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Article

Accelerating Decarbonization in Public Institutions: A Scalable Model for LED Lighting Retrofits

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Abstract: Public and educational institutions represent a significant share of global electricity consumption and play a critical role in achieving national decarbonization targets. This study addresses this challenge by conducting a comprehensive lighting retrofit assessment for a university engineering building in Malaysia, with the objective of evaluating the energy, economic and environmental impact of replacing conventional fluorescent lighting with light-emitting diode (LED) technology. A methodology was adopted, comprising a detailed on-site lighting audit, development of LED replacement scenarios, energy consumption modelling based on operating profiles, life-cycle cost (LCC) and payback period analyses, emission reduction assessment using national grid emission factors and sensitivity analysis to test economic robustness under varying assumptions. A total of 1831 luminaires were audited, establishing a baseline annual lighting consumption of 158,410 kWh. Retrofit simulations indicate that replacing existing fluorescent and CFL lamps with LED alternatives reduces daily lighting energy use from 434 kWh to 240 kWh, corresponding to annual energy savings of 70,810 kWh or 44.7%. Financial analysis demonstrates strong economic viability, with payback periods of 2.21 years (20W_LED), 2.14 years (10W_LED) and 1.90 years (9W_LED). Over a 10-year assessment horizon, cumulative cost savings exceed RN225000, driven by reduced electricity consumption and lower maintenance requirements resulting from LED lifespans of up to 50,000 h. Environmentally, the retrofit yields cumulative emission reductions of approximately 130,285 kg CO_2, 408 kg SO_2, 275 kg NO_x and 106 kg CO over 10 years, supporting national objectives to reduce greenhouse gas intensity and improve urban air quality. Overall, the study provides a structured, scalable and evidence-based framework for LED lighting retrofits in educational buildings, demonstrating that lighting upgrades can deliver rapid economic returns while contributing meaningfully to long term decarbonization goals

Keywords: lighting retrofit; energy efficiency; cost-benefit analysis; emission reduction; life cycle cost

1. Introduction

In recent years, rapid urbanization and population growth across many countries have significantly increased energy consumption, particularly in electricity demand [1]. As sustainable and green energy production becomes a global priority, greenhouse gas emissions are increasingly used as a benchmark for sustainable development models. Carbon dioxide, among other gases, poses severe environmental challenges. Consequently, energy conservation and emission reduction have become critical priorities in all development strategies [2]. Previous studies have shown that buildings are among the largest contributors to global energy consumptions, accounting for approximately 40% [3]. Within this sector, lighting alone represents about 20% of total building energy use [4]. Therefore, improving the efficiency of lighting system is essential to achieve significant energy savings, which is turn provides both environmental and economic benefits.

As mentioned that lighting has significant contribution in energy consumption in the energy building which account for 20 to 40% in total, it is wise to induce proper designed light source as well the controlling system to reduce unnecessary wastage [5]. The National Electrical Manufacturers Association (NEMA) has argued that lighting controls offer greater potential for energy savings in critical applications than improvements in source efficiency. Although Malaysia does not formally adopt NEMA regulations, the manufacture of electrical appliances in Malaysia is governed by Malaysian Standards (MS), which are largely based on International Electrotechnical Commission (IEC) standards and designated as MS IEC. These standards may contain technical overlaps or reference equivalencies with NEMA requirements [6]. Despite this, lighting controls are not included in federal energy efficiency standards and are only partially addressed through state and local building codes. For over three decades, researchers have examined the energy saving potential of lighting controls in commercial buildings, however, comprehensive assessment of these studies remains lacking. The effectiveness of lighting controls depends on numerous factors, including application type, site orientation, occupancy patterns, architectural design, surface reflectance, user behaviour and system configuration during installation and commissioning [7,8]. These variables complicate predictions of cost savings and make it challenging to generalize the overall impact of lighting control technologies, as individual studies differ widely in the objectives, methodologies, scope and outcomes.

