Assessing Energy Efficiency in Conventional Office Buildings through Retrofitting Strategies

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Received: 11 December 2024 | Revised: 19 February 2025 and 18 March 2025 | Accepted: 22 March 2025

 DOI: https://doi.org/10.48084/etasr.9916

ABSTRACT

This study evaluates the energy efficiency of a conventional office building in Malaysia through the implementation of passive and active Energy Conservation Measures (ECMs). The retrofitting strategies included roof insulation, shading devices, HVAC optimization, and LED lighting upgrades, targeting key inefficiencies in the building's baseline energy performance. The energy modeling is performed with the eQUEST tool. Implementing ECMs demonstrated a 59.58% reduction in energy consumption contributing to reducing the annual usage from 292,330 kWh to 118,170 kWh, and additionally achieving CO_2 emission reductions of 132,013.28 kg. The payback period of 3.65 years highlights the economic feasibility of these measures. The annual cost savings reached MYR 88,647.44. The findings emphasize the importance of integrating passive and active strategies to optimize energy performance, reduce environmental impact, and enhance sustainability in office buildings.

Keywords-energy conservation measures; equest; energy efficiency; passive and active strategies; CO_2 emission reduction; sustainable buildings

I. INTRODUCTION

To combat climate change and resource depletion, energy efficiency in office buildings is considered a priority. This is especially critical in tropical climates, where energy demand for cooling systems dominates operational costs and environmental impacts [1]. Buildings in such regions experience significantly higher energy consumption due to the persistent high temperatures, humidity, and solar radiation effects [2]. These climatic conditions necessitate energy-intensive cooling and lighting systems which often account for up to 60% of the total energy use in commercial buildings [3]. This reliance highlights the need to implement targeted solutions and enhance energy performance while reducing operational costs and environmental impacts [4].

ECMs offer a pathway to improve energy efficiency in tropical office buildings [5]. These measures include both passive and active strategies [6]. Passive retrofitting focuses on reducing energy demand by enhancing the building envelope and leveraging natural resources, such as insulation, shading, or high-performance glazing [7]. On the other hand, active retrofitting involves upgrading mechanical and electrical systems to improve efficiency, such as high-efficiency HVAC systems, LED lighting, and smart energy management technologies [2]. The combination of these strategies is particularly effective in tropical climates.

Studies have demonstrated that integrating passive design elements can significantly reduce the cooling energy demand in tropical climates [8]. Authors in [3] highlight that increasing the indoor temperature setpoint to 26 °C can reduce cooling energy consumption by up to 36% while maintaining occupant thermal comfort. Similarly, adopting active measures has proven to be effective. For example, transitioning from fluorescent lighting to LED systems results in lighting energy reductions exceeding 50% and secondary cooling load savings due to lower heat generation [9]. The adoption of ECMs in tropical office buildings remains uneven. Several stakeholders prioritize initial cost savings over long-term benefits, limiting the implementation of advanced technologies and integrated strategies. Case studies have shown that retrofitting building envelopes with improved glazing, insulation, and shading devices can achieve up to a 26.8% reduction in total energy use [10].

Financial and regulatory barriers coupled with a lack of awareness prevent the adoption of such measures. An integrated approach to ECM implementation, combining passive and active strategies to maximize energy savings and cost-effectiveness, is necessary. While previous studies have extensively analyzed individual active or passive retrofitting strategies, few of them have investigated the combined impact of these approaches in tropical office buildings. Moreover, existing research often lacks a comprehensive Techno-Economic Analysis (TEA) that evaluates both energy performance and cost-effectiveness under varying inflationary conditions. The present study addresses these research gaps by integrating passive and active retrofitting strategies into a holistic framework, using advanced energy modeling with eQUEST. It also provides valuable insights into tropical climates, where cooling energy demand dominates operational costs, highlighting the economic feasibility and environmental benefits of the proposed measures. The knowledge gap is especially pertinent in Malaysia, where office buildings face significant challenges, including outdated infrastructure and rising energy costs. Addressing these challenges requires a comprehensive evaluation framework that considers energy performance, CO_2 emission reductions, and the economic feasibility of ECMs.

