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Energy and Cost Performance of Tropical Air- and Water-Cooled HVAC Systems: A Conceptual Case for Integrated STEM Education

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Research profile: Quantitative descriptive-comparative operational-data study | Reporting guideline: APA JARS-Quant, adapted to a nonexperimental engineering case | Preregistration/protocol: Not reported

ABSTRACT

Background and Objective: Operational HVAC data can support authentic interdisciplinary STEM tasks, but a technical comparison does not by itself demonstrate student learning. This descriptive case examines reported air- and water-cooled HVAC performance at Manado Town Square, Indonesia, and proposes an instructional application. **Methods:** The case draws on 2025 building records, system specifications, field observations and reported electrical-load measurements. Cooling capacity, power, coefficient of performance (COP) and energy figures were examined descriptively; the engineering evidence was translated into proposed STEM learning objectives, tasks and assessment criteria. No educational intervention occurred. **Results:** Reported nominal/calculated chiller COP values were 3.8 (air-cooled) and 5.2 (water-cooled); calculated system COP values were 3.455 and 4.523, respectively. A separate author-reported scenario implies 28.8% lower monthly electricity consumption, but cannot be independently reconciled with section-level records. Consequently, the associated IDR 5.184 billion annual savings and 2.3–2.9-year simple payback remain conditional illustrations rather than verified comparative outcomes. **Conclusion:** The dataset provides a potentially valuable critical-data-analysis case for integrated STEM education; both comparative engineering estimates and educational effectiveness require further validation.

Keywords: Authentic STEM learning; Energy efficiency; HVAC systems; Sustainability education; Tropical buildings

INTRODUCTION

Energy-intensive buildings provide a concrete sustainability problem with direct relevance to integrated science, technology, engineering, and mathematics (STEM) education. In tropical commercial buildings, Heating, Ventilation, and Air Conditioning (HVAC) systems are major contributors to electricity demand because high temperature, humidity, internal heat gains, and long operating hours increase cooling loads. Their performance therefore affects thermal comfort, operating expenditure, and environmental impact (Lara et al., 2016; REHVA, 2019; Curto, 2019; Zhao et al., 2022). For STEM education, such systems offer an authentic context in which scientific principles can be connected to technological components, engineering design decisions, mathematical modelling, and sustainability considerations rather than being taught as isolated disciplinary content.

Research on HVAC performance has shown that air-cooled and water-cooled systems differ in heat-rejection mechanisms, compressor workload, and energy efficiency. Water-cooled configurations can benefit from lower and more stable condensing temperatures, while architectural design, thermal zoning, and Building Management Systems also influence whole-building performance (Hattingh, 2018; Díaz-Torres et al., 2017; Avantaggiato et al., 2021; Xu et al., 2025). Studies have additionally examined condenser efficiency, chiller replacement, and advanced control strategies (Setiyo et al., 2023; Soewono et

al., 2023; Ramkumar et al., 2025). In parallel, integrated STEM scholarship emphasizes authentic problem solving, engineering design, systems thinking, and cross-disciplinary reasoning (Kelley & Knowles, 2016). Indonesian and sustainability-oriented studies similarly highlight engineering design and real socio-environmental problems as productive STEM contexts (Abdurrahman et al., 2023; Laksmiwati et al., 2023; Martínez-Borreguero et al., 2026), while experiential architectural-engineering education demonstrates the value of real building systems and operational evidence (Jung et al., 2026).

Engineering research reports HVAC efficiency, equipment and control performance, whereas integrated STEM scholarship foregrounds authentic problem framing, interdisciplinary reasoning and justified decisions (Kelley & Knowles, 2016). The gap addressed here is not the absence of real-world STEM examples; rather, it is the limited demonstration of how discrepant operational energy, design-capacity and economic records can be converted into a transparent, teachable evidence-evaluation task. The proposed contribution is a documented case and instructional-design framework in which learners must audit data comparability, calculate conditional estimates, identify uncertainty and defend an engineering decision. This is a conceptual translation of engineering records, not an intervention or validation of improved educational outcomes.

