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Research Article

A pragmatic retrofitting approach to enhancing the thermal, energy and economic performance of an educational building: a case study in Malaysia

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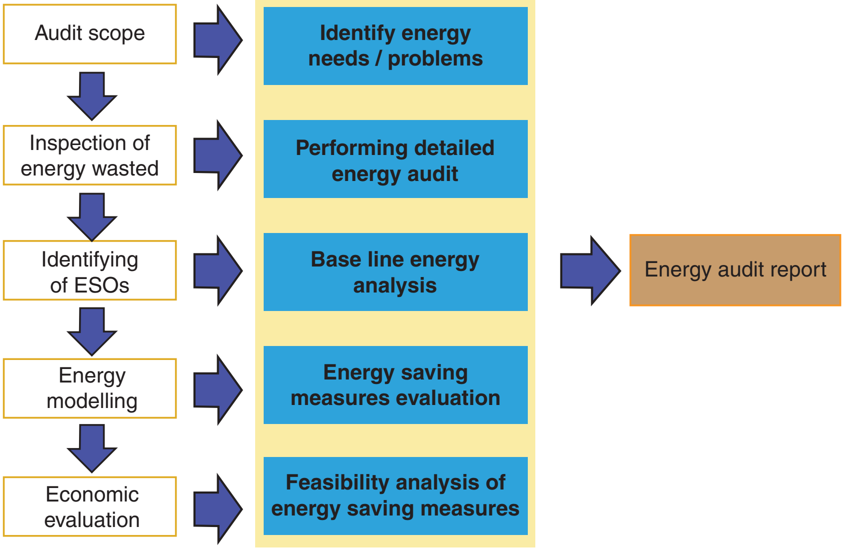
Abstract

Building retrofit procedures play a crucial role in improving the energy performance and economic indicators of a building. In this context, an energy audit is typically recommended, but it is seldom used as a comprehensive approach due to the complexity and associated costs. This article aims to conduct a holistic energy audit approach for a university building in Malaysia, with the objective of diagnosing energy efficiency deficiencies, identifying areas of energy waste and proposing practical retrofit measures accordingly. The approach involved multiple stages, including measurements, surveys and simulation work. Eight energy-saving measures were proposed, targeting improvements in envelope elements, cooling and lighting systems, and operation and control. The Design-Builder software was utilized for energy simulation, assessing the annual energy savings. Economic evaluation indices, such as net present value and simple payback period, were used to assess the economic feasibility of the measures. The results demonstrated significant potential for energy reduction, with each measure achieving annual energy reductions ranging from 2% to 18%, and a cumulative impact of 41% on annual energy consumption when combined. The investment payback period for the energy-saving measures varied from 0.8 to 8.9 years, with a payback period of 3.9 years for the combined energy-saving measures. Furthermore, the net present value was positive, indicating the economic feasibility of investing in the proposed energy-saving measures. These findings provide valuable energy-saving opportunities that can be applied to improve similar buildings on the university campus.

Graphical Abstract



Keywords: energy saving; building retrofits; educational building; energy-saving opportunities; energy audit

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Introduction

One of the biggest challenges facing human societies in achieving sustainable development is protecting the environment and conserving resources while global energy demand is increasing. In recent years, it has become apparent that the current global energy provision strategy is no longer viable due to the dwindling fossil fuel reserves and the inextricable link between the growing population, energy needs and climate change. The building sector plays a vital role in this trend globally, consuming 30% of primary energy in Southeast Asia [1, 2], 40% in countries of the International Energy Agency (IEA) [3] and 50% worldwide [4]. This figure is likely to increase in the future due to population expansion, development, increased demand for improved building services and comfort levels, and increased time spent in buildings. This conclusion is supported by the annual increase rate of building energy consumption in several countries Fig. 1, derived from Pérez-Lombard *et al.* [5] and Nazi *et al.* [6]. Changes in sustainable building laws, legislation and incentives emphasize the need for improved building energy efficiency. Due to a large number of unsustainable existing buildings, there has been great interest in building retrofitting to improve energy efficiency [7].

In many cases, building retrofitting is more cost-effective and has less environmental impact than complete demolition and rebuilding [8–10]. However, the efficacy of the process depends on the fundamental structure of the building and the retrofit measures applied [11]. As a result, strategies to identify effective retrofitting measures to predict energy-saving opportunities (ESOs) are critical [12]. Several organizations, notably the US Department of Energy (DOE) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), have released general energy retrofit guides and energy-efficient measures (EEMs) (in collaboration with other institutes) to meet the growing demand for building renovation [13, 14]. However, due to variation in design, subsystems and geographic locations, retrofit solutions can have various effects on different buildings, making the selection of retrofit measures particularly complex [15, 16].

ESOs can be divided into three basic types, depending on the energy-saving measures (ESMs) that can be implemented: (i) no-cost measures that include facility upgrades without interfering with building operations; (ii) low-cost measures, which entail adjustments in operational measures that require a relatively low investment; and (iii) high-cost measures that require a relatively greater capital investment to achieve energy efficiency [17].

Several studies have demonstrated the potential of energy audit procedures to propose ESMs to improve the energy performance of existing buildings. In European nations, several existing buildings were retrofitted with ESMs [18, 19]. In one such project [20], EEMs included implementing insulation material for walls and roofs, replacing current windows with high-performance ones, improving ventilation systems, installing efficient lighting systems and upgrading the heating systems. Photovoltaic (PV) models and solar-thermal systems were also used as on-site renewable energy sources. The degree to which these measures were used varied from building to building. Savings in heating energy demand ranged from 28% to 60%, depending on the building structure and prevailing climate. Furthermore, electrical energy savings consumption ranged from 22% to 91%. Field research in Eger, Hungary found that integrating a heat wheel into an external ventilation unit could minimize cooling energy by ≤25.1% during the cooling period [21].

In a Mediterranean climate, a validated building model was used to assess ESMs for an Italian educational facility [22]. The simulation process evaluated the effectiveness of some passive measures, including the use of unique coatings, low-emissivity windows, solar screens, thermal mass, thermal insulating layers and specialized plasters. Active strategies such as the selection of a new high-efficiency air-source heat pump, ground-source heat pump and water-cooled chiller with the cooling tower were also explored. Passive and active measures were carefully chosen and then integrated with PV panels. The findings indicated that the current condition of the building could be improved to that of net-zero energy performance. Another simulation procedure for an existing building in the same country found that various retrofitting measures such as window replacement; integrating solar screens; using heat recovery systems; optimizing the operation of heating, ventilation and cooling (HVAC) systems; and installing PV panels could provide annual reductions of 81% and 45% for energy demand and energy costs, respectively [23]. Lucchi [24] conducted a critical review of the application of infrared thermography as a visualization method for auditing building energy

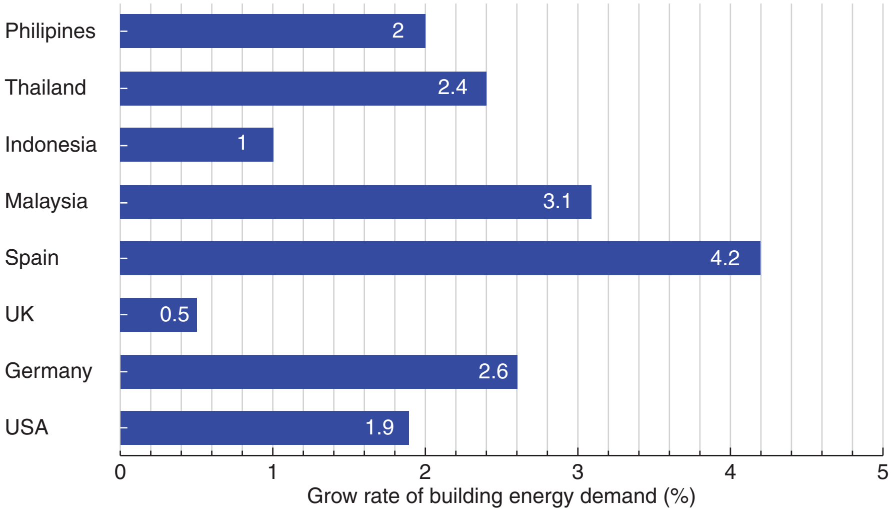

Fig. 1: Annual growth rate of building energy demand by country [5]

consumption. The study examined how this method can be utilized to detect excessive heat walls and test building insulation, enabling standard and detailed energy audits. The findings indicated that the proposed method was highly effective and efficient in identifying ESOs in the building envelope.

In a subtropical climate, energy audits were used for an Australian institutional building [25]. A calibrated simulation model was used to evaluate various ESMs. Changes to the thermostat set point for cooling and heating were examples of no-cost ESMs. Low-cost ESMs included installing double glazing and daylighting controls. High-cost ESMs included changing the current HVAC system to variable air volume and improving chillers with low coefficient of performance (COP). According to the simulation results, energy savings of 41.87% were realized when all ESMs were used. For thermal comfort applications, HVAC systems are among the largest end uses of energy. Therefore, implementing operational measures for HVAC systems can achieve significant energy savings. In a hot and dry climate, the ventilation and air conditioning systems of the HVAC system of an Egyptian airport were the main study subjects, targeting ESOs [26]. The results showed that increasing the cooling set point from 25°C to 27°C could result in a 24.5% reduction in the HVAC energy used during the hot season. A simplified energy audit method, based on calculating normalized performance indicators (NPI), was conducted at Princess Sumaya University for Technology in Jordan [27]. The study aimed to explore two ESOs in the building: optimizing the operating hours of air conditioners (ACs) within the working day and insulating the building envelope using ThermaCote® material. The results demonstrated the effectiveness of these approaches in reducing costs and energy consumption. Specifically, there was a 12.5% reduction in both energy and cost, and the NPI improved by 3.59% compared with both hypothetical and actual cases.