II. METHODOLOGY

This study aims to implement ECMs and assess their impact on energy savings. In addition, it evaluates CO_2 emissions and analyzes the reductions achieved through the implementation of ECMs. Finally, it performs a comprehensive TEA of energy efficiency measures, focusing on their feasibility and cost-effectiveness.

More specifically, the current work employs the eQUEST simulation tool to assess the impact of retrofit and design modifications on building energy performance. The energy model is validated using actual energy bills. The research focuses on two-story conventional office building located in Subang Jaya, Malaysia. Its geographical coordinates are 3.0567 °N and 101.5851 °E. This building has a total area of 1,143.75 m² and a wall area of 913.39 m². The operational hours are from 8:00 AM to 5:00 PM daily. A comparative analysis is performed to evaluate the effect of retrofits on energy efficiency and compliance with industry standards.

A. Data Collection

The data were collected through facility assessments, architectural drawings, and operational records. Building envelope information, including insulation, lighting, glazing, and HVAC systems, was obtained from the facility management. Energy consumption patterns were analyzed using 12 month data from utility bills, serving as a baseline for model calibration. Additionally, interviews with the building personnel provide insights into occupancy schedules and operational settings. Table I presents the baseline parameters of the building.

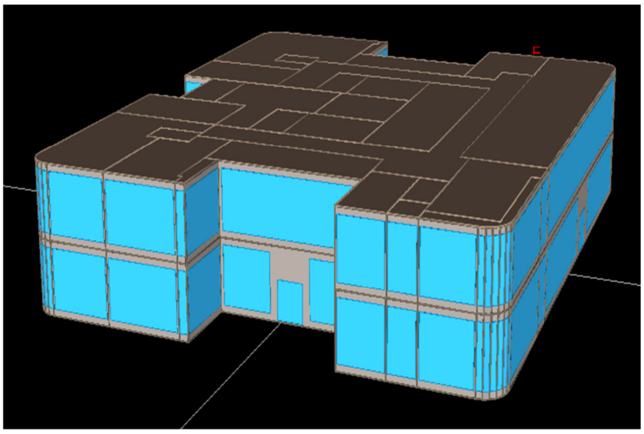

Fig. 1. 3D model representation of conventional office building in eQuest.

TABLE I. CONVENTIONAL OFFICE BUILDING BASELINE PARAMETERS

SN	Block	Description	Baseline value
1	HVAC	EER	9
2		Overall efficiency of supply fan and motor	53%
3		Supply fan static pressure	0.739 kPa
4	Building envelope	Roof	8.99 W/m²K
5		Walls	9.72 W/m²K
6		Infiltration	1.2 ACH (not airtight)
7		U-Value	2.27 W/m²K
8	Windows and doors	Glazing type	Single glazed 1/8"
9		SHGC	0.62
10		Overhangs	None
11		Fins	None
12	Lighting	Lighting Power Density (LPD)	10.76 W/m²
13		Daylight control	None
14	Thermostat setpoint	Cooling setpoint	24.5 °C
15	Climatic conditions	Dry bulb temperature	As per weather data
16	Energy performance	Building Energy Intensity (BEI)	255.7 kWh/m²/year
17	Energy performance	Cooling load intensity	20.44 W/m²
18	Environmental impact	CO_2 emissions	221,586 kg/year

The collected data are fed into the eQUEST simulation tool, and are processed generating yearly energy performance reports. The building is divided into thermal zones based on usage, and HVAC systems are modeled accordingly. Lighting, fan loads and other installed equipment are also recorded through an energy audit and incorporated into the model. The final simulation results are then compared with measured energy consumption values for validation and improvement purposes. Figure 1 presents the generated 3D building model after processing in eQUEST.