Three guiding questions were addressed: (1) What energy-performance differences are indicated by the available HVAC figures, and what cannot be inferred because the system boundaries differ? (2) Which reported design and operating conditions may explain the contrasts or confound comparison? (3) How can the record be organized into a proposed integrated STEM case with learning objectives, tasks, evidence requirements and assessment criteria? The deliverable for Question 3 is an instructional case framework, not measured student achievement.

METHOD

Research Design and Reporting Standard

A descriptive comparative case-study design was used to examine reported operational and technical records from three sections of one shopping-mall complex. Mantos 1 and Mantos 2 use air-cooled configurations; Mantos 3 uses a water-cooled plant. These are distinct installations of different sizes, not a controlled experiment or independently verified matched comparison. Section-level reported monthly electricity figures, equipment capacities and engineering COP calculations are described separately; a second, apparently normalized energy scenario cannot be reconstructed from the available records. Potential confounders include conditioned floor area, occupancy, operating hours, weather, cooling load, equipment coverage and measurement periods. A subsequent conceptual design exercise translated selected evidence into STEM tasks; no student participants or learning-effect estimates were involved.

Context, Setting, and Study Period

The study setting was Manado Town Square, North Sulawesi, Indonesia, under a hot-humid tropical climate. The accessible material identifies records as relating to 2025 but does not establish exact measurement dates, monitoring frequency, seasonal coverage, floor area, occupancy, simultaneous cooling loads or run hours for each section. These omissions preclude a defensible matched-period comparison and should be addressed with original facility logs before a quantitative comparative claim is finalized.

Participants, Sampling, or Data Sources

Units of analysis were the three HVAC installations; numerical evidence comprised reported nameplate/design specifications, section-level monthly energy records and calculated performance values. Facility staff were reportedly consulted, but the available materials do not establish the number, roles, recruitment, interview protocol or analysis of their responses. Interviews are therefore used only as contextual information, not as independently validated qualitative evidence. Author confirmation and documentation are required for personnel consent and facility-record access.

Variables, Constructs, and Operational Definitions

Technical variables were installed and actual electrical power (kW), cooling capacity (BTU/h and refrigeration tons [TR]), monthly energy consumption (kWh), chiller COP, system COP, annual operating

and maintenance costs, and life-cycle cost (LCC). Chiller COP represented cooling output relative to compressor input, whereas system COP used total system power including reported auxiliary loads. Economic outcomes included annual energy-cost savings and simple payback based on additional capital investment divided by annual operating savings. The educational construct was the conceptual alignment of the case evidence with science, technology, engineering, and mathematics domains.

Instruments, Measures, and Data Collection

The available technical account refers to electrical-load measurements with a power meter, technical specifications and facility energy/cost records. However, manufacturer/model, calibration, accuracy, monitoring points, intervals, duration, repeated-reading protocols and quality-control checks are not documented. Consequently, Table 1 is presented as reported site data and Table 2 as engineering performance calculations, not as directly comparable simultaneous measurements. Verification requires meter logs, nameplate schedules, billing extracts and a measurement protocol.

Procedure or Intervention

The technical workflow comprised problem definition, literature/context review, unit and variable identification, evidence gathering, calculation and comparison, and interpretation. A seventh, explicitly conceptual stage translated case variables to educational objectives, a data-audit task sequence, expected student products and rubric criteria. This final design stage does not represent teaching, learner recruitment or instructional evaluation. Figure 1 depicts the technical stages only; the instructional translation is specified in the proposed module below.