The influence of occupant behaviours on the energy profile of US office buildings was studied by Sun *et al.* [28]. The ESMs proposed included changing the HVAC cooling set point and the operating schedule, the lighting operation schedule and window control. The findings illustrated that applying each energy-saving measure individually might result in energy savings of ~22% while combining all the proposed measures was expected to save 41% of the energy demand of the building. Studies conducted in harsh climates have shown the potential of ESMs to improve building energy performance. For example, in Saudi Arabia, an energy audit was conducted for an office building, resulting in the identification of various ESMs, including insulation of walls and roofs, high-performance glass windows, efficient lighting and HVAC systems, and operation options such as cooling set point, thermostat back point, and lighting and equipment operation scheduling during low occupancy periods [29]. The implementation of all proposed ESMs led to a 36% reduction in energy consumption. Another energy audit study was carried out in Kuwait for typical government facilities, focusing primarily on the operating schedules of the mechanical and electrical building systems during unoccupied times [30]. The findings indicated that all the selected buildings could achieve an energy reduction of between 3% and 13% during unoccupied times, with an average of 9%.

According to the literature, the energy audit procedure has been proven to significantly enhance the energy efficiency of existing buildings. For example, China achieved a 20% reduction in energy demand and met its energy efficiency target in 2010 through the implementation of this procedure [31]. However, it is important to acknowledge a potential limitation of energy audits highlighted in the previous study. These audits often focus on evaluating specific subsystems of buildings, such as air-conditioning or lighting systems. This narrow focus may not fully capture the best opportunities for energy savings when considering the entire facility. As a result, the implementation of retrofit measures based solely on these audits can be costly in relation to the energy saved and the return on investment from the perspective of stakeholders. Furthermore, recent studies have identified the lack of a holistic approach to energy audits as a major weakness in building energy analysis [32, 33]. To address this issue, this study aims to conduct a comprehensive diagnostic energy audit that includes a systematic approach to data collection in the pre-audit stage, various levels of evaluation during the energy audit stage, development of a base-case energy model and performance of energy and economic analysis. By following these steps, stakeholders interested in building retrofits can acquire valuable insights into enhancing energy efficiency.

Section 1 of the paper introduces the methodology utilized in the research, along with its application to the case study. Section 2 focuses on analysing the results obtained from the study and provides a comprehensive discussion of the findings. Finally, in Section 3, the paper concludes by summarizing the key conclusions derived from the research, discussing the limitations of the study and providing recommendations for future work.

1 Research methodology

The main aim is to apply a holistic approach of an energy audit for one of the buildings of the Mechanical Engineering Department of Universiti Teknologi Malaysia. For this purpose, an energy audit team was formed under the supervision of the university maintenance department. The first task was to obtain information and data on the main areas of energy breakdown in the building and how to improve energy performance, followed by defining the scope of the energy audit, including the areas to be audited and the anticipated energy savings. The implemented methodology consisted of four stages: the pre-audit stage for data collection, the energy audit stage, the energy analysis stage and the economic analysis stage. Each stage was further divided into substages, as shown in Fig. 2.

1.1 Pre-audit stage

The pre-audit stage involved collecting critical data and information about the building characteristics, construction drawings, specifications and historical electrical billings. These data were based on documented evidence provided by the maintenance department (Pejabat Harta Bina). The following section describes the outcome of this phase.

1.1.1 *Case study building description*

The case study building (E07) is one of the faculty blocks of the mechanical engineering department, located on the campus of Universiti Teknologi Malaysia at 1°33’42.9’N latitude and 103°39’20.3’E longitude. This building consists of two rectangular parts connected at an angle of 135°, with five floors, as shown in Fig. 3. The gross floor area of the building is ~1470 m^2 and it consists of various instructional facilities such as classrooms, laboratories and lecturer offices. During the academic year, the building is used with irregular occupancy from 8 a.m. to 5 p.m., 5 days a week. The geometric parameters of the building are summarized in Table 1.

The structural system of the exterior walls consists of brickwork with plaster on both sides with a total thickness of 0.12

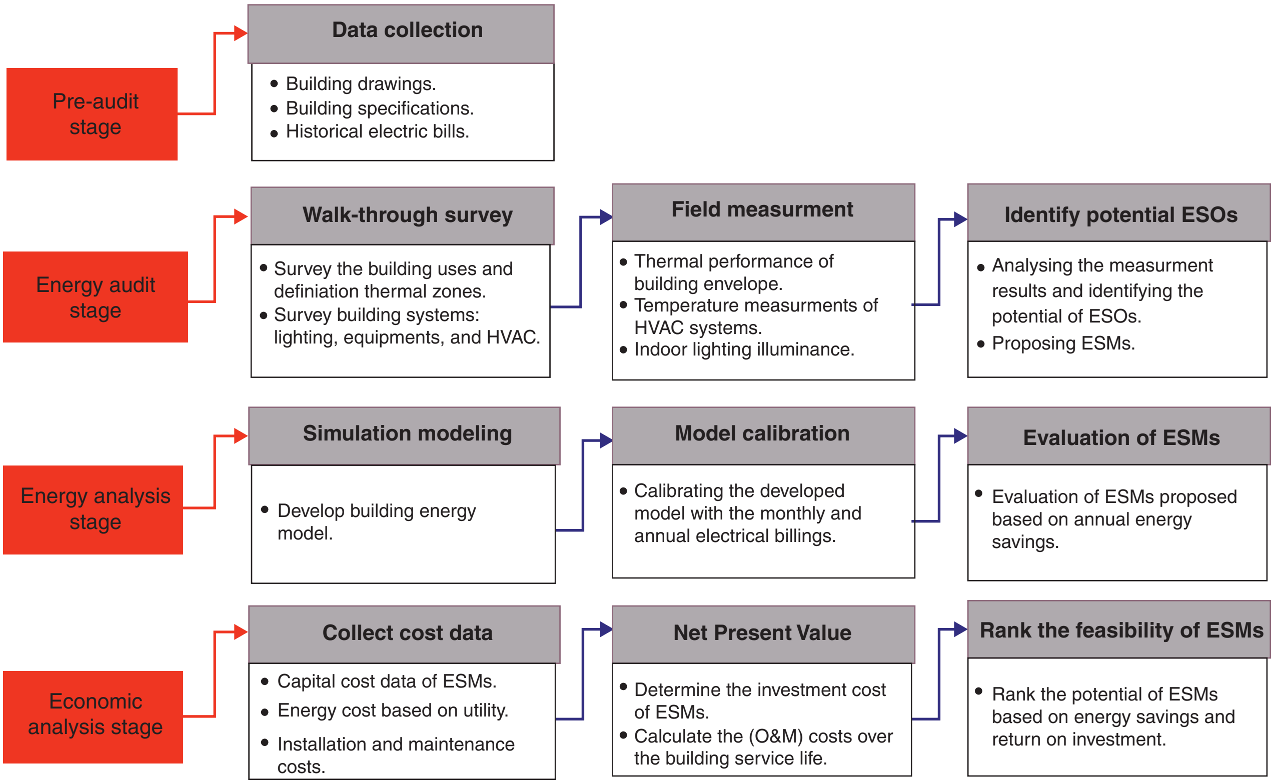

Fig. 2: The research methodology

Fig. 3: The view of the case study building

m. The roof is a reinforced concrete slab with a total thickness of 0.20 m. The windows are single-glazed panels with a thickness of 6 mm and aluminium frames. The heat transfer coefficients for the wall, roof and windows are 2.7, 5.8 and 5 W/m^{2}K, respectively. This building has been selected because it shares similarities with numerous existing buildings on the university campus, as they were constructed with little consideration for energy performance. Furthermore, as a public building, it has the potential to serve as an example for future projects within the campus. Also, the management department of the university has recently introduced its sustainable blueprint for 2023–30, demonstrating a commitment to promoting a sustainable environment culture and reducing carbon emissions. Therefore, the proposed configuration outlined in this paper holds the potential for rapid implementation in alignment with these sustainability goals.

1.1.2 *Energy profile and electrical load*

The monthly energy consumption bills and cost data were provided by the maintenance department for the year 2019. This year was specifically chosen because it contained more accurate energy consumption data compared with 2020–22, due to the coronavirus pandemic, which left most of the university buildings incompletely occupied. The annual energy consumption was 359 034 kWh, which corresponded to an energy cost of ~\$35 903.4, with an average electricity cost of \$0.101/kWh. Fig. 4 shows the monthly energy consumption and energy cost for the year 2019.

Additionally, the energy profile of the building has been analysed to identify monthly variations in electricity consumption throughout the year. Owing to the tropical climate, the cooling demand fluctuates throughout the year, which increases the energy consumption. As a result, the highest district energy consumption occurs in March, with ~25 396.41 kWh, followed closely by April and November, with an ~1000-kWh difference. Fig. 4 also highlights that the overall energy consumption from May to August is lower compared with other months. The reason behind this is that this period is the beginning of examination season followed by the semester break, which means that the classrooms are not fully occupied.