B. *Standard Testing and Compliance*

The study follows MS 1525:2019, Malaysia's energy efficiency standard for non-residential buildings, which provides guidelines on thermal performance, HVAC efficiency, LPD, and renewable energy integration suited to the tropical climate. The standard sets a BEI benchmark of smaller or equal to 135 kWh/m²/year for compliance.

C. *Validation*

To ensure the reliability of the simulation tool in predicting energy consumption, its results are validated against real-world data. This process assesses the accuracy and confidence of the model's predictive capability. Following ASHRAE Guideline 20 (2022), the accuracy is evaluated using Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CVRMSE). These metrics quantify the deviation between simulated and actual data. The formulas for these metrics are:

$$\text{MBE} = \frac{\sum_{Period}(S-A)_{interval}}{\sum_{Period} A_{interval}} x\ 100 \qquad (1)$$

$$\text{CVRMSE} = \sqrt{\frac{\frac{1}{N}\sum_{Period}(S-A)^2_{interval}}{\frac{1}{N}\sum_{Period} A_{interval}}}\ x\ 100 \qquad (2)$$

where S is the simulated energy consumption per month, A are the actual measured data per month, and N is the total number of months. An MBE within ±5% and CVRMSE below 15% indicate acceptable accuracy per ASHRAE standards.

D. *Proposed Energy Conservation Measures*

To enhance energy efficiency, ECMs in compliance with MS 1525:2019 are utilized along with passive and active strategies. Passive measures improve the building envelope by upgrading roof insulation, replacing single-glazed windows with double reflective A-M tint glass, reducing air infiltration to 0.3 ACH, and installing shading devices to minimize solar heat gain. On the other hand, active measures optimize operational systems by replacing the HVAC system with DC Inverter AC units for better cooling efficiency and upgrading to LED lighting to reduce electricity consumption. These ECMs are integrated into the proposed energy model. Table II summarizes the improvements in thermal resistance, air infiltration, and overall system performance.

TABLE II. PROPOSED ENERGY CONSERVATION MEASURES

ECM type	Measure	Baseline condition	Proposed
Passive	Roof insulation	U-value: 8.99 W/m²K	U-value: 0.35 W/m²K
	Glazing	6 W/m²K; SHGC: 0.62	2.5 W/m²K; SHGC: 0.38
	Infiltration	1.2 ACH	0.3 ACH
	Shading	No shading	0.91 m overhang, 0.61 m fins
Active	HVAC optimization	COP: 2.8; Standard motor	COP: 3.5; Premium motor
	Lighting upgrade	LPD: 10.76 W/m²	LPD: 3.23 W/m²

III. RESULTS AND DISCUSSION

A. *Validation of Baseline eQUEST Model*

The baseline eQUEST model is validated to ensure its accuracy in representing the building's energy performance under real-world conditions. This validation process compared simulated energy consumption data with actual utility bill records following the standards of ASHRAE Guideline 20 (2022). The validated model established a strong foundation for evaluating the effectiveness of the proposed ECMs. A year-long simulation is performed using eQUEST to estimate monthly energy consumption. Any deviations of the simulated results are corrected by refining critical parameters, such as operational schedules and building envelope characteristics.

The model predicted energy usage by dividing consumption into the following components: (a) Space Cooling (SP), (b) Ventilation Fans (VFs), (c) Pumps and Auxiliary Systems (PAS), (d) Miscellaneous Equipment (ME), and (e) Area Lights (AL). The close alignment, as shown in Figure 2, between actual bill data and eQUEST simulation results demonstrates the accuracy of the eQUEST model, establishing it as a reliable baseline for assessing the impact of the proposed ECMs. The model achieved an NMBE of 4.58% and a CVRMSE of 11.28%, both within the acceptable thresholds outlined in Table III. These metrics confirm the reliability of the eQUEST model in predicting the building's energy performance, making it a valid baseline for further analysis.