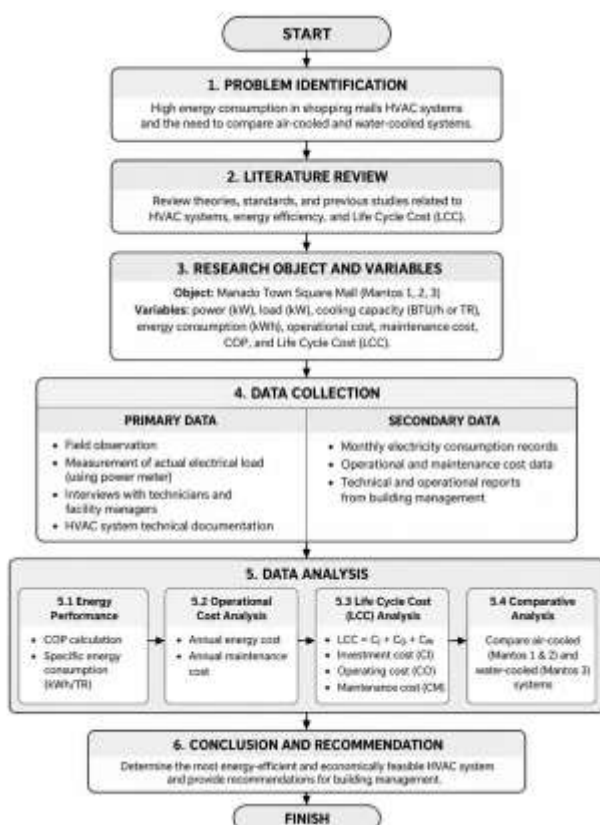


Figure 1. Technical research framework for HVAC performance analysis

Data Analysis

For a consistent measured boundary and interval, $COP = \text{useful cooling output (kW thermal)} / \text{electrical input (kW)}$; system COP must include compressors, pumps, towers and fans where applicable. Monthly electricity is $E = \sum(P_t \times \Delta t)$ in kWh; to compare systems on an equal basis, one would require matched hours, equivalent cooling load and conditioned area, or a documented model such as kWh/TRh, with every

adjustment disclosed. Electricity cost = $E \times \text{tariff}$; conditional annual saving = $(E_{\text{air}} - E_{\text{water}}) \times \text{tariff} \times 12$; simple payback = incremental capital cost / verified annual net savings. A discounted LCC would be upfront capital expenditure + $\Sigma[(\text{annual electricity} + \text{maintenance} + \text{water} + \text{replacement costs})/(1+r)^t] - \text{discounted residual value}$, for a stated horizon n and discount rate r . The supplied figures do not establish normalized TRh, r , n , maintenance/water cash flows or empirical uncertainty. Accordingly, no complete LCC, confidence interval or sensitivity analysis is claimed. The illustrative 10% and 15% auxiliary multipliers in Table 2 are calculation assumptions requiring equipment-level verification.

Research Quality and Rigor

Evidence was cross-checked at the descriptive level, but triangulation cannot substitute for equivalent system boundaries or documented normalization. The reported 2025 monthly totals are 574,088, 407,691 and 2,246,377 kWh for Mantos 1, 2 and 3. These cannot reproduce the separately stated 1,250,000 and 890,000 kWh scenario. Record periods, covered equipment and cooling demand are unverified; therefore quantitative savings, CO₂ and payback estimates drawn from the second scenario are treated as conditional, author-reported examples rather than validated empirical comparisons. No inferential causal estimate is made.

Ethical Considerations

The technical records do not contain a verifiable institutional ethics review/exemption, staff consent/waiver documentation or written authorization for publication of facility data and photographs. Because personnel reportedly provided operational information, the authors must obtain the actual ethics/exemption determination and permission statements from the appropriate institution and facility before publication; no approval is asserted here.

RESULTS

Building and HVAC System Characteristics

Mantos 1 and 2 have air-cooled HVAC equipment; Mantos 3 has an approximately 3,000-TR water-cooled plant and a separately listed AHU distribution figure of approximately 2,792 TR. Chiller production capacity and AHU distribution capacity may refer to the same cooling service and must not be added without an engineering explanation. The earlier sum of 5,792 TR is therefore not accepted as verified total plant capacity. Table 1 reports equipment/site records, whereas Table 2 uses nominal cooling-output and modelled input-power assumptions. In particular, the reported 4,211 kW for Mantos 3 in Table 1 and the calculated 2,171.26 kW in Table 2 have unresolved equipment boundaries.

Table 1. Reported HVAC capacity, power, and monthly energy values at Manado Town Square

*CAUTION: The 5,792-TR sum for Mantos 3 appears to add AHU distribution and plant capacities, potentially double-counting the same cooling service; it is NOT a verified net cooling capacity.