Several studies have investigated the impact of lighting control systems on energy savings, though the scope and methods vary considerably. For example, some research, such as that conducted under the U.S. Environmental Protection Agency program, has relied on monitoring existing data from multiple buildings [9]. In contrast, studies by the National Research Council of Canada and the Florida Solar Center were limited to one or two laboratory tests or controlled experiments [10]. Nevertheless, the insights gained from individual investigations on lighting control remain valuable. Roisin, Bodart [11] evaluated the energy saving potential of various lighting control systems in office environments. Their findings showed that dimming laps based on available daylight could achieve savings of 45 to 61%, with additional reductions possible through sensor-based controls. Fernandes, Lee [12] monitored the actual performance of lighting systems at the New York Times headquarters, reporting that dimming controls reduced energy consumption by 20% compared to code requirements. Xu, Pan [13] investigated the energy performance and control strategies of different lighting systems in open-plan offices, including daylight dimming and occupancy-based on and off control. Using an online monitoring and data acquisition system, they tested various strategies and compared their performance against a benchmark office. Their analysis highlighted the potential of integrated strategies, particularly those combining background dimming with task lighting to maximize energy savings.

Nevertheless, implementing complex control systems such as Building Management System often requires operators with advanced engineering knowledge, along with substantial capital investment [14]. As a result, relying on control systems as the primary driver for energy savings can be challenging and, in some cases, impractical for small-scale companies or buildings. In such contexts, lighting replacement or retrofit schemes provide a more practical and cost-effective solution [15]. Lighting systems have undergone significant technological evolution, with the choice of lamp typically depending on task requirements and lamp characteristics [5,16]. Traditional incandescent bulbs, once the dominant technology, are now largely phased out due to their low efficiency and short, lifespan, with nearly 90% of the energy dissipated as heat rather than light [17]. Compat Fluorescent Lamps (CFLs) emerged as a more efficient alternative, offering substantial energy saving and contributing to reduced national peak power demand [18]. However, CFLs present drawbacks such as harmonic distortion, elevated operating temperatures and mercury content that raises environmental concerns [16,19].

In addition to energy performance, human comfort is a critical consideration in lighting design. Without adequate visual comfort, lighting retrofit efforts become unjustifiable. Lighting design encompasses factors such as luminaire placement, illuminance level and correlated colour temperature, all of which vary according to building function and occupancy patterns. Zamarreño-Suárez, Alcala-Gonzalez [20] investigated a lighting retrofit across a university campus, emphasizing balanced luminance distribution within occupied activity spaces. In compliance with national standards, the LED illuminance level was maintained at 500 lux. Similarly, Guevarra, Fernandez [21] demonstrated that the use of higher wattage luminaires can reduce the total number of fixtures while maintaining illuminance levels within the recommended range of 300 to 750 lux. Hegde, Tyne [22] further highlighted the role of educators in influencing lighting demand in university settings, as teaching schedules directly govern student activities and space utilization. The authors study targeted lighting retrofits that comply with illuminance levels of 400 lux and above, alongside circadian performance criteria defined by the WELL Standard and the Circadian Stimulus metric. Nevertheless, both educational and commercial buildings commonly adhere to established interior lighting standards, such as the European Standards and the ISO, which typically recommend illuminance levels of approximately 500 lux for general indoor environments [23].

Light Emitting Diodes (LEDs) represent the current benchmark for efficient lighting, providing high luminous efficacy, long lifespans and reduced environmental impact [24–26]. Although initial costs remain higher than conventional lamps, studies show that retrofitting fluorescent tubes with LEDs yields substantial long-term savings and sustainability benefits [27,28]. Nevertheless, issues such as inconsistent colour quality and performance variability across LED products have been noted [29]. Retrofit approaches for improving lighting efficiency can be categorized into 3 main strategies, where firstly replacing electromagnetic ballasts with electronic ballasts, secondly reducing wattage by substituting older bulbs with new-generation lamps and thirdly upgrading systems with adaptive lamp adapters to accommodate energy saving bulbs [5]. These retrofit options, along with optimized lighting control strategies, form the core methods for achieving building lighting energy optimization. Dunn, Oyegoke [30] provided valuable insights into power consumption related issues, encompassing both human factors and technical availability. However, their study did not report detailed technical specifications of the LED systems or corresponding lumen performance results. Furthermore, retrofit analyses are often conducted at the residential scale, where uncertainties in lumen performance may be exacerbated when extrapolated to commercial scale applications [31,32]. In summary, the transition from incandescent to CFL and LED technologies reflects a clear trajectory toward higher efficiency and sustainability. While LEDs offer the most promising long-term solution, the success of any retrofit initiative depends on balancing economic, technical and environmental considerations [33].