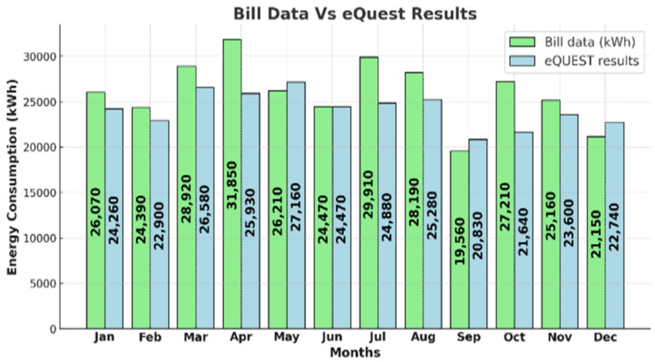

Fig. 2. Energy consumption per month of actual bills (green bar) against eQuest results (blue bars).

TABLE III. CALIBRATION CRITERIA OF THE ASHRAE GUIDELINE 20

Calibration metric	ASHRAE guideline 20	Model result
Monthly NMBE	±5%	4.58%
Monthly CVRMSE	15%	11.28%

Figure 2 compares the monthly energy consumption from utility bills with the eQUEST simulation results. Table IV presents the total annual energy consumption of 292,310 kWh and its monthly breakdown by end-use.

TABLE IV. MONTHLY ENERGY CONSUMPTION OF BASELINE MODEL

Month	SP	VFs	PAS	ME	AL	Total
Jan.	13.04	1.68	0.69	3.23	5.82	24.45
Feb.	12.41	1.65	0.62	2.92	5.26	22.87
Mar.	13.61	1.81	0.69	3.23	5.82	25.14
Apr.	14.96	1.91	0.72	3.34	6.07	27.00
May	14.08	1.78	0.69	3.22	5.82	25.59
June	13.48	1.63	0.69	3.21	5.81	24.81
July	13.44	1.65	0.72	3.35	6.08	25.25
Aug.	12.2	1.38	0.69	3.22	5.82	23.31
Sep.	11.74	1.29	0.69	3.21	5.81	22.73
Oct.	13.27	1.62	0.72	3.35	6.08	25.04
Nov.	11.56	1.46	0.59	2.82	5.02	21.45
Dec.	12.93	1.6	0.72	3.35	6.08	24.69
Total	156.73	19.46	8.22	38.46	69.47	292.34

B. *Passive and Active ECMs Implementation*

The implementation of passive and active ECMs significantly improved building energy performance. The BEI is reduced from 255.7 kWh/m²/year to 103.4 kWh/m²/year. Before ECM implementation, the total annual energy consumption was 292,330 kWh, while after the implementation it is reduced to 118,170 kWh, achieving total energy savings of 174,160 kWh or 59.58%. The passive strategies contributed to energy savings, with roof insulation saving 4,550 kWh, infiltration rate reduction saving 15,577 kWh, and shading improvements saving 17,620 kWh. The active strategies, including DC Inverter AC units, reduced cooling energy use by 47,150 kWh. An LED lighting upgrade saved 66,170 kWh.

Cooling loads are significantly reduced, from 20.44 W/m² to 8.26 W/m², achieving a 59.58% reduction. Figure 3 depicts the monthly energy savings, highlighting the substantial reductions achieved each month.

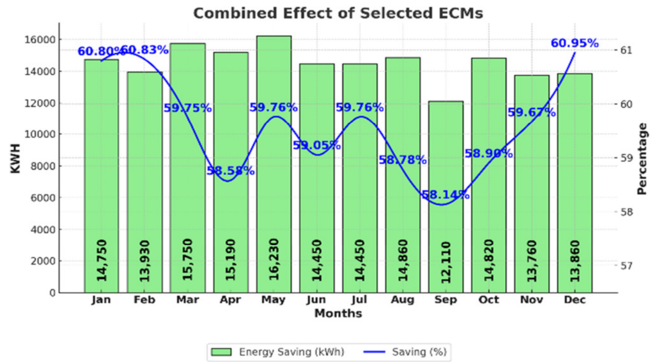

Fig. 3. Energy consumption and percentage savings per month.