Metric	Mantos 1	Mantos 2	Mantos 3
Total AHU (BTU/h)	20,250,000	13,900,000	33,500,000
Total AHU (TR)	1,688	1,158	2,792
Total outdoor units (PK)	1,688	1,390	0
Total outdoor capacity (TR)	353	291	0
Chiller capacity (TR)	0	0	3,000
Reported capacity sum (TR; NOT net cooling)	2,040	1,449	5,792*
Electrical power, AHU (kW)	1,595	1,132	2,182
Electrical power, chiller (kW)	0	0	2,029
Total electrical power (kW)	1,595	1,132	4,211
Monthly energy (kWh)	574,088	407,691	2,246,377

Note. AHU = air handling unit; BTU/h = British thermal units per hour; PK = as reported in facility records; TR = ton of refrigeration. AHU distribution capacity and chiller plant capacity should not be summed as independent delivered cooling capacity. Table 1 consists of author-reported site figures with unverified operating points; the listed 4,211 kW for Mantos 3 does not reconcile with calculated Table 2 system input power.

Air distribution was organized through Air Handling Units and supply/return diffusers integrated with the interior layout. Figure 2 illustrates the diffuser placement in corridor and atrium areas, where mechanical elements were coordinated with public-space design.



Figure 2. Air-supply diffuser installation in the atrium and corridor areas

Note. Source: authors' documentation, 2025.

Comparative Energy Performance

Table 2 presents a design/engineering comparison based on reported thermal capacity and calculated input power, rather than documented measurements at equivalent load and time. On these assumptions, chiller COP is 3.80 (air) and 5.20 (water), and system COP is 3.455 and 4.523. The +10% air-cooled and +15% water-cooled auxiliary additions require validation against measured equipment demand. Neither this contrast nor the differing building sections identifies a causal effect of cooling technology.

Table 2. Reported cooling capacity, power demand, and coefficient of performance

Metric	Mantos 1	Mantos 2	Mantos 3
Cooling capacity (TR)	1,687.50	1,158.33	2,791.67
Cooling capacity, Q (kW thermal)	5,934.69	4,073.69	9,817.86
Chiller COP	3.80	3.80	5.20
Compressor power, full load (kW)	1,561.76	1,072.02	1,886.05
Total power incl. auxiliary load (kW)	1,717.94 (+10%)	1,179.23 (+10%)	2,171.26 (+15%)
System COP (Q/Wtotal)	3.455	3.455	4.523

Note. COP = coefficient of performance. The +10% and +15% auxiliary loads are unverified calculation assumptions; the tabulated powers are not established as simultaneously measured whole-system values. In particular, the 2,171.26 kW calculated for Mantos 3 differs materially from the 4,211 kW reported in Table 1, pending reconciliation of equipment and load boundaries.

The relative chiller-COP ratio was calculated as follows:

$$\eta = \frac{COP_{water-cooled}}{COP_{air-cooled}}$$

With $COP_{water-cooled} = 5.2$ and $COP_{air-cooled} = 3.8$, then:

$$\eta = \frac{5.2}{3.8} = 1.37$$

The ratio of 1.37 indicates that the reported water-cooled chiller COP was about 37% higher than the air-cooled chiller COP under the comparison used in the manuscript.

Energy and Economic Outcomes

A separate author-reported illustrative comparison gives 1,250,000 kWh/month for an air-cooled scenario and 890,000 kWh/month for a water-cooled scenario. Arithmetic yields $(1,250,000 - 890,000)/1,250,000 \times 100 = 28.8\%$; at an assumed IDR 1,200/kWh the difference would equal IDR 432 million/month or IDR 5.184 billion/year. An incremental capital cost of IDR 12–15 billion would imply a simple payback of approximately 2.31–2.89 years if these annual savings were verified and all other cash flows ignored. However, the scenario is not derived from the section totals in Table 1, nor supported by disclosed matched periods, cooling loads, floor areas, run hours or normalization coefficients. These values are scenario outputs, not demonstrated savings, and cannot substantiate a comparative economic conclusion at present.

The separately reported avoidance estimate of 3,672 tCO₂/year lacks a cited grid factor, emissions boundary and reference year. As an arithmetic check, a hypothetical 360,000 kWh/month saving equals 4,320,000 kWh/year; 3,672 tCO₂/year would require 0.85 kg CO₂/kWh. This is an implied assumption, not a verified local grid factor, so no confirmed emissions reduction is claimed.