An outline assessment of the building energy performance has been established by looking at the energy use intensity (EUI) index, which is the ratio of annual energy consumption to gross floor area. The calculated EUI is ~248 kWh/m^2/year, which exceeds the average limit (136 kWh/m^2/year) recommended by Malaysian Standard code MS1525 [34] for non-residential buildings. Therefore, a high level of energy consumption and associated costs may suggest the possibility of a potential decrease.

1.2 Energy audit stage

An energy audit is an effective process to identify potential opportunities for energy savings in existing buildings. It involves assessing the building operating conditions, the condition of its envelope and the performance of existing equipment. Furthermore, it provides accurate data for developing an energy simulation model to conduct a comprehensive analysis of the energy efficiency of the building.

This stage involves conducting a walk-through assessment, which is a simple but crucial requirement [35, 36]. The walk-through audit serves as a performance indicator, allowing the assessment of energy efficiency and identification of potential ESOs in the building through visual inspections during multiple visits. These visits aim to verify the accuracy of building drawings, survey different categories of building systems and diagnose any energy waste or thermal deficiencies. While the walk-through audit provides valuable insights, it may not provide a comprehensive understanding of energy consumption patterns and deficiencies within the building. To address this, field measurements were conducted to investigate the thermal performance of the elements of the building envelope and assess the efficiency of the cooling and lighting systems. Several measurement devices were utilized during the energy audit phase, as depicted in Fig.

Table 1: Building geometric characteristics

Total building area	**3656.54 m^2**	**Conditioned area**	**3044.55 m^2**	**Unconditioned area**	**611.99 m^2**
Floor height (m)	3.5				
Geometry	**Total**	**North**	**East**	**South**	**West**
Cross wall area (m^2)	2121.21	479.90	527.51	673.9	439.84
Window opining area (m^2)	338.59	59.09	89.79	59.1	34.29
Window–wall ratio (%)	15.96	12.31	17.02	20.9	11.03

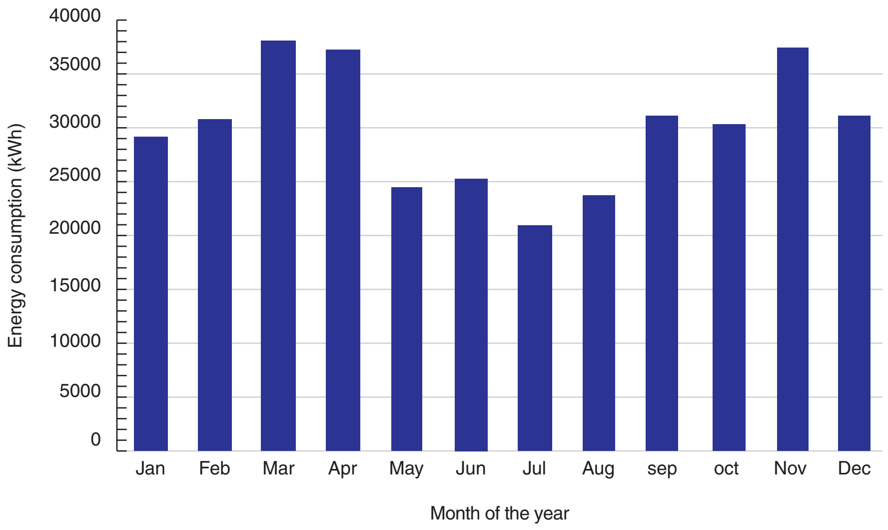

Fig. 4: Monthly energy consumption for 2019

5. The time frame and budget for this stage were determined by the working hours of the audit team, spanning from the initial collection of information to the completion of the audit report. Fortunately, the department had most of the necessary devices readily accessible since they are used for practical training courses.

The equipment used for the measurements included an infrared camera, specifically the FLIR E5-XT, with a temperature range of –20°C to 400°C, which was employed to capture thermal images to identify any thermal deficiencies in the elements of the building envelope (Fig. 5a). Additionally, K-type thermocouples with a measurement range of –50°C to 350°C, along with the Picotech TC-08 USB data logger, were utilized to measure and record temperatures in the condenser and evaporator tubes to evaluate the COP of the HVAC systems (Fig. 5b and c, respectively). The Testo 545 lux meter, with a range of 0–100 000 lux, was used to measure indoor lighting quality in various building zones, while a compass was employed to specify the measurement direction (Fig. 5e and d, respectively). Finally, the Testo 425-KIT hygro-thermal anemometer, with a temperature range of –20°C to 70°C and a velocity range of 0 to +20 m/s, was utilized to measure indoor and outdoor temperature as well as air leakage from windows and doors (Fig. 5f).

During the walk-through energy audit, the lighting system and equipment were examined, revealing the presence of four different types of fluorescent lamps: circular luminaires with compact fluorescent lights, metal halide lamps, 120 × 30 mm lighting luminaires with two fluorescent lamps and 60 × 30 mm with four fluorescent lamps. The quantities and locations of each type are listed in Table 2. Please note that the wattage of fluorescent types includes an additional 4 watts per bulb for ballast losses.

The building equipment was surveyed to determine its wattage and operation schedules as provided by the operation staff. Six types of thermal zones have been identified, as shown in Fig. 6, to represent the general loads in terms of lighting, equipment and occupant-occupied zones, which can vary depending on the function of the zone and the number of occupants (see Table 3).

Regarding the HVAC systems, the building is equipped with two different types of electrical HVAC systems: split units and fan coil units (FCUs). The specifications of the HVAC systems used in the building are summarized according to the manufacturer specifications in Table 4. In more detail, split AC systems are installed in small zones such as post-graduate and professor offices, while the larger zones such as classrooms, studios and laboratories use FCU systems.

1.3 Energy analysis phase

Field studies are widely regarded as a reliable approach to improving the energy efficiency of a building. However, the use of validated simulation models has emerged as an attractive and cost-effective alternative to understand energy consumption patterns and identify areas in need of improvement [37]. In this study, Design-Builder simulation software was used to model the base-case building and predict the energy savings resulting from the ESMs explored. Design-Builder serves as a graphical user interface (GUI) for EnergyPlus, a well-recognized and reliable dynamic thermal simulation engine developed by the US DOE

Fig. 5: Measurement devices used. (a) Infrared camera; (b) TC-08 data logger; (c) K-type thermocouples; (d) compass; (e) lux meter; and (f) hygro-thermal anemometer.

Table 2: Summary of lighting fixtures of the building

Location	Fixtures with 36-W fluorescent lamps	Fixtures with 24-W fluorescent lamps	Fixtures with single compact 18-W fluorescent lamp	Metal halide 250-W fixtures
Number in first floor	222	22	20	26
Number in second floor	176	24	10	–
Number in third floor	18	609	10	–
Number in fourth floor	108	52	15	–
Number in fifth floor	64	54	55	–

[38, 39]. Although EnergyPlus is known for its reliability and capabilities in modelling heat transfer mechanisms, heating and cooling demand, ventilation and other energy flows in building applications [40, 41], it lacks a GUI. Therefore, Design-Builder was used interchangeably as a user-friendly tool to implement EnergyPlus simulations.

The baseline model was established based on the data and information collected during the pre-audit stage, such as the building layout and orientation, gross floor area, air-conditioned area, structural system with its thermophysical properties and operation schedules. The lighting specifications and equipment loads for each building zone were included based on the data collected during the energy auditing process. Thus, survey features were taken into account. Control settings and occupancy rates reflect the highest uncertainty variables during the model calibration phase. More specifically, during survey operations, it was discovered that most air-conditioned zones frequently had residents set the cooling set point at 21°C. The HVAC specifications for each building zone were included based on the survey results regarding size and cooling capacity, as well as the COP measurements described in Section 2.1. As a result, the energy model for HVAC is anticipated to be as realistic in technical aspects of the model as the actual building. The default constant value for air leakage, as given by the typical Design-Builder modelling template, was left at 0.7 air changes per hour (ac/h). The minimum fresh air supply was assumed based on the ASHRAE requirements of 10 litres/person.

A specific weather file was developed for Johor Bahru. These data were based on the set of updated typical meteorological year (TMY) called the TMYx data set published by the creators of EnergyPlus software. The TMYx data set provides for the EnergyPlus weather files (epw) ~16 100 locations worldwide, covering the period from 2006 to 2021 (source: https//www.ladybug.tools/epwmap/). Table 5 provides a summary of site weather data. The building model and the path of the Sun are shown in Fig. 7.

Table 3: Load data of the building thermal zones

Thermal zone	Average occupant rate (m²/person)	Average lighting power (W/m²)	Average internal load (W/m²)
Classroom	2.7	26.8	10.3
Hall office	12.5	10	12.5
Office	14.4	10.3	15.6
Meeting room	6.6	10.5	12.2
Studio	4.96	10	3
Laboratory	5.87	14.8	84

1.3.1 *Model calibration*

To ensure that the building model accurately depicts reality and that its data outputs are reliable, it must be properly validated and verified. Only then can it be trusted to provide insightful results. The building energy model is typically calibrated by comparing the data produced by the model with comparable data measured from the actual building, coupled with a weather file from a location near the site of the building. As a result, model flaws can be found and corrected until the model is a good enough representation of the real building.