TABLE V. MONTHLY ENERGY CONSUMPTION AFTER IMPLEMENTATION OF ECMS

Month	SP	VFs	PAS	ME	AL	Total
Jan.	4.33	0.42	0.26	3.3	1.27	9.51
Feb.	4.23	0.44	0.24	2.9	1.15	6.97
Mar.	5.1	0.55	0.28	3.5	1.3	10.61
Apr.	5.39	0.61	0.26	3.1	1.27	10.74
May	5.4	0.57	0.26	3.5	1.3	10.93
Jun.	4.82	0.46	0.26	3.2	1.29	10.02
July	4.52	0.44	0.29	3.3	1.19	9.73
Aug.	4.82	0.44	0.24	3.4	1.15	10.42
Sep.	4.00	0.37	0.28	2.95	1.33	8.72
Oct.	4.87	0.51	0.25	3.5	1.21	10.4
Nov.	4.34	0.42	0.26	3.00	1.21	9.3
Dec.	3.95	0.36	0.35	3.1	1.21	8.68
Total	55.73	5.04	3.14	38.46	15.19	118.17

This study surpasses the results from previous studies conducted in tropical climates, reinforcing the benefits of an integrated retrofitting approach. Authors in [8] reported 40.2% savings using passive strategies, like enhanced glazing and insulation, but lacked active interventions, such as HVAC optimization and LED lighting, which significantly contributed to this study's results. In [5], 47% energy savings were presented, by combining passive measures with HVAC upgrades. However, the study did not include infiltration control and advanced cooling load optimizations, which were key in the present research. Similarly, in [7], 47% reductions were reported in government office buildings but did not assess detailed infiltration rate reductions or high-efficiency HVAC integration.

C. *Cost Savings*

The implementation of selected passive and active ECMs resulted in significant monthly cost savings, ranging from MYR 6,163.99 or € 1,269.78 in September to MYR 8,261.07

or € 1,701.78 in May, as presented in Figure 4. These measures contributed to total annual savings of MYR 88,647.44 or € 18,261.37, highlighting the financial benefits of sustainable building practices. The combination of ECMs not only reduced costs, but also supported environmental sustainability by minimizing energy demand.

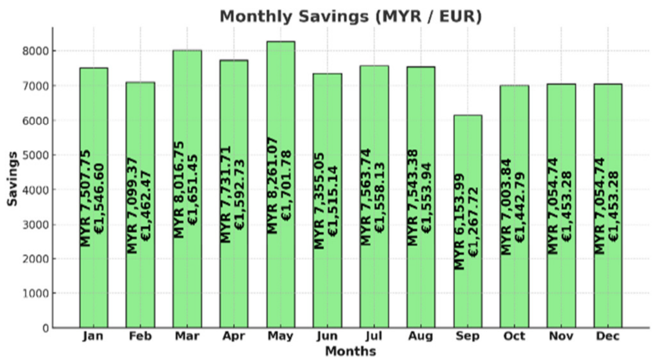

Fig. 4. Monthly cost savings in MYR and EUR.

IV. TECHNO-ECONOMIC ANALYSIS OF ECMS

TEA evaluates the economic feasibility of a project by integrating technical performance data with financial metrics. For ECMs, TEA assesses implementation costs and expected benefits to determine financial viability. This study focuses on three components: initial incremental costs, projected annual energy savings, and the payback period, providing a framework for informed decision-making and cost-effective energy solutions.

