, whereas those at COE are predominantly dry. This is an inference from the inventory rather than a measured moisture balance. It matters because ASHRAE guidance recommends an RH band of 35 to 60% for laboratories, and the CSM mean is above it, so dedicated dehumidification, rather than lower setpoints, is the appropriate response (Lim et al., 2018; Shehadi, 2018).

Illuminance and Lighting Power Density

Illuminance was inadequate throughout both buildings, and the two do not differ (Figure 8). Mean task-plane illuminance was 166.5 ± 105.0 lx at COE, and 158.0 ± 115.1 lx at CSM ($p = 0.576$, $g = 0.08$), and under the 300-lx criterion, 86.0% of COE rooms and 88.2% of CSM rooms were under-lit, with indistinguishable compliance distributions (chi-square = 1.25, $p = 0.535$). Under-lighting is therefore a condition of the estate rather than of one college.

The diagnostic question is whether luminaires are inefficient or if too few are installed. Installed LPD averaged 3.29 ± 3.49 W m^{-2} at COE and 2.58 ± 2.45 W m^{-2} at CSM ($p = 0.099$), against a typical code allowance for educational occupancies of roughly 8 to 12 W m^{-2}. A total of 95.6% of rooms fall below that allowance, and 86.1% are simultaneously below the allowance and below 300 lx, while LPD correlates positively with delivered illuminance ($r = 0.52$, $p < 0.001$), as it must if the deficit is one of provision. Installed system efficacy was similar in both buildings, with medians of 52.2 and 47.8 lx m² W^{-1},

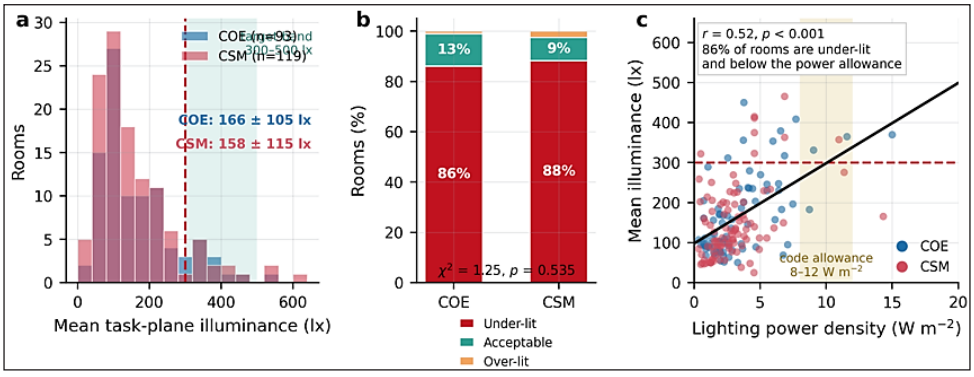

Figure 8. Illuminance and lighting power. (a) Distribution of mean task-plane illuminance by building against the 300-lx minimum and the target band of 300 to 500 lx. (b) Compliance classification by building. (c) Mean illuminance against installed lighting power density, where the shaded band marks a typical code allowance for educational occupancies

so the luminaires are not unusually poor; these buildings are under-lit because too little lighting power is installed.

This inverts the usual retrofit recommendation. A like-for-like LED replacement would halve lighting energy but leave 87% of rooms non-compliant, improving an energy metric while entrenching a health, safety and academic performance problem, since adequate illuminance supports visual comfort and task accuracy (Boyce, 2014; Oliveira et al., 2024; Rea, 2000). Relighting to 300 lx with LED luminaires instead requires a median installed density of only 1.9 W m^{-2} at COE and 2.1 W m^{-2} at CSM, and 99.4% of rooms would remain within a 10.5 W m^{-2} allowance. The measure is close to energy-neutral overall and net-negative at COE, saving 8.0 MWh y^{-1} despite roughly tripling delivered light, so adequate lighting and lower lighting energy are here the same intervention.

Room-Level Determinants of Energy Intensity

Across the 138 matched rooms, annual energy correlated with equipment count (r = 0.61) and equipment diversity (r = 0.69), and negatively but weakly with temperature (r = −0.26), RH (r = −0.25), and illuminance (r = −0.12), consistent with a causal direction running from conditioning to environment. Table 4 reports the two OLS models on air-conditioned rooms. The energy model explains 98.6% of variance in cooling energy intensity, essentially entirely through installed input power density and operating hours, with no residual building effect and no contribution from set-point (p = 0.520), while the gap model explains 91.2% of variance in the set-point gap, driven almost wholly by the set-point itself. Set point, therefore, predicts the shortfall almost perfectly and predicts consumption not at all, so lowering the thermostat changes what is asked for but neither what is delivered nor what is spent.