The case study building did not have an energy consumption monitoring system. Therefore, no energy consumption data were obtained for each subsystem. Therefore, the model was calibrated based on actual energy performance for 1 year using overall monthly electrical utility data and real weather data that corresponded to the billing period. ASHRAE Guideline 14 [42] recommends using the coefficient of variation of the root-mean-square error (CV(RMSE)) and the mean bias error (MBE) for model calibration, with values not exceeding 15% and 5%, respectively, using the following equations:

$$MBE_{month}\,(\%) = \frac{(M - S)_{month}}{M_{month}} * 100 \tag{1}$$

$$CV\,(RMSE_{month})\,\% = \frac{RSME_{month}}{A_{month}} * 100 \tag{2}$$

where M indicates the measured electrical use in kWh, S is the simulated electrical use in kWh, $RMSE$ is the mean square error and A_{month} is the mean of the utility billing.

According to Fig. 8, the monthly calibration of the building model shows an error of <5% on a monthly basis. Furthermore, CV(RMSE) and MBE values were determined to be 12% and 1.72%, respectively, which adhere to the acceptable margin of error specified in ASHRAE Guideline 14 [42]. Table 6 provides a summarized comparison of real and simulated data,

Fig. 6: The main thermal zones of the building

Table 4: Details of HVAC systems used in the building

System type	Model	Quantity	Capacity (BTU)	Power usage (kW)
Split	York, YSL09C	10	9000	2.63
Split	York, YSL15C	21	13 000	3.80
Split	York, YSL18C	5	18 000	5.27
Split	York, YSL20C	4	19 500	5.71
Split	York, YSL25C	14	24 000	7.03
FCU	York, YSL40C	8	50 000	14.65
FCU	York, MYSS80C	2	77 000	22.50
FCU	York, MYSS100B	4	101 000	29.59
FCU	York, MYSS125B	1	125 000	36.60
FCU	ACSON, ALCY40FR	4	35 000	10.25

Table 5: Summary of site weather data

Weather data information	Description
Location	Johor Bahru, Malaysia
Latitude (deg)	1.64 N
Longitude (deg)	103.67 E
Elevation (m)	41.10
Time zone	8 h ahead of GMT
Weather file	Johor. AP JH MYS SRC-TMYx WMO#=486790
Reference file	JOHOR BAHRU/SENAI
ASHRAE climate zone	1A
ASHRAE description	Very hot-humid

demonstrating that they fall within the limits set by reliable references. This confirms the calibration of the model, as it accurately reproduces the behaviour of the actual building. As a result, the model can be confidently utilized to explore various potential energy management opportunities and assess retrofitting options.

1.3.2 *Economic analysis phase*

For building retrofits, Pombo *et al.* [43] have listed several economic indices, including the net present value (NPV), rate of return, benefit–cost ratio, discounted payback period (DPB) and simple payback period (SPP). In the current study, the SPP and NPV were used for the economic evaluation of ESMs. These indices were chosen because they consider the criteria that decision-makers typically take into account when analysing the profitability of an expected investment or comparing different investment options. The NPV must be positive (NPV ≥ 0) for each ESM to be considered economically feasible. Equations (3) and (4) were used to calculate SPP and NPV, respectively:

$$SPP = \frac{Total\ capital\ cost}{Annual\ cost\ savings} \tag{3}$$

$$NPV = Annual\ cost\ savings\frac{(1-(1+d^{N})}{d} - Capital\ cost \tag{4}$$

where d is the discount rate and N is the life cycle of the design parameter (years).

The cost of energy is considered using the structure of the current tariff for non-residential buildings mandated by the Malaysian electricity utility (TNB) of 0.101$/kW. For the discount rate, the common practice for determining the discount rate involves assuming its constancy throughout the life cycle, under the assumption that all costs increase at the same rate [44]. In addition, predicting inflation rates over a long period (from 30 up to 100 years) increases uncertainty [45]. Therefore, a fixed discount rate of 9% has been assumed, which is recommended for Malaysia [46].

2 Results and discussion

The results of the study are based on ESOs obtained from short-term measurements and simulation findings of proposed ESMs. The following sections describe the results of the study.

2.1 Measurement results

During the walk-through audit, it was found that the perimeter zones of the building were hotter than the core. Thermal anemometer spot measurements were conducted to explore the reasons. The measured outside temperature was ~33.5°C, while the average inside air temperature near the windows and doors was close to 32.8°C. The reason for this temperature difference was related to gaps in the windows and door frames, and the heat conductivity of envelope materials. This finding was supported by thermal imaging, as seen in Fig. 9. As a result, two significant opportunities for energy savings were identified during the walk-through audit to improve the thermal performance of the building envelope. The first opportunity was to reduce air leakage through the window and door frames, while the second opportunity was to reduce heat gain in the opaque building envelope (i.e. walls and roof).

The lighting quality in the building was evaluated over a 3-day period during daytime hours, due to constraints imposed by the operational schedule. A lux meter was used to measure the lighting intensity and assess the impact of transparent envelope elements on the energy performance of the building. Two zones on the second floor were selected for measurement, facing the south-east and south-west, respectively. Geometric measurements such as length, width, height and window size were taken for each zone and window orientations were determined using a compass. The zone index and the number of measurement points in each zone were determined based on the methodology

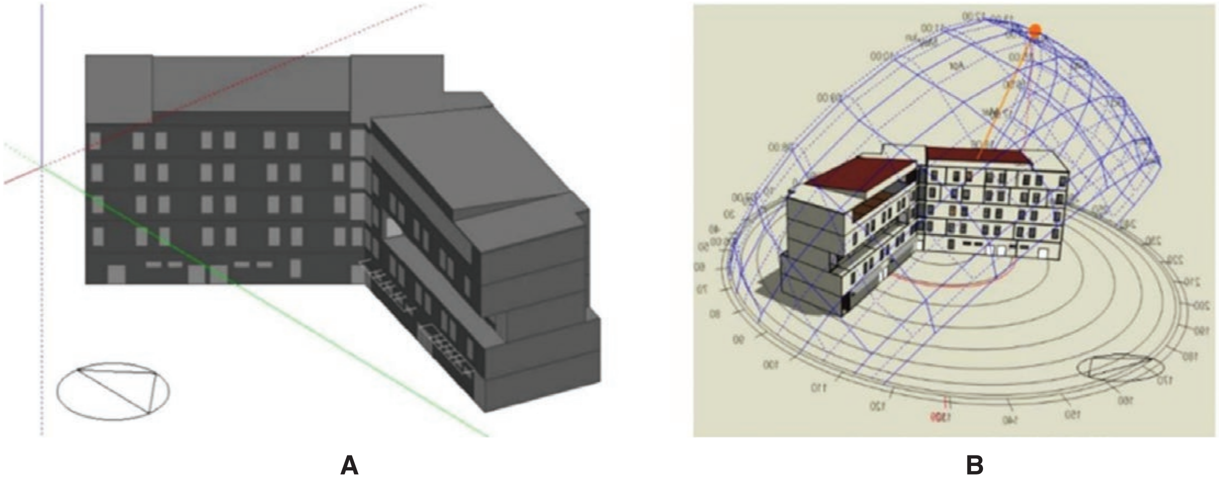

Fig. 7: (a) Complete building model for simulation; (b) the Sun path of the building

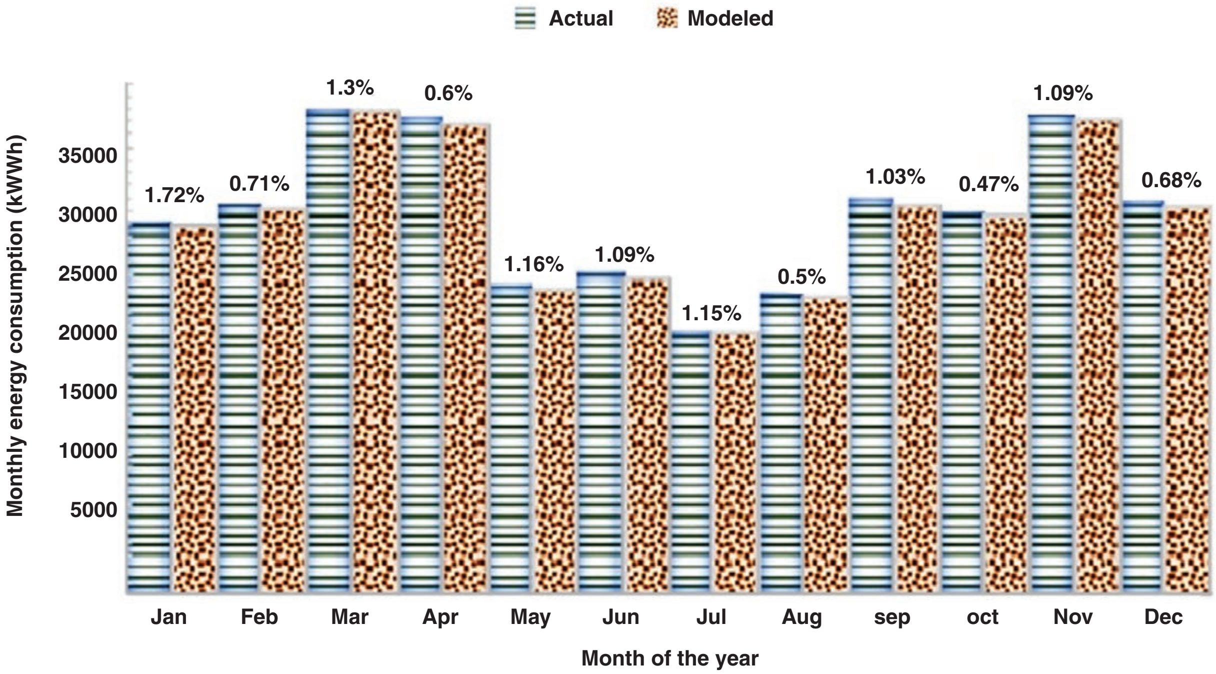

Fig. 8: Monthly building model calibration results

Table 6: Tolerances between actual and simulated data

	Actual	Simulated	Tolerance
Total gross floor area (m^2)	1470	1429.85	2%
Air-conditioned area (m^2)	3018.45	3066.46	–1.6%
Building energy consumption (kWh/year)	359034	353 639	1.5%
Building energy intensity (kWh/m^2)	244.24	247.32	–1.26

outlined by Kandar *et al.* [47]. Fig. 10 shows the number of measurement points and images of the surveyed zones.