A. Key Measures and Initial Incremental Costs

The initial incremental costs of ECMs represent the upfront financial investment required for implementation. These costs were calculated using current market rates, with unit costs for materials, equipment, and services multiplied by physical parameters, such as area, weight, or quantity. For instance, roof insulation costs are determined by multiplying the total roof area (1,055 m²) by the market price of polyisocyanurate insulation (MYR 31.87/m² or € 6.57/m²). Key ECMs and detailed breakdowns are presented in Table VI. These measures are selected for their potential to optimize energy efficiency and reduce operational costs. Among the ECMs, double glazing had the highest investment cost, amounting to MYR 124,596.10 or €25,666.80, which accounted for 37% of the total initial costs. The total initial cost for all ECMs was calculated as MYR 334,765.09 or €68,961.61.

B. Payback Period

The payback period evaluates the time required to recover the initial investment of MYR 334,765 or €68,973.22 through annual energy savings of MYR 88,647 or €18,261.37. Historical inflation rates in Malaysia, reported by the Department of Statistics Malaysia (DOSM), averaged 1.56% between 2019 and 2023, with rates ranging from -1.2% to 3.3% [11]. Projections by International Monetary Fund (IMF) indicate that inflation will have stabilized between 2.5% and 2.7% up to 2028, reflecting anticipated moderate economic conditions [12]. Three scenarios are analyzed: the optimistic scenario assumes an inflation rate of 2.5%, reflecting stable economic conditions as projected by the IMF; the base scenario uses a rate of 1.56%, derived from historical averages provided by DOSM; and the pessimistic scenario incorporates an inflation rate of 2.7%, representing the highest IMF-projected rate for 2024. The simple payback period ranged between 3.55 and 3.75 years, while the discounted payback period extended to between 3.65 and 4.03 years. Table 1 summarizes these results.

TABLE VI. KEY MEASURES AND INITIAL INCREMENTAL COSTS

Measure	Details	Cost calculation	Total cost
Roof Insulation	50.8 mm polyisocyanurate (1,055 m²)	1,055 m² × MYR 31.87/m² / €6.57/m²	MYR 33,588.55 / €6,919.24
Building sealing	Silicon sealants for windows (33 tubes)	33 tubes × MYR 9.09/tube / €1.87/tube	MYR 300.00 / €61.80
Double glazing	Reflective glass (913.39 m²)	913.39 m² × MYR 136.45/m² / €28.11/m²	MYR 124,596.10 / €25,666.80
HVAC units	DC inverter (42 units)		MYR 81,381.82 / €16,764.65
	- 1.5 Ton (12 units)	12 × MYR 2,581.82/unit / €531.85/unit	MYR 30,981.82 / €6,382.25
	- 1.0 Ton (12 units)	12 × MYR 1,745.45/unit / €359.56/unit	MYR 20,945.45 / €4,313.76
	- 0.5 Ton (18 units)	18 × MYR 1,636.36/unit / €337.09/unit	MYR 29,454.55 / €6,067.63
Shades and Blinds	Roller shades (913.39 m²)	913.39 m² × MYR 13.67/m² / €2.82/m²	MYR 12,459.61 / €2,566.69
	Bracketed shades (280.81 m²)	280.81 m² × MYR 31.87/m² / €6.57/m²	MYR 8,940.13 / €1,841.68
	Fin shades (6,243.9 kg)	6,243.9 kg × MYR 11.36/kg / €2.34/kg	MYR 70,953.44 / €14,622.51
LED Lighting	Energy-efficient LEDs (400 lamps)	400 lamps × MYR 6.36/lamp / €1.31/lamp	MYR 2,545.45 / €524.36
Total			MYR 334,765.09 / €68,973.22

C. CO_2 Emission Savings

The implementation of ECMs led to significant CO_2 emission reductions in Peninsular Malaysia, calculated using the emission factor of 0.758 kg CO_2 per kWh. The annual CO_2 emissions decreased from 221,586.14 kg in the base case to 89,572.86 kg in the proposed case, resulting in savings of 132,013.28 kg. Among the ECMs, energy-efficient LED lighting achieved the greatest CO_2 reduction, decreasing emissions by 49,145.31 kg annually. In addition, LED lighting delivered the highest energy savings at 66,170 kWh. These results highlight the environmental benefits of the selected ECMs, which effectively reduce the building's carbon footprint while supporting sustainability targets. Table VIII summarizes the CO_2 emissions for both scenarios