Table 4
Ordinary least squares models for air-conditioned rooms (n = 92)

Model	Predictor	B	SE	t	p	95% CI
a	Intercept	−66.45	9.997	−6.65	<0.001	−86.33 to −46.58
	Building (CSM)	1.18	3.584	0.33	0.743	−5.95 to 8.30
	Input power density (W m^{-2})	1.333	0.018	75.35	<0.001	1.297 to 1.368
	Set-point (°C)	−0.244	0.378	−0.65	0.520	−0.996 to 0.507
	Daily operating hours	8.979	0.682	13.17	<0.001	7.623 to 10.334
	Window-type capacity share	−3.064	3.571	−0.86	0.393	−10.16 to 4.04
b	Intercept	27.105	0.752	36.03	<0.001	25.61 to 28.60
	Building (CSM)	−0.174	0.324	−0.54	0.593	−0.818 to 0.470
	Input power density (W m^{-2})	−0.0024	0.0016	−1.48	0.144	−0.0056 to 0.0008
	Set point (°C)	−1.007	0.034	−29.37	<0.001	−1.075 to −0.939
	Window-type capacity share	0.045	0.323	0.14	0.889	−0.597 to 0.687

Appraisal of Energy Conservation Measures

Table 5 and Figure 9 appraise five measures, and the sequence matters as much as the content. ECM-1, replacement of window-type units with inverter split systems (Ebrahimi et al., 2023; Olatunde et al., 2024), is the largest single measure at 107.1 MWh y^{-1}, worth PHP 1.28 million and 59.5 t CO_2 y^{-1}, for an indicative PHP 5.90 million and a 4.6-year payback, concentrated at CSM where 120 window units are installed. Within the sensitivity range of 30% to 55% input reduction, payback ranges from 3.7 to 6.7 years. It is a prerequisite because it restores the capacity without which no control measure can act.

ECM-2, set-point governance at 24 °C, is credited at 58.0 MWh y^{-1} with a 0.4-year payback, but only after ECM-1, which is the practical expression of the central finding. Applied to the buildings as they stand, a thermostat policy would deliver no savings, because units that never reach 19 °C will likewise never reach 24 °C and will run continuously in either direction, or it would remove the only lever available to occupants without restoring any comfort. Sequenced after capacity restoration, it becomes one of the cheapest measures available, and it is not an unpopular imposition, since survey respondents endorsed switching air conditioning off during defined periods at 4.31 out of 5 and scheduled use of classrooms and laboratories at 4.34 out of 5. Audits recommending a set-point policy without first testing attainment risk prescribe an intervention that cannot work.

ECM-5, envelope sealing and solar-control glazing, delivers 48.0 MWh y^{-1} at a 4.0-year payback, addressing both the loss mechanism consistent with the observed net cooling of 1.75 °C and the unobstructed western exposure of COE, where vertical greenery

Table 5
Appraisal of energy conservation measures for both buildings combined

Measure	MWh y^{-1}	PHP y^{-1}	t CO_2 y^{-1}	CapEx (PHP)	Payback (y)	% base
ECM-1 Inverter split replacement of window-type units	107.1	1,284,786	59.5	5,895,000	4.6	9.3
ECM-2 Set-point governance at 24 °C, after ECM-1	58.0	695,999	32.2	300,000	0.4	5.0
ECM-5 Envelope sealing and solar control	48.0	575,620	26.6	2,308,808	4.0	4.2
ECM-4 Plug-load and standby governance	25.7	307,833	14.3	160,000	0.5	2.2
ECM-3 LED relighting to 300 lx	9.8	117,102	5.4	1,302,750	11.1	0.8
Package total	248.4	2,981,340	138.0	9,966,558	3.3	21.6

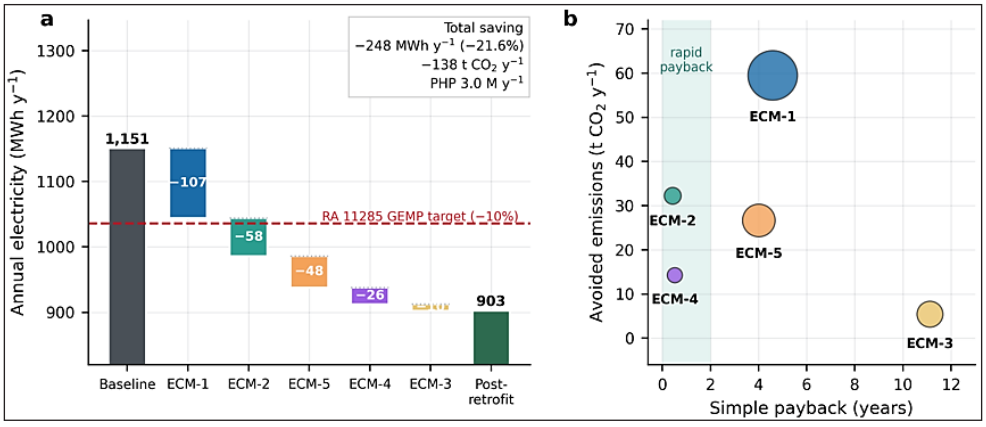

Figure 9. Appraisal of energy conservation measures. (a) Cumulative effect of the five measures on annual consumption, referenced to the 10% reduction target of the Government Energy Management Program under Republic Act 11285. (b) Avoided emissions against simple payback, where the bubble area is proportional to the indicative capital cost