Work plane illuminance measurements were taken in two phases at a height of 0.8 m above the floor level. In the first phase, the blinds were fully open and the artificial lights were turned off. For the second phase, the blinds were closed and the artificial lights were turned on. These measurements were taken over 3 days, from 12 to 14 November 2022, during daytime hours due to operational constraints. Table 7 shows the illuminance of the work plane for each point under both lighting conditions.

The measurement results indicated that the highest illuminance level, of >600 lux, was only recorded at three points (A1, B1, C1) for Zone 1 and two points (A1, B1) for Zone 2. These areas were located closest to the windows. According to the MS1525 standard, an illuminance value of between 300 and 400 lux is typical for educational buildings. Additionally, daylighting illuminance levels of >500 lux can cause thermal and glare problems due to the increasing daylight factor. Therefore, the window glazing sheets used and the lack of window shading systems may have contributed to the increase in building heat gain and energy demand. This presents another opportunity to improve the energy performance of the building. In terms of indoor lighting quality, the results from Phase 2 showed that the intensities of artificial lighting in almost all spaces were ~322 lux on average, which falls within the range specified by the MS1525 standard.

The evaluation of the efficiency of the HVAC system is determined by its COP, which was evaluated using CoolPack software. K-type thermocouples were used to measure temperatures at the condenser inlet and outlet, as well as the evaporator tubes. The temperatures at four different positions were averaged to obtain the condenser and evaporator temperatures. The thermocouples were calibrated using a GRANT water bath with an accuracy of ±0.5°C within the temperature range of 5°C to 90°C). They were connected to a TC-08 data logger that was interfaced with a laptop computer. Since the case study building was equipped with different types of systems in terms of size and cooling capacity, a sample for each type was considered during the measurement processes. The condenser temperature range of 51°C to 63°C and the evaporator temperature range of −3°C to 14°C were used during the simulation. Analysis of the results showed that the average COP for split HVAC systems was 2.1 and for FCU systems it was 2.0. The Code of Practice on Energy Efficiency for Non-Residential Buildings (MS1525) provides technical guidance for the minimum COP requirements for HVAC systems. Table 8 summarizes the minimum COPs for air-cooled and water-cooled chillers. However, when comparing the measured COP values with the standards, it was identified that the HVAC system was in a critical situation, indicating the need for energy efficiency retrofits in terms of improved operation and maintenance for existing HVAC systems.

2.2 Simulation results of ESOs

To enhance the energy performance of the building, it is crucial to analyse the energy consumption profile and thermal

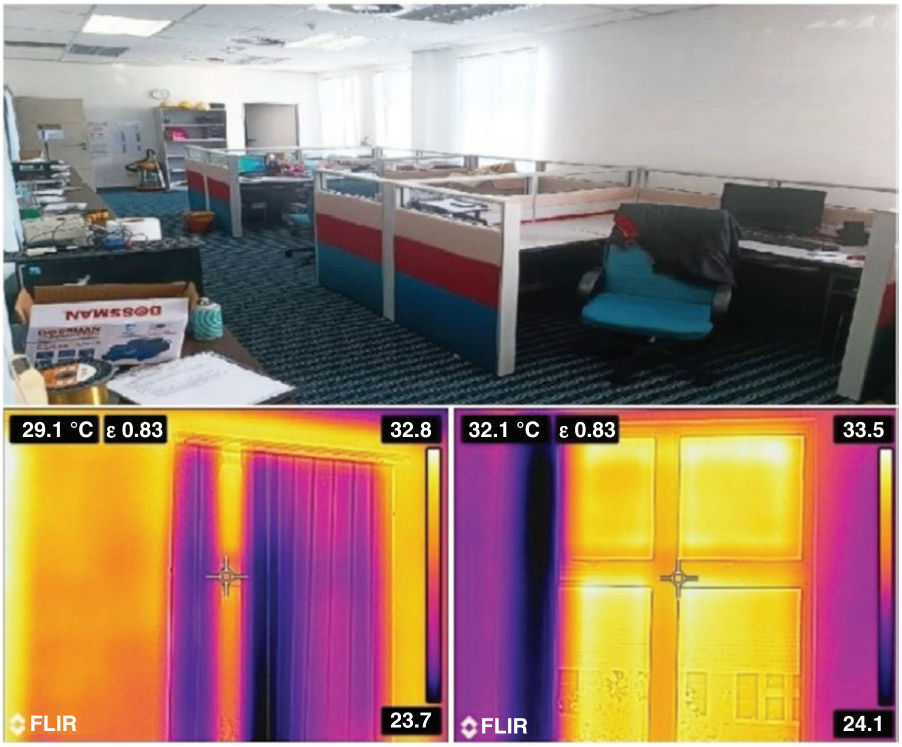

Fig. 9: Typical picture and thermal image of glazed windows

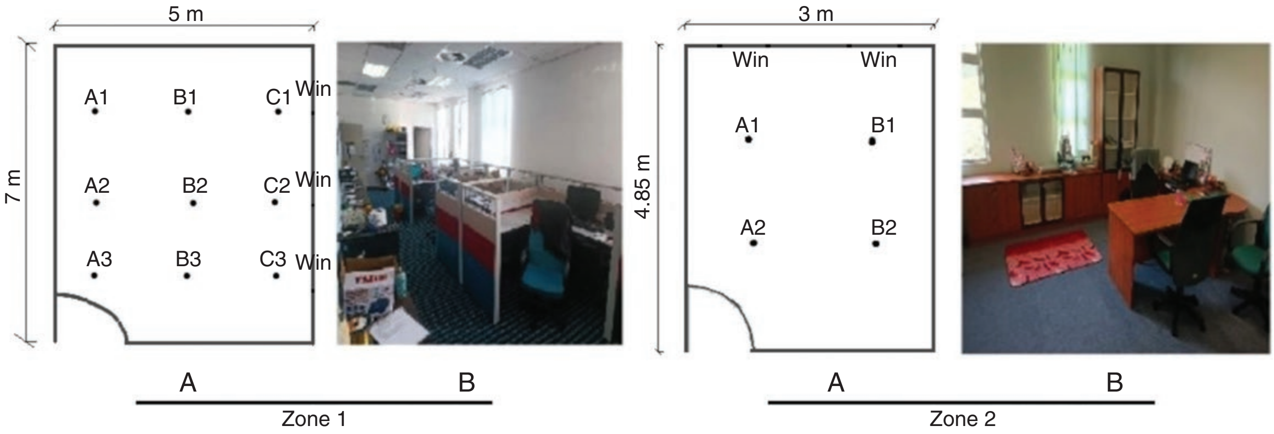

Fig. 10: (a) number of measurement points; (b) Measured zones

Table 7: Average illuminance of the work plane for Phases 1 and 2 (lux)

	Points	A1	A2	A3	B1	B2	B3	C1	C2	C3
Phase 1	Zone 1	178	129	161	249	216	241	671	609	653
	Zone 2	515	218	–	531	199	–	–	–	–
Phase 2	Zone 1	322	326	331	318	324	320	369	341	351
	Zone 2	331	316	–	324	329	–	–	–	–

performance by utilizing a calibrated building energy model. This analysis helps determine the breakdown of energy consumption and identify areas that require further improvement. The results of the annual building energy performance simulation for temperature and heat gain are depicted in Fig. 11.

The air temperature (blue line) remains above the cooling set point and does not drop below 24°C (Fig. 11 top). This indicates that the cooling system may be suffering from degradation and ageing, leading to overheating as a result of system faults or failure. Consequently, modifying or repairing the system is necessary to achieve more efficient outcomes. The heat balance graph (Fig. 11 middle) illustrates the increase in zone sensible cooling load primarily due to the external envelope element surfaces absorbing heat (yellow line). This results in high heat gains from the exterior windows, which exceeded 330 kWh for all months. This excessive heat gain from exterior windows is likely another cause of the thermal loads of the building increasing, leading to overheating. Therefore, retrofit measures are necessary to decrease the heat gain. Fig. 11 (bottom), the total fresh air graph, indicates that the variance in air leakage is significant and warrants further consideration. Although air leakage was set at a constant value according to the Design-Builder modelling default, reducing the variability of the air infiltration rate should be evaluated with respect to its impact on the building energy demand.