This study investigates the energy saving potential of building lighting systems at the University of Malaya, using an administrative building as the primary case study. The novelty of this work lies in the development of a systematic and replicable LED retrofit workflow, encompassing baseline assessment, luminaire selection, performance evaluation, and post-retrofit impact analysis. The proposed framework is applied to design an optimized retrofit strategy and to quantify its effectiveness in terms of energy savings, payback period and environmental benefits. In addition, the sensitivity analysis of the workflow is assessed to ensure its applicability and plausibility for broader future implementations.

2. Materials and Methods

The case study adopts a systematic assessment framework comprising building lighting auditing, LED replacement recommendation and post-retrofit energy evaluation including energy rate and environmental impact factor. Baseline lighting energy consumption is first established through an on-site audit. Appropriate LED retrofit options are then identified, followed by energy cost analyses based on the wattage input and operating profiles of the existing and proposed LED. The findings quantify the effectiveness of the retrofit strategy in achieving lighting energy reductions.

2.1. Choice of Building and Existing Lamp Layout

The research selected Block L, an eight-story building in the Faculty of Engineering, University of Malaya as the prototype for analysis. The building was chosen for its diverse functions, including lecture halls, offices, laboratories and administrative spaces, which create varied lighting demands throughout both weekdays and weekends. By focusing on this block, the study ensures that the results are representative of campus-wide usage patterns. Campus buildings are energy-intensive due to their continuous operation, heavy reliance on artificial lighting and high occupancy rates. In this study, Block L was simplified as a public office type building to allow for comparability with existing benchmarks. All floors are fully equipped with lighting system, making it a suitable candidate for energy consumption analysis and retrofit evaluation. It should be noted that this study is intended to reflect the general characteristics of educational buildings, independent of specific space areas, luminaire configurations or occupant activities, which differ fundamentally from those of commercial buildings. The satellite map of the location of the selected building is shown in Figure 1.

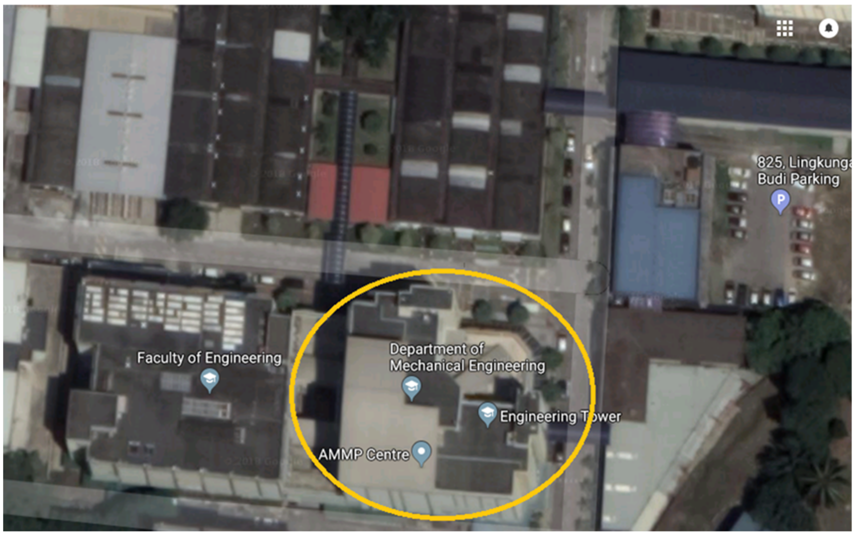


Figure 1. Location of Target Building.

The methodology began with a walking audit, in which the type and number of existing lighting fixtures were manually recorded. To minimize errors in data collection, these results were cross verified with the official lighting layout plans obtained from officials, the university's facilities management department. The layouts detailed the placement and specifications of lighting fixtures across all floors. The most common lighting types identified were illustrated in Table 1. The distribution of lights was digitized in AutoCAD, mapping the position of each luminaire floor by floor. This ensured accurate baseline representation of installed systems and operating conditions.

Table 1. Types of lights used in the building.