TABLE VII. PAYBACK PERIOD ANALYSIS

Year	Cash flow (MYR / EUR)	Net cash flow (MYR / EUR)	Discounted cash flow (optimistic) (MYR / EUR)	Discounted cash flow (base) (MYR / EUR)	Discounted cash flow (pessimistic) (MYR / EUR)
0	MYR -334,765.00 / €-68,961.59	MYR -334,765.00 / €-68,961.59	MYR -334,765.00 / €-68,961.59	MYR -334,765.00 / €-68,961.59	MYR -334,765.00 / €-68,961.59
1	MYR 90,870.00 / €18,719.22	MYR -243,895.00 / €-50,242.37	MYR 89,250.00 / €18,385.50	MYR 88,647.00 / €18,261.28	MYR 87,560.00 / €18,037.36
2	MYR 93,135.00 / €19,185.81	MYR -150,760.00 / €-31,056.56	MYR 88,480.00 / €18,226.88	MYR 87,253.00 / €17,974.12	MYR 85,365.00 / €17,585.19
3	MYR 95,463.00 / €19,665.38	MYR -55,297.00 / €-11,391.18	MYR 87,715.00 / €18,069.29	MYR 85,860.00 / €17,687.16	MYR 83,185.00 / €17,136.11
4	MYR 97,855.00 / €20,158.13	MYR 42,558.00 / €8,766.95	MYR 86,950.00 / €17,911.70	MYR 84,467.00 / €17,400.20	MYR 81,020.00 / €16,690.12

TABLE VIII. MONTHLY CO_2 EMISSIONS AND SAVINGS

Month	Base case CO_2 emissions (kg)	Best case CO_2 emissions (kg)	CO_2 savings (kg)
Jan	18,389.08	7,216.58	11,172.50
Feb	17,358.20	6,798.66	10,559.54
Mar	19,980.88	8,042.38	11,938.50
Apr	19,654.94	8,141.92	11,513.02
May	20,587.28	8,285.94	12,301.34
Jun	18,548.26	7,605.16	10,943.10
Jul	18,328.44	7,375.34	10,953.10
Aug	19,162.24	7,898.36	11,263.88
Sep	15,789.14	6,611.76	9,177.38
Oct	19,071.28	7,837.32	11,233.96
Nov	17,479.48	7,055.40	10,424.08
Dec	17,236.92	6,726.64	10,510.28
Total	**221,586.14**	**89,572.86**	**132,013.28**

V. CONCLUSION

This study highlights the critical role of retrofitting strategies in enhancing energy efficiency and reducing environmental impacts in conventional office buildings. The study implemented selected Energy Conservation Measures (ECMs), including roof insulation, shading devices, HVAC optimization, and LED lighting. The implementation of these measured led to energy consumption reduction by 59.58% with substantial financial savings of MYR 88,647.44/ / € 18,261.37 annually. These measures not only improve operational efficiency, but also align with sustainability goals by significantly lowering CO_2 emissions. The payback period of 3.65 years demonstrates the economic feasibility of these retrofitting strategies, offering long-term benefits in terms of energy savings and reduced operational costs.

This study provides a novel contribution by integrating both passive and active ECMs into a comprehensive techno-economic framework specifically for tropical office buildings. In contrast to previous research that solely focuses on either passive or active retrofitting strategies, this work emphasizes their combined effect, offering a holistic and optimized approach to energy efficiency. Moreover, the validation of the modeled results through real world data along with financial analysis enhances the practical applicability of the findings. This research provides a practical framework for improving energy performance in office buildings and contributes to advancing sustainable building practices.

ACKNOWLEDGMENT

The research was supported by the Ministry of Higher Education (MoHE), through the Fundamental Research Grant Scheme (FRGS/1/2021/TK0/UTAR/02/34).

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