The energy breakdown of the case study building by end-use systems, including HVAC and lighting systems, as well as various equipment and devices such as pumps, elevators and plug loads, is depicted in Fig. 12. The figure clearly illustrates that the HVAC system dominates the energy consumption, accounting for 66% of the total energy used by the building. In contrast, the lighting and other equipment consume 15% and 19% of the energy of the building, respectively.

The energy audit processes implemented were beneficial in identifying thermal performance issues, internal load profiles, operational characteristics and opportunities for energy conservation in buildings. The findings highlighted several ESMs that can substantially improve the energy performance of the building. Table 9 summarizes these measures, which focus on improving the thermal performance of both opaque and transparent parts of the building envelope and reducing the energy consumption for cooling and lighting systems. The study does not consider equipment, including office equipment and laboratories, as they are expensive to replace compared with the potential energy savings [32]. After proposing the ESMs, they were evaluated using the calibrated building energy model with a TMY file of the building site.

2.2.1 *Potential energy savings from proposed ESMs of building envelope elements*

The full-scale dynamic simulation carried out for the building shows that external envelope elements contribute to the increase in zone sensible cooling load, which is mainly caused due to the rise in the surfaces of the external envelope element to absorb heat. Thus, improving the thermal properties of the external envelope elements can result in significant energy savings, particularly in the cooling demand.

Table 8: Recommended COP values by MS1525

Cooling capacity	Air-cooled	Water-cooled
<19 kW	2.6	2.9
>19 kW	2.7	2.7

The first measure analysed (ES-01) involves implementing an insulation layer of expanded polystyrene to the external walls and roof, which has a thermal conductivity of 0.035 W/m^{2}K. According to the simulation results, adding 50 mm of insulation to the external walls could reduce the annual cooling energy demand by 8%. The glazed area within the building envelope, specifically windows, is a primary source of heat loss and gain in the building. Therefore, altering the window glazing and features can assist in reducing building heat gain and enhancing overall energy efficiency. Since the current exterior windows consist of 3-mm single clear glass sheets, the second measure being investigated (ES-02) involves replacing the current glazing sheets with 6-mm single reflective clear glass sheets. These sheets have a shading coefficient of 0.202 W/m^{2}K and a visible light transmission of 0.14, which falls within the range specified by the Malaysian Standard (MS1525) for non-residential buildings. The findings indicate that the installation of single reflective glazing sheets can lead to an annual cooling energy reduction of 3%. To further enhance the thermal performance and minimize direct sunlight penetration into the interior of the building, a third measure (ES-03) investigated involves the use of window shading devices that can be easily integrated into the building architectural design. External louvre shading devices were applied separately on the north-eastern, north-west and south-western windows. The number of louvres was set to 10, with a vertical offset from the top of the window of 0.2 m. Each slat measured 0.20 m in depth and 0.30 m in width, sufficient to cover the window facade. The louvre angles were set at 20°, based on recommendations from previous studies conducted in similar climates and facade orientations [48, 49]. The analysis of the simulated results showed that the application of louvre shading devices resulted in annual cooling energy savings of 3%. However, it also led to a slight increase in annual lighting energy consumption by 1%, which can be attributed to a decrease in direct sunlight entering the building and an increased reliance on artificial lighting to achieve the required illumination levels for the occupants. High air leakage was identified as a significant issue in the building, so a fourth measure (ES-04) involving the installation of air barrier strips was proposed to minimize air leakage through doors and windows. This measure resulted in an 8% reduction in annual cooling energy demand.

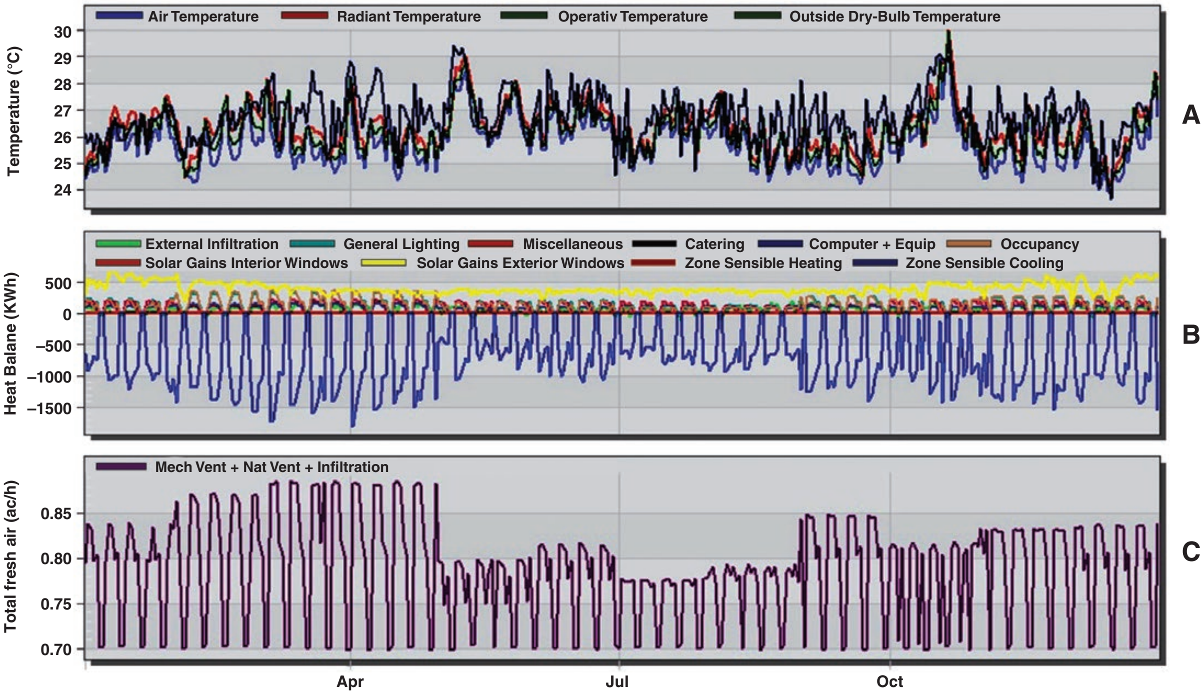

Fig. 11: Annual energy simulation results for temperatures (top), heat balance (middle) and total fresh air (bottom)

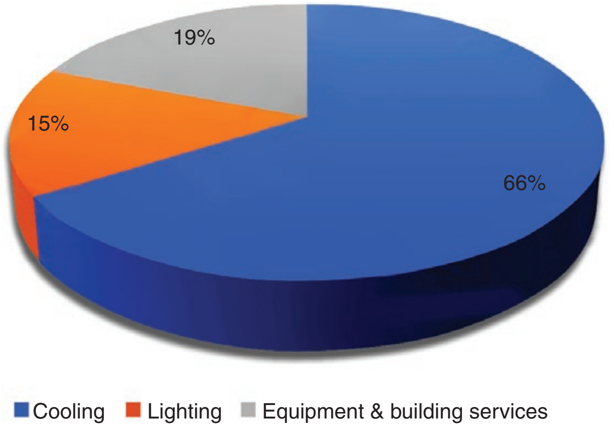

Fig. 12: Overall building energy consumption breakdown

2.2.2 *Potential energy savings from proposed ESMs of HVAC systems*

The HVAC system is the main contributor to the overall energy consumption of the building. However, in the current situation, the cooling control and management of the building are not considered. Currently, on average the cooling set-point temperature is 21°C at whole conditioned zones from 8 a.m. to 5 p.m. on working days.

The first measure proposed for the HVAC system (CS-01) deals with a simple and basic control strategy by setting the cooling set point to within the range of 23–26°C, which is recommended by MS1525. The new set-point temperature of 24°C was chosen based on previous studies on the thermal comfort of occupants in Malaysia [4]. Simulation results indicate that increasing the thermostat set point to 24°C with a setback point of 30°C during occupied hours can reduce cooling energy consumption by ~27% annually. For the second proposed measure (CS-02), a regular maintenance plan is suggested for the HVAC systems, including the detection of freon charge, cleaning of evaporator and condenser coils, and air filters. It is assumed that implementing this measure can save ≤10% of the cooling energy annually, according to laboratory investigations by Mowris *et al.* [50] and Zhuang and Wang [51].

2.2.3 *Potential energy savings from proposed ESMs of lighting systems*

Fluorescent lamps with power ratings of 36, 24 and 18 W are widely used in the E07 building. These lamps consist of a bulb and a ballast, which results in substantial electricity consumption. However, LED lights offer several advantages over current lighting solutions. They provide better light intensity while consuming less energy and have a longer lifespan. Additionally, LED lights do not contain mercury, which could harm the environment and occupants if improperly handled. On average, fluorescent tubes have a typical lifespan of ≤25 000 hours, while LED tubes can last for ≤50 000 hours. Table 10 compares the characteristics of the current and proposed lighting options.