Model	Images	Description
OSRAM DULUXSTAR 18W/654 CFL bulbs (18W_CFL)		1050 lumens, 10,000-h lifespan
Philips Lifemax TLD 18W/54-765 (18W_TLD)		1050 lumens, 15,000-h lifespan
Philips Lifemax TLD 36W/54-765 (36W_TLD)		2600 lumens, 15,000-h lifespan

2.2. Retrofit Lighting Replacement

While CFLs and fluorescent tubes provide moderate efficiency compared to incandescent lamps, they are significantly less efficient than modern LEDs. LEDs consume 30 to 40% less energy than fluorescent lamps and up to 80% less than incandescent lamps, while offering extended lifespans (up to 50,000 h) and environmental advantages such as mercury-free operation. Commercial white LED lamps generally exhibit luminous efficiency in the range of 90 to 120 lumens per watt under the practical operating conditions, accounting for driver losses and thermal effects. Consequently, typical luminous flux values are approximately 1000 lumens for 9 W LED lamps, 1200 lumens for 10 W and 2600 lumens for 20W. These values are consistent with reported performance of contemporary LED retrofit lamps used in residential and commercial lighting applications [34,35]. The retrofit options selected were illustrated in Table 2:

Table 2. Types of lights replacing previous model.

Model	Images	Replaced lamp
20W LED tube (20W_LED)		36W_TLD
10W LED tube (10W_LED)		18W_TLD
9W LED bulb (9W_LED)		18W_CFL

2.3. Illuminance and Lighting Uniformity Verification

To verify that the proposed LED retrofit maintains comparable lighting conditions, a lighting simulation is conducted using DIALux Evo software. A simplified indoor test environment is created to evaluate the illuminance distribution produced by both the existing lamps and the proposed LED replacements. The simulation model consisted of a rectangular room measuring 3 m × 4 m with a ceiling height of 3m (similar to the office in the test site), representing a typical indoor workspace. The luminaire was installed on the ceiling at the centre of the room (with 2 units of the lamp arranged) to ensure consistent comparison between lamp types. A working plane height of 0.8 m above the floor level is defined to represent the typical desk or working surface in office environments. The simulation calculated the average illuminance (E_{ave}), minimum illuminance (E_{min}), maximum illuminance (E_{max}) and illuminance uniformity ratio ($U_o = E_{min}/E_{ave}$) across the working plane. The same room geometry, luminaire position and surface conditions were maintained for all simulations to ensure that difference in lighting performance were attributed solely to the lamp characteristics. The results obtained from the simulation were used to verify whether the LED retrofit provides comparable illuminance levels and acceptable lighting uniformity relative.

2.4. Energy Consumption and Savings Calculations

2.4.1. Electricity Consumption

The baseline annual electricity consumption (*EC*) of the building's lighting system was calculated using [5]:

$$EC = N \times W \times OH \tag{1}$$

where N = number of lamps, W = wattage of each lamp, OH = annual operating hours.

2.4.2. Energy Savings

Energy savings (ES) from the retrofit scenario were determined as the difference between baseline ($EC_{existing}$) and post-retrofit consumption ($EC_{retrofit}$). This provided a clear measure of the absolute reduction of electricity use attributable to the lighting retrofit.

$$ES = EC_{existing} - EC_{retrofit} \tag{2}$$

2.4.3. Bill Savings

Electricity cost savings (BS_i) per year, while total electricity cost savings (BS_T)were calculated as [36]:

$$BS_i = ES \times ET_i \tag{3}$$

$$BS_T = ES \times ET_0\,(1+g)^{T-1} \tag{4}$$

where ET is the electricity tariff. An annual tariff escalation (g) of 2% was assumed to reflect realistic market conditions in total of year (T).

2.5. Financial Evaluation

2.5.1. Operating Cost

Operating costs (OC) for the retrofitted system were estimated using [36]:

$$OC = N \times W \times OH \times ET \tag{5}$$

2.5.2. Present Worth Factor

The present worth factor (PWF) represents the discount multiplier for a uniform annual cash flow and forms the basis of the net present value (NPV) calculation when annual savings are constant over the analysis period [37,38].

$$PWF = \frac{1}{r}\left[1 - \frac{1}{(1+r)^n}\right] \tag{6}$$

$$NPV = -I + BS_T \times PWF \tag{7}$$

where, n = number of payments, r = interest rate per payment period and I = initial capital cost.