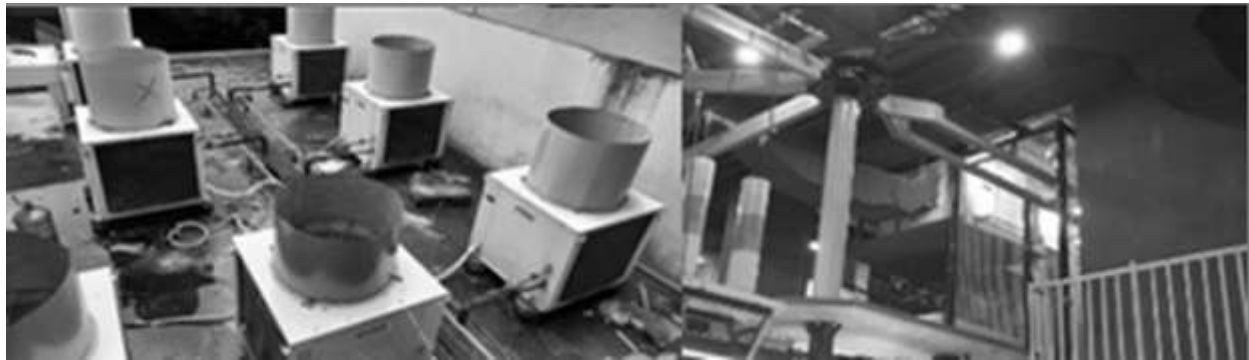


Figure 3. Outdoor and indoor components of the air-cooled system

Note. Source: authors' documentation, 2025.

Conceptual Mapping to Integrated STEM Learning

Table 3 provides a proposed curriculum-mapping framework rather than evaluated instruction. Mapping criteria were: direct traceability to a case datum, relevance to a STEM concept, feasibility of a learner-generated artefact, and a criterion enabling evidence-based assessment. The categories and activities have not been subjected to formal expert validation. A worked university/vocational module appears immediately below.

Table 3. Mapping the Mantos HVAC case to integrated STEM learning opportunities

STEM domain	Evidence from the case	Learning focus	Example learning activity
Science	COP differences; condensing temperature; heat rejection; refrigeration cycle	Thermodynamics, heat transfer, energy conversion	Explain why lower condensing temperature can reduce compressor work and increase COP.
Technology	Air-cooled units; water-cooled chiller; cooling tower; pumps; BAS/BMS	System components, sensing, control, and operations	Compare system architectures and identify the role of monitoring and control technologies.
Engineering	System selection; spatial integration; cooling-load and maintenance constraints	Design trade-offs, systems thinking, optimization	Develop and defend an HVAC recommendation for a tropical public building under stated constraints.
Mathematics	Power demand; kWh; TR; COP; tariff; payback; LCC	Quantitative modelling and engineering economics	Recalculate energy savings, operating costs, payback, and alternative life-cycle scenarios.
Sustainability	Energy and cost reduction; carbon implications; tropical-climate response	Evidence-based sustainability evaluation	Compare technical, economic, and environmental consequences and justify a balanced decision.

Note. BAS = building automation system; BMS = building management system; LCC = life-cycle cost. This is a conceptual pedagogical mapping based on the empirical HVAC findings, not a measured learning-outcome result.

DISCUSSION

The reported COP values favor the water-cooled design under the calculation assumptions, but the available data do not permit a matched causal or life-cycle superiority claim. Building-section sizes, load conditions, equipment boundaries and auxiliary-energy accounting differ or remain unknown. Thermodynamic explanations for potential efficiency advantages are plausible and consistent with engineering literature, yet remain distinct from the measured evidence here. The pedagogical value of this case lies particularly in interrogating such discrepancies through authentic multidisciplinary reasoning, rather than treating conditional calculations as settled evidence (Kelley & Knowles, 2016).