The first proposed measure (LS-01) suggests replacing the current fluorescent lighting system with LED lights. Energy performance simulations were conducted to compare the two lighting systems. The results show that replacing fluorescent lights with efficient LED lights can reduce annual lighting energy consumption by 60% with a decrease in cooling energy consumption by 4%. For areas facing sunlight directions, where natural sunlight penetrates over a large area of the zone during working hours, installing daylight sensors can further save energy by reducing the reliance on artificial lighting. Daylight sensors can dim or switch electric lighting on/off based on daylight availability. Therefore, the second proposed measure (LS-02) explores the installation of separate controls for daylight sensors in areas near windows and glazed facades. The sensor set point for the building zones was based on the illuminance values recommended by MS1525, with the sensor placed 0.8 m above the floor. Based on the simulation results, installing

Table 9: Proposed energy-saving measures

Building system category	Designation	Proposed energy-saving measures
Building envelope system (ES)	ES-01	Insulation of the external walls and roof with a layer of insulation material
	ES-02	Replacement of existing glazing sheets for external windows with more efficient ones
	ES-03	Installation of shading devices for the north-eastern and south-western windows
	ES-04	Installation of air barrier strips to reduce air infiltration from doors and windows
Cooling system (CS)	CS-01	Variation of space cooling set-point temperature at the range recommended by MS1525
	CS-02	Implementation of a regular maintenance schedule for cooling systems
Lighting system (LS)	LS-01	Replacement of current lighting systems with more efficient ones
	LS-02	Installation of a separate control for lighting in areas near windows and glazed facades

Table 10: Comparison of the current and proposed lighting systems [46]

Description	Fluorescent (24 and 36 W)	PLC downlight (18 W)	LED tube (10 W)
Light output (lumens)	1300–2700	400	950
Correlated colour temperature (K)	4000–5000	3000	6500
Colour rendering index	65–80	65	≥80
Typical lifespan (h)	25 000	12 000	50 000

daylight sensors will reduce lighting energy consumption by ~26% and cooling energy consumption by 2%.

2.3 Annual reduction in overall building energy demand

Although all the ESMs investigated have the potential to reduce energy consumption for cooling and lighting compared with the base-case building, further investigation has been conducted to evaluate their impact on overall building energy demand. Fig. 13 shows the potential of the individual ESMs proposed on the overall energy demand. The proposed ESMs provide a noticeable change in overall building loads. Among the ESMs investigated to improve the thermal performance of building envelope elements, ES-01 shows a significant decrease in annual cooling loads due to reduced thermal and solar gains, resulting in an 8% reduction in annual cooling energy consumption. The overall decrease in annual building energy consumption compared with the base case is 5.35%. ES-02 and ES-03 provide minor effects on cooling energy demand by 3%, respectively, with a reduction in overall energy consumption of 2% for both. In contrast, applying ES-03 leads to an undesired increase in annual lighting energy consumption of 1%. However, the increase in lighting energy consumption can be explained by the decrease in direct sunlight passing through windows into the building zones, which led to an increase in the reliance on artificial lighting to achieve the required level of illumination for the occupants. Additionally, ES-04 contributes to the annual cooling energy demand with an 8% reduction and a 5% reduction in overall energy consumption compared with the base case.

A comparison between simulation results for the base case and investigated ESMs for cooling systems indicates a drastic decrease in cooling loads in the building. The implementation of CS-01 and CS-02 provides annual energy savings for cooling consumption by 27% and 10%, respectively, corresponding to an overall building energy demand decrease of 18% and 7%. For the ESMs investigated for the lighting system, LS-01 and LS-02 contribute to an annual lighting energy consumption reduction of 60% and 26%, respectively. Additionally, they reduce internal heat gain, resulting in a 4% and 2% decrease in cooling energy consumption. The total decrease in overall consumption compared with the base case is 13% and 5%, respectively. Replacement of window glazing sheets and the implementation of a window shading system is less effective than the other opaque envelope system measures, as each measure affects only ~2% of the overall energy demand. Based on the results presented above, the high ESOs of the building are attributed to the ESMs targeting the cooling and lighting systems compared with other measures applied to the envelope system; therefore, they are not effective if implemented individually. However, they will be reinvestigated based on economic indicators.

2.4 Estimated overall energy reduction

According to the measures implemented and outlined in the above sections, eight ESMs were suggested and implemented to improve overall building energy performance and reduce energy consumption. These ESMs showed a high potential for energy reduction, achieving annual energy reductions in the range of 2–18% for each measure, as demonstrated in Fig. 13. Therefore, all these ESMs were combined using a calibrated building model to evaluate their effectiveness when implemented simultaneously on the energy performance of the building. The cumulative impact of these measures was estimated to reduce annual energy consumption by 41%. This reduction is consistent with previous studies in similar climates [4, 32, 46], which have reported improvements in total yearly energy consumption of between 47% and 56% by implementing various ESMs, including those measures that have high investment costs. The energy performance of the proposed ESMs is summarized in Table 11 and a comparison of monthly energy consumption before and after implementing the combined ESMs is shown in Fig. 14.

According to the results, implementing the ESMs mentioned above led to significant energy savings, reducing annual building energy consumption from 359 034 to 211 206.8 kWh. Consequently, the building energy intensity (BEI) is reduced from ~248 to 147.7 kWh/m^2/year, which is nearly close to the maximum allowable BEI of 136 kWh/m^2/year recommended by

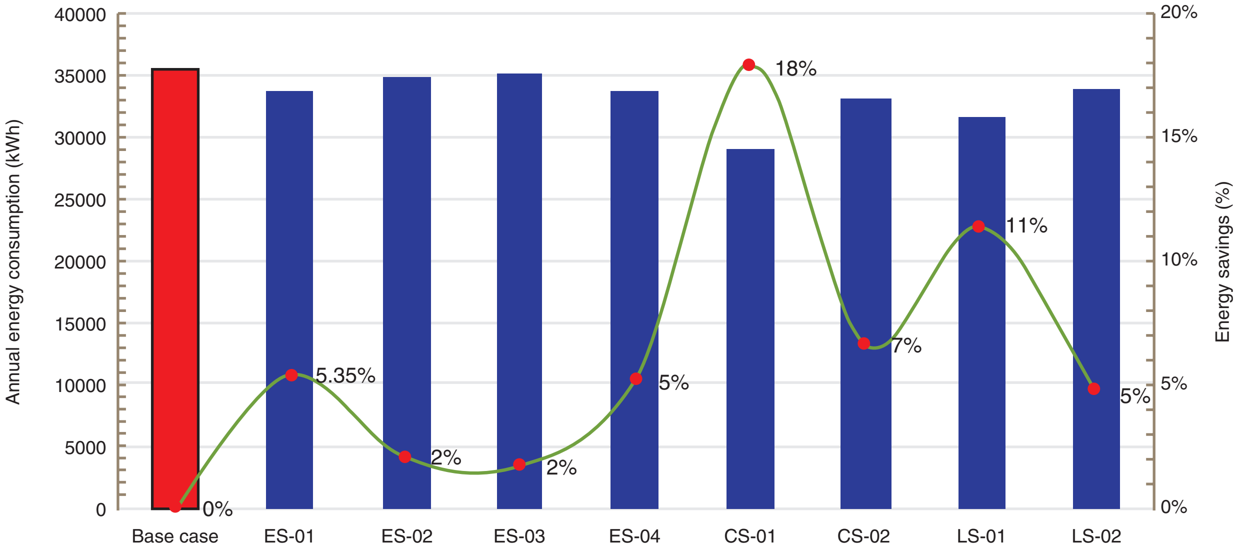

Fig. 13: Comparison of the overall energy reduction of the base case with the implementation of proposed ESMs

Table 11: Estimated energy performance for the proposed measures

Proposal measures	Total energy consumption (kWh)	Total cooling load (kWh)	Total lighting load (kWh)	Overall energy reduction (kWh)	Overall energy reduction (%)	Cooling load reduction (%)	Lighting load reduction (%)
Initial	359 034	235 838.8	51 795.1	n/a	n/a	n/a	n/a
ES-01	336 506.5	216 830.3	51 795.1	19 008.5	5.3	8	–
ES-02	348 231.6	228 555.4	51 795.1	7283.4	2	3	–
ES-03	349 506.7	229 416.4	51 954.6	6008.31	2	3	–1
ES-04	336 893.7	217 217.5	51 795.1	18 621.3	5	8	–
CS-01	291 829.7	172 153.6	51 795.1	63 685.2	18	27	–
CS-02	331 931.1	212 255	51 795.1	23 583.8	7	10	–
LS-01	314 958.2	226 398.3	20 678.9	40 302.1	11	4	60
LS-02	338 471	232 123.8	38 211.5	17 044	5	2	26
Combined	211 206.8	130 196.9	12 874.2	143 071.1	41	45	75

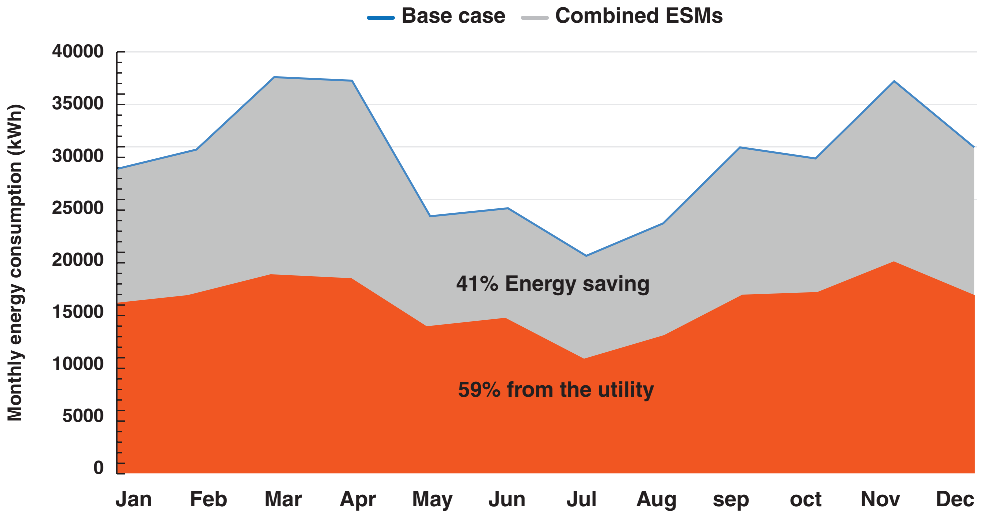

Fig. 14: The monthly energy demand of the combined ESMs model vs the base-case building

MS1525 standards for non-residential buildings. Therefore, it can be asserted that, regardless of the energy-saving tolerances of the investigated ESMs, they can be considered reasonable when combined to achieve overall building energy saving throughout the year.