2.5.3. Payback Period

The payback period (PAY) was defined as [39]:

$$PAY = \frac{\Delta PC}{\Delta OC} \tag{8}$$

where ΔPC is the incremental purchase cost of LED fixtures relative to existing lamps, and ΔOC is the annual saving in the operating cost. The equation assumes ΔOC is constant each year. If PAY is less than the expected lifespan of the LED products, the investment is deemed economically feasible.

2.5.4. Life Cycle Cost

The life cycle cost (LCC) analysis combined both the upfront investment cost and discounted operating costs over the product lifetimes. This provided a holistic financial evaluation of the retrofit strategy [37].

$$LCC = PC + \sum \frac{OC}{(1+r)^n} \tag{9}$$

2.6. Emission Reduction Assessment

In Malaysia, coal is the dominant fuel for electricity generation, with natural gas and other fuels contributing smaller fractions. Emissions associated with electricity use were calculated using emission factors (kg/kWh) for CO_2, SO_2, NO_x and CO based on national grid conditions. The general formula for emission magnitude (EM) applied was [40]:

$$EM = EF \times FC \tag{10}$$

where EF is the emission factor per kWh and FC is the equivalent electricity consumptions. By applying these factors to the calculated energy savings, the study estimated avoided emissions.

Projected emissions from electricity generation between 2017 and 2027 are based on scenario analyses that reflect local conditions. Scenarios serve as tools to explore possible future environments, allowing decision-makers to anticipate challenges and opportunities. While the results may not precisely predict future outcomes, they provide valuable guidance for policymakers and researchers in assessing potential consequences and identifying feasible strategies. The projected values are summarized in Table 3. This enabled a direct link between reduced lighting consumption and environmental benefits such as decreased greenhouse gas and air pollutant emissions.

Table 3. CO_2, SO_2, NO_x and CO emission production per kWh of electricity generation [17]

Fuels	**Emission (kg/kWh)**			
	CO_2	**SO_2**	**NO_X**	**CO**
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Natural Gas	0.53	0.0005	0.0009	0.0005
Hydro	0.00	0.0000	0.0000	0.0000
Other	0.00	0.0000	0.0000	0.0000

2.7. Sensitivity Analysis

The baseline assumptions for lighting operation, electricity tariff, tariff escalation and discount rate were set at 8 h per day, RM 0.50/kWh, 2% and 7%, respectively, to ensure the robustness and economic feasibility of the proposed retrofit. In addition, the analysis incorporates a 20% variation in capital costs to account for potential uncertainties and unforeseen increases in market prices.

3. Results and Discussion

Before proposing any optimizing strategy, the building's lighting electricity consumption was established using both actual utility data and calculation results over one year of period to validate baseline demand. For 2017, Faculty of Engineering electricity use totaled 6,144,567 kWh (RM 3,125,986.20), of which Block L consumed 1,337,417 kWh, the lighting subsystem within Block L accounted for 15,760 kWh (around 1.15% of Block L's total). This baseline, coupled with a detailed lamp inventory, underpins the retrofit scenarios, cost-benefit analysis and emissions assessment that follow.