Theoretical and Methodological Contribution

The study's contribution is not a new thermodynamic theory but an integrative case that links engineering performance, economic evaluation, tropical-building context, and educational interpretation. Methodologically, the same operational dataset supports multiple levels of reasoning: physical explanation of heat transfer and refrigeration, technological analysis of equipment and controls, engineering evaluation of design constraints, and mathematical comparison of energy and cost. This structure aligns with integrated STEM frameworks in which disciplinary knowledge is mobilized around authentic problems rather than presented as disconnected content (Kelley & Knowles, 2016). It also extends experiential building-science approaches by showing how operational evidence from a commercial facility can be converted into a structured case for learning (Jung et al., 2026).

Implications for Education, Policy, and Practice

A proposed case-based teaching unit for advanced secondary vocational or undergraduate engineering/STEM learners would use the reported Mantos data to practice energy concepts and source-critical quantitative reasoning. Students should distinguish observed figures from assumptions, test whether capacities are additive, check conflicting power boundaries, calculate COP and conditional operating costs, and compare design choices subject to water use, maintenance and uncertainty. Learners would submit an annotated data audit, spreadsheet calculations and a justified recommendation. These are instructional design proposals only; no learning benefits were measured.

Limitations and Future Research

Limitations are material to the central quantitative conclusions: this is a single-site, unbalanced comparison across installations; exact observation dates and equipment boundaries are undocumented; Table 1 and Table 2 power values are unreconciled; AHU and chiller capacities may overlap; the stated normalized monthly energy example has no auditable derivation; and the economic, emissions and LCC inputs are incomplete. Interview procedures, instrument calibration, institutional ethics disposition, photo/data permissions and expert validation of the STEM mapping also require confirmation. The proposed instructional case has not been piloted. Future studies should obtain matched interval/load data, meter and plant schematics, full cost assumptions and an evaluated teaching protocol.

CONCLUSION

The reported engineering COP calculations suggest a potential performance advantage for water-cooled HVAC under stated assumptions, but installation differences and inconsistent power and energy boundaries prevent an independently verified estimate of comparative energy, cost, carbon or life-cycle savings. The 28.8% monthly energy difference and related economic figures remain conditional scenario calculations pending source-data reconciliation. The study's defensible educational contribution is a proposed authentic STEM data-audit and decision-making case; its learning outcomes have not been evaluated.

TABLES AND FIGURES

All three tables and three figures are embedded in the manuscript immediately after their first substantive mention, in accordance with the journal template. Tables are editable Word tables; figures include source notes and descriptive alternative text.

DECLARATIONS

Acknowledgments

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Author Contributions (CRediT)

Author contributions (CRediT) are pending written verification and approval by Frits O. P. Siregar, Raymond Ch. Tarore and Esli D. Takumansang.

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Ethics Approval

The source manuscript does not report ethics-committee approval, exemption, reference number, or approval date. Because structured interviews with building personnel were used as an operational data source, the authors should provide the applicable institutional ethics or exemption statement before submission.

Informed Consent and Assent

The source manuscript does not report the consent procedure used for structured interviews with facility managers and technicians. No minors were involved according to the described study context. The authors should provide the applicable informed-consent or waiver statement before submission.

Consent for Publication

No identifiable individual information or direct participant quotations are published in the manuscript. Consent for publication is therefore not applicable to the reported text; the authors should confirm permission for any identifiable or third-party images before submission.

Data, Code, and Materials Availability

The study used operational energy records, maintenance and cost records, technical specifications, field measurements, and author documentation. No public repository or access procedure is reported in the source manuscript. Data availability is therefore subject to author and building-management confirmation and any applicable confidentiality restrictions. No analytic code was reported.

Preregistration and Protocol

No preregistration or registered protocol was reported for this study.

Conflict of Interest

A conflict-of-interest statement was not included in the source manuscript. The authors should confirm and disclose any financial or non-financial competing interests before submission.

Use of Generative AI and AI-Assisted Technologies

OpenAI ChatGPT (GPT-5.6 Sol) was used to assist with academic-language editing, structural alignment with the EDUCATIONE template, and organization of the manuscript's STEM-education implications. It was not used to generate or analyze the underlying HVAC measurements or operational data. All scientific claims, calculations, references, disclosures, and the final manuscript require verification and approval by the human authors, who remain fully responsible for accuracy, originality, confidentiality, and research integrity.

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