2.5 Economic evaluation for the proposed ESMs

An economic analysis was conducted to assess the feasibility of implementing potential ESMs as well as the combined ESMs model. Investment costs were obtained through a survey of the Malaysian online market, while labour costs for material installation and maintenance were obtained from homewyse.com. However, note that these prices assume bulk purchases, making them more relevant for a potential government upgrade scheme rather than individual owners, who may incur higher costs.

Table 12 summarizes the SPP and NPV values of the implemented ESMs and the combined ESMs model. The NPV calculations for the investigated ESMs were based on a 30-year life cycle, including those with shorter life cycles such as ES-04, with a life cycle of ~5 years. In such cases, the reinvestment cost is factored in every 5-year cycle, with the cost occurring six times over the 30-year life cycle, which is the minimum life cycle for any ESM. This approach was also used to calculate the NPV values for other ESMs with a life cycle of <30 years.

The SPP range for the various ESMs varies, with the shortest payback period of 0.8 years for ES-04 (i.e. installation of air barrier strips to reduce air infiltration of doors and windows) and the longest payback period of 8.9 years for CS-02 (i.e. implementation of a regular maintenance schedule for cooling systems). All ESMs have a positive NPV value, which indicates that the investment is profitable. Therefore, the combination of ESMs is also economically viable, with a payback period of only 3.9 years. Additionally, it can reduce annual energy costs by 41.2%. Within this framework, it can be confidently stated that the results of the payback period for the implemented retrofit strategy implemented are encouraging and closely align with the findings of other similar studies [30, 32, 36, 52]. These studies indicate a range of payback periods spanning from 2 to 6.2 years, which vary depending on the specific measures implemented. Although certain improvements in energy efficiency may require costly interventions and longer payback periods, the trade-off becomes justifiable when considering the substantial energy savings achieved and the overall improvement in indoor environmental conditions [53].

3 Conclusion

Despite the detailed descriptions of energy audits provided by professional and governmental organizations, their comprehensive execution remains infrequent due to the complexity of the process and the scarcity of case studies and examples. This study aimed to address these challenges by conducting a holistic energy audit of a mixed-use educational facility, diagnosing energy performance deficiencies and proposing practical retrofit measures that can be easily implemented without altering the characteristics of the building or incurring high investment costs.

The energy audit approach implemented in this study consisted of four essential stages: pre-audit, energy audit, energy analysis and economic analysis. Throughout these stages, various ESMs were identified, including insulation of the roof and exterior wall, implementation of a window shading system, replacement of window glazing sheets, efficient lighting and daylight sensors, adjustments to the cooling set points, improvements to airtightness and regular maintenance schedules for cooling systems.

The proposed retrofit measures were evaluated based on their impact on energy consumption and investment/return analysis. A detailed and comprehensive energy model of the base-case building was created using the Design-Builder tool, incorporating dynamic energy performance and considering operational hours, actual utility data and real weather conditions. The results of the simulation and cost analysis demonstrated the significant potential of the proposed measures, with annual energy reductions ranging from 2% to 18% for each measure. Notably, the cooling and lighting systems presented the highest ESOs, with approximate reductions of 18% and 13%, respectively. Comparatively, the highest annual reduction in energy consumption achieved among envelope system measures was ~5% for envelope insulation and air infiltration reduction ESMs.

It is essential to consider the cost-effectiveness of measures within the calculation period and their payback periods. Some individual measures may not be cost-effective, emphasizing the importance of implementing them collectively. A simulation evaluating the cumulative impact of all ESMs simultaneously showcased the potential for significant energy and cost reductions, surpassing 41% for both. Furthermore, the implementation of the combined measures led to a reduction in BEI to 147.7 kWh/m^2, which is close to the maximum allowable of 136 kWh/m^2/year recommended by MS1525 standards for non-residential buildings. The return on investment for the ESMs ranged from 0.8 to 8.9 years, with a payback period of 3.9 years for the combined measures. Furthermore, the positive NPV indicated the economic feasibility of investing in the proposed ESMs.

These findings highlight valuable ESOs that can be used to enhance similar buildings within the university campus and beyond. By addressing energy efficiency deficiencies and implementing practical retrofit measures, buildings can achieve substantial energy reductions, improve economic indicators and contribute to a sustainable future. It is important to note that the effectiveness of the proposed ESMs should be considered in the context of the specific characteristics of the building, including its size, layout, occupancy patterns and HVAC system. Adjustments or modifications may be necessary when applying the results and recommendations to different types of buildings, emphasizing the need for tailored solutions based on individual building characteristics.

3.1 Limitations and future work

Despite the comprehensive analysis carried out in this study, there are certain limitations that must be acknowledged. In addition, future research should further enhance the understanding and applicability of the findings:

(i) Simulation and climate change: the simulation of the proposed ESMs was based on a trained EnergyPlus weather file (epw) that predicts weather data for only 1 year. However, considering the potential influence of climate change on future energy performance, it is important to investigate the effects of climate change on the building thermal load. Future research should incorporate climate change scenarios and long-term weather data to assess the robustness of the proposed ESMs under different climate conditions. This will provide valuable insights into the adaptability and resilience of the retrofit measures in the face of changing climatic conditions.

Table 12: Economic analysis of the ESMs implemented

	Initial cost	Annual energy and costs				Economic indices		
	Capital cost ($)	Electrical consumption (kWh)	Electrical cost ($)	Annual savings ($)	Energy cost savings (%)	SPP (years)	N (Years)	NPV ($)
Base case	0.0	359 034	36 262	n/a	n/a	n/a	n/a	n/a
ES-01	10 700	336 506.5	33 987	2275	6.2	4.7	30	12 672.5
ES-02	6576	348 231.6	35 171.4	1090.6	3	6	30	4628.4
ES-03	7242	349 506.7	35 300	962	2.6	7.5	30	2641.2
ES-04	1800	336 893.7	34 026.2	2235.8	6.1	0.8	5	21 168.3
CS-01	0.0	291 829.7	29 474.7	6787.3	18.7	0.0	n/a	69 726
CS-02	24 600	331 931.1	33 525	2737	7.4	8.9	1	28 092.6
LS-01	5940	314 958.2	31 810.7	4451.3	12.2	1.3	26	39 971
LS-02	1350	338 471	34 185.5	2076.5	5.7	0.6	15	19 981.8
Combined	58 208	211 206.8	21 331.8	14 930.2	41.2	3.9	Varies	95 179.7

(ii) Occupant behaviour and uncertainty analysis: occupant behaviour is a significant source of uncertainty in predicting building energy performance. The assumption of occupancy hours based on the results of the survey may not accurately reflect the actual patterns of building operation, leading to potential overestimation of energy savings of the investigated ESMs [54–56]. Furthermore, the lack of feasibility in incorporating occupancy detection sensors within building simulation software adds to this limitation. Future research should include an uncertainty analysis of changes in occupancy conditions to account for variations in occupancy patterns and their potential impact on energy savings. This will provide more accurate assessments of energy savings and improve the reliability of the results.

(iii) Economic evaluation and long-term energy costs: the economic evaluation of the ESMs showed a positive NPV using the current electricity tariff of commercial buildings in Malaysia. However, it is essential to consider the potential for future increases in energy costs. Future research should explore different scenarios of energy prices and conduct sensitivity analyses to assess the profitability and long-term financial viability of the proposed ESMs. This will provide valuable insights into the resilience of the retrofit measures and their ability to deliver sustainable economic benefits over an extended period.

(iv) Holistic evaluation: the study focused on the energy-saving potential and economic indicators of the proposed measures. To provide a more comprehensive evaluation, future work should consider other aspects such as occupant comfort, indoor air quality and environmental impacts. Incorporating these additional parameters will contribute to a more holistic assessment of the retrofit measures and enable decision-makers to prioritize strategies that optimize multiple objectives.

By addressing these aspects, future research will contribute to the advancement of energy retrofit strategies, ensuring their effectiveness, adaptability and long-term sustainability. The findings will guide stakeholders in making informed decisions, leading to improved building energy performance.

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Conflict of interest statement

There are no conflicts of interest.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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