3.1. Ideal Lighting Technology

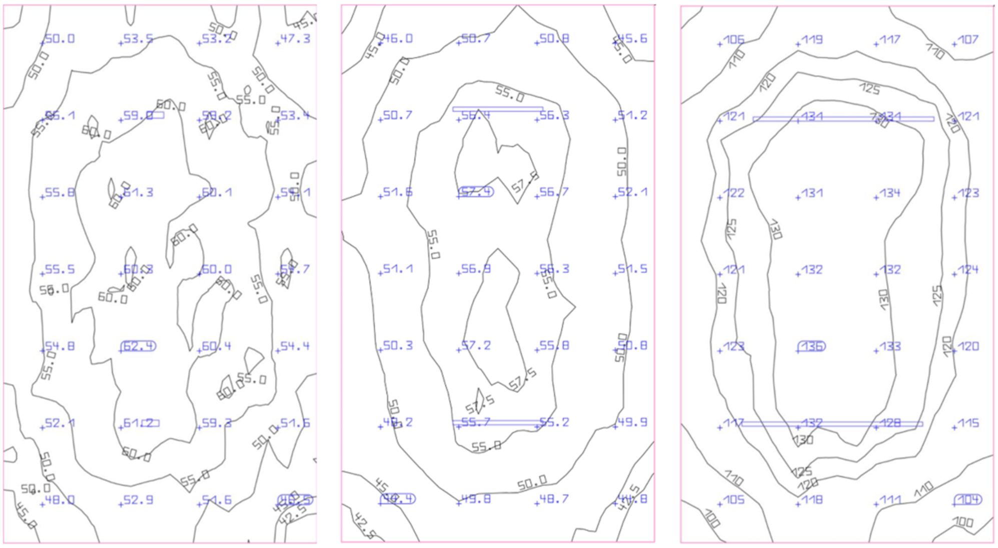
Table 4 summaries Block L's lamp inventory (walkthrough audit corroborated against buildings layout drawings) with the amount of 1831 luminaires comprising 1168 units of 36 W Philip Lifemax TLD, denoted as 36W_TLD, 438 units of 18 W Philips Lifemax TLD, denoted as 18W_TLD and 225 units of OSRAM DULUXSTAR 18 W/654 CFLs, denoted as 18W_CFL (details are shown in Table 4). The predominance of 36W_TLD tubes is operationally significant because any wattage reduction there scales immediately to material energy savings. In the engineering buildings with extended weekly operating hours (interviews respond from office personnel and postgraduate students), lamps were assumed to operate 8 h per day and 7 days per week annually. The assumption serves to normalize variations in occupancy patterns, including intermittently unused spaces, nighttime activities and academic holidays.

Table 4. Lamps quantity of Block L in each floor.

Floor	**18W_CFL**	**18W_TLD**	**36W_TLD**
1	47	10	15
2	110	50	134
3	23	210	164
4	24	132	133
5	4	4	235
6	4	10	201
7	6	14	139
8	7	8	147
Total	225	438	1168

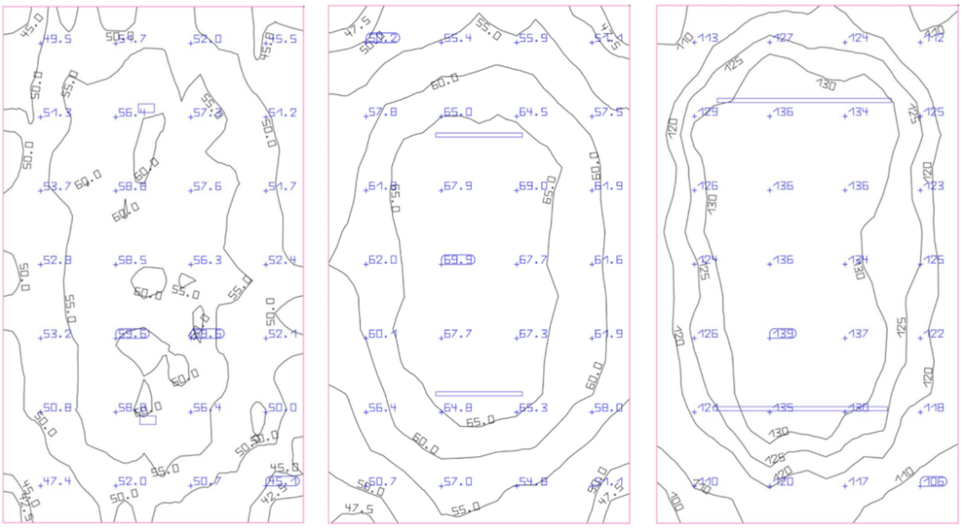
3.2. Verification of Illuminance and Lighting Uniformity

To ensure that the lighting retrofit does not compromise visual performance, the illuminance distribution and uniformity across the working plane (space of test site) were evaluated using simulations for both the conventional lighting system and the proposed LED replacements. The simulation results indicate that the average illuminance levels remain comparable following the retrofit. 18W_CFL produced an average illuminance of 55.1 lx, whereas the 9W_LED replacement yielded 53.2 lx. Similarly, the 18W_TLD provided 51.7 lx compared with 60.4 lx for the 10W_LED, while the 36W_TLD produced 122 lx compared with 125 lx for the 20W_LED replacement. In addition, the horizontal illuminance uniformity ratios for all cases ranged from 0.74 to 0.79, exceeding the commonly recommended minimum threshold of 0.60 for indoor environments. The information is stated in Figures 2 and 3 and Table 5. The uniformity ratio satisfies the recommended minimum values of exceeding 0.60 commonly specified in indoor lighting guidelines such as EN12461-1 and ISO lighting standards. These results indicate that the spatial distribution of light across the working plane remains consistent after the retrofit.