and window gardens offer additional passive options in tropical and subtropical settings (Mohammad Shuhaimi et al., 2022; Ren et al., 2022). ECM-4, plug-load and standby governance, offers 25.7 MWh y^{-1} at a 0.5-year payback and is attractive at COE, where operations equipment is 29.3% of load. ECM-3, LED relighting to 300 lx, yields 9.8 MWh y^{-1} and an 11.1-year payback on energy grounds alone, and is recommended as a compliance measure that happens to be energy-neutral to negative.

Together, the package delivers 248 MWh y^{-1}, equivalent to 21.6% of baseline, worth PHP 2.98 million and 138 t CO_2 y^{-1}, at a blended payback of 3.3 years, more than twice the reduction of at least 10% required of state universities under the Government Energy Management Program of Republic Act 11285.

Limitations of the Study

Six limitations bound the interpretation. Energy is estimated from nameplate power and reported schedules rather than from metered data, so absolute EUI values are scoping estimates, whereas comparisons between end uses and buildings are more robust. The campaign covers three months of the first semester and omits the second semester, the summer term, and the examination periods. The thermal survey uses repeated spot measurements at three times of day rather than continuous logging, so it characterises the occupied-hours envelope but not overnight recovery or cycling. The canopy estimate is a plan-view screening analysis from a single-date image without ground truth, so it describes the site but cannot quantify a shading effect, for which façade-level irradiance and surface temperature measurement is required. The occupant survey, used only as corroboration, drew responses solely from undergraduate students and is not room-linked. The appraisal of conservation measures uses literature-derived savings fractions and indicative capital costs, so measurement and verification should accompany implementation.

CONCLUSION

This audit quantified 1,151 MWh y^{-1} of electricity, PHP 13.81 million in annual cost, and 639.5 t CO_2 y^{-1} across two large academic buildings at MSU-IIT, with cooling accounting for 47.2% of demand at COE and 56.3% at CSM, at energy use intensities of 107.2 and 112.0 kWh m^{-2} y^{-1}. Set points averaged 20.1 °C and fell below the 24 °C guideline in 71% of observations, a pattern routinely read as occupant profligacy. Measurements in the same rooms show the set-point attained in 2.0% of observations, with delivered temperature almost insensitive to it (slope of 0.097), and air-conditioning holding rooms only 1.75 °C below free-running conditions, so these buildings are capacity- and envelope-limited rather than control-limited. An occupant survey corroborates the low set-points to within 0.5 °C, placing the constraint in the plant rather than in behaviour. The difference in cooling energy between buildings is explained by installed capacity, which accounts for 86% of the logarithmic difference and reflects a technology mix at CSM dominated by window-type units. Cooling nonetheless dehumidifies 6.42 g kg^{-1}, isolating sensible capacity and envelope losses as the binding constraint. The thermal difference between the buildings is associated with afternoon solar exposure rather than with the quantity of vegetation, since outdoor temperatures were indistinguishable at every time of day while the indoor difference relative to ambient widened from 0.15 °C in the morning to 0.77 °C in the afternoon, matching a geometry in which the western façade of COE faces Iligan Bay unobstructed while CSM is screened by tall, mature trees and by COE itself. Separately, 87.3% of rooms fall below 300 lx, although the lighting power density averages 2.9 W m^{-2} against an allowance of 8 to 12 W m^{-2}, indicating a provision deficit in under-lighting.

The practical implication is an ordered program. Window-type units should be replaced with correctly sized inverter split systems and refrigerant charge and condenser condition restored, the envelope sealed and solar control applied to the western façade of COE in particular, and only then a 24 °C set-point policy instituted, which becomes among the cheapest measures once units can reach it and which occupants already endorse. Plug loads should be governed, and rooms relit to 300 lx with LED luminaires, raising illuminance roughly threefold while reducing installed lighting power. Together, these deliver 248 MWh y^{-1}, or 21.6% of the baseline, with a 3.3-year blended payback period, more than twice the statutory 10% target under Republic Act 11285.

Set-point and room temperature should be recorded together as a routine audit variable, because their relationship distinguishes interventions that can work from those that cannot at negligible cost, and energy and indoor environmental quality should be assessed in the same rooms, because the central question for a cooling-dominated building is not how much energy it uses but how much comfort that energy buys. Future work should extend the campaign across a full academic year, install sub-metering, log thermal conditions continuously alongside façade irradiance, surface temperature and resolved canopy height, and extend the survey to staff.

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