18W_CFL 18W_TLD 36W_TLD

Figure 2. Luminance contour of conventional lighting.



9W_LED 10W_LED 20W_LED

Figure 3. Luminance contour of LED lighting.

Table 5. Illuminance and lighting uniformity data before and after retrofitting.

Model	E_{min} (lx)	E_{max} (lx)	E_{ave} (lx)	U_o
18W_CFL	40.8	62.8	55.1	0.74
18W_TLD	40.4	58.0	51.7	0.78
36W_TLD	96.1	137.0	122.0	0.79
9W_LED	40.8	60.2	53.2	0.77
10W_LED	45.4	69.9	60.4	0.75
20W_LED	97.4	140.0	125.0	0.78

3.3. Potential Energy Saving

Using the duty cycle obtained from staff interview (8 h per day, 7 days per week), Table 6 compares daily energy use by lamp type before and after LED substitution. Calculated daily lighting consumption drops from 434 kWh (baseline) to 240 kWh (all LED), a reduction of 44.7%. Scaled annually, this translates to 70,810 kWh saved and RM 35,405 avoided cost as a base tariff of RM0.50/kWh (assuming a modest tariff escalation). The majority of savings come from replacing 36W_TLD lamps with 20W_LED, owing to their high population (1168 units) and long operational hours. Secondary contributions arise from converting 18W_TLD to 10W_LED and 18W_CFL to 9W_LED. Keeping luminaire counts preserves illumination levels while leveraging efficacy gains and consistent with good engineering practice in education spaces. The reduction aligns with recent program and research findings. Programmatic case studies and meta-reviews report 40 to 60% reductions for one to one LED replacements in offices, depending on baseline technology, operating hours and product quality [3]. International Energy Agency [3] reports paybacks as short as four months for LED tubes in highly use application when tariffs and hours are favourable, underscoring the leverage of hours-of-use and electricity price on economics.

Table 6. Daily energy consumption between before and after lamp replacement.

Before Replacement		After Replacement	
Model	**Power Consumed (kWh)**	**Model**	**Power Consumed (kWh)**
18W_CFL	33	9W_LED	17
18W_TLD	64	10W_LED	36
36W_TLD	337	20W_LED	187
Total	434	Total	240

The present scenario models a technology-only substitution. Contemporary studies show that networked lighting controls (NLCs) with occupancy sensing daylight harvesting, high-end trim, task tuning, can produce an additional 20 to 50% savings on top of LED retrofits, depending on use pattern and commissioning quality [41,42]. This suggests that the 44.7% achieved here should be viewed as a floor which integrating controls could push total savings well past 50%, subject to design and user acceptance. The energy model assumes constant operating hours and no behavioral variability across semesters, exam periods or public holidays. A more granular schedule (academic calendar, cleaning shifts, partial-load evenings) would likely refine results which typically reducing absolute savings if hours are overestimated, but not changing the qualitative conclusion that LED retrofit is strongly beneficial.

The annual electricity cost for the existing fluorescent lighting system remains fixed in terms of energy use but increases slightly over time due to tariff escalation, rising from RM 79,205 in 2017 to RM 96,629 in 2027. In contrast, the cost of operating the LED system declines significantly as a result of reduced energy consumption, starting at RM 77,178 in 2018 and decreasing further to RM 53,436 by 2027. In terms of savings, the first year of retrofit (2018) produces an actual savings of approximately RM 3611. Over the years, annual savings grow steadily due to the combined effect of rising tariffs and the declining consumption of LED lamps. By 2027, the yearly savings are estimated to reach RM 43,193. Cumulative BS also demonstrate a strong financial case. After five years (2022), total cumulative savings are approximately RM 37,529, and by the end of the 10-year period (2027), cumulative BS are projected at RM 223,901 (Table 7). This outcome confirms the economic viability of LED retrofits, which not only deliver significant cost reductions but also support long term sustainability goals by lowering operational expenditure and reducing energy demand.

Table 7. Annual billing and cost savings data for current lamps and LED lamps.

Year	Current EC (kWh)	LED EC (kWh)	Tariff (RM/kWh)	Cost_Current (RM)	Cost_LED (RM)	Annual BS (RM)	Cumulative BS (RM)
2017	158,410	158,410	0.50	79,205.00	0	0	0
2018	158,410	151,329	0.51	80,789.10	77,177.79	3611.31	3611.31
2019	158,410	144,248	0.52	82,373.20	75,008.96	7364.24	10,975.55
2020	158,410	137,167	0.53	83,957.30	72,698.51	11,258.79	22,234.34
2021	158,410	130,086	0.54	85,541.40	70,246.44	15,294.96	37,529.30
2022	158,410	123,005	0.55	87,125.50	67,652.75	19,472.75	57,002.05
2023	158,410	115,924	0.56	88,709.60	64,917.44	23,792.16	80,794.21
2024	158,410	108,843	0.57	90,293.70	62,040.51	28,253.19	109,047.40
2025	158,410	101,762	0.59	93,461.90	60,039.58	33,422.32	142,469.70
2026	158,410	94,681	0.60	95,046.00	56,808.60	38,237.40	180,707.10
2027	158,410	87,600	0.61	96,630.10	53,436.00	43,194.10	223,901.20

3.4. Payback Period and Life Cycle Cost Analysis

The financial viability of replacing conventional fluorescent and CFLs with LED technology was evaluated through both PAY and LCC analyses. These tools allow a comprehensive assessment of not only the short-term feasibility of the retrofit but also its long-term economic impact.

The payback period represents the duration required for the cumulative BS to equal the initial investment cost of the retrofit. Tables 8 to 13 present detailed payback and cost breakdowns for the 3 major categories of lamps in Block L. Firstly, the replacement of 36W_TLD with 20W_LED, secondly 18W_TLD with 10W_LED and thirdly 18W_CFL with 9W_LED. The analysis shows that the PAY for the 20W_LED retrofit is 2.21 years (Table 8). For the 10W_LED, the PAY is slightly shorter at 2.14 years (Table 10). The 9W_LED achieves the most rapid recovery of investment, at only 1.9 years (Table 12). These results indicate that, despite higher upfront purchase and installation costs, LED retrofits yield financial returns in under 3 years across all lamp categories. The logic behind these figures can be understood by comparing the incremental capital costs with the annual operating cost reductions. For instance, while 20W_LED requires a higher investment (RM 71,248 compared to RM 14016 for fluorescent equivalent), its operating costs are reduced from RM 64,118 per year to RM 38,266 per year (Table 8). The annual savings of RM 25,852 therefore allow the initial outlay to be recouped in just over two years. Similarly, doing retrofitting, though modest in scale, achieves a rapid payback due to the significant efficiency gains and lower unit price of LED bulbs relatives to tubes.

While PAY periods highlight the short-term attractiveness of an investment, they do not account for the full economic implications over time. To capture these, LCC analysis was conducted for each retrofit scenario, assuming a 10-year analysis and a discount rate of 7%, as commonly applied in building energy economics.

The LCC analysis integrates capital costs, operating costs (electricity bills) and maintenance costs, discounted to present values. Tables 8 to 13 detail these calculations. For the 20W_LED, the 10-year LCC is substantially lower than that of the existing 36W_TLD, even after accounting for higher upfront capital requirements (Table 8). Specifically, the LCC of the LED system amounts to approximately RM 654,096, compared with RM 823,308 for existing fluorescent system, yielding a net saving of RM 169,212 over the analysis period. Similar patterns are observed for the 10W_LED (Table 10) and 9W_LED (Table 12), with cumulative net savings of RM 123,057 and RM 61,036 respectively.

The sensitivity analysis was conducted to test how the results respond to uncertainty in the main assumptions used in the retrofit model, namely operating hours (6 to 10 h per day), electricity tariff (RM 0.45 to 0.60/kWh), discount rate (5 to 10%), tariff escalation (2 to 5%) and LED capital cost (20%) variation), while keeping the audited lamp counts and wattages unchanged. Using the baseline operating condition, the PAY across three LED replacement group is 2.18 years, total net investment RM 73,369 recovered by RM 33,728/year savings. When the sensitivity parameters are applied, payback remains consistently attractive but shifts as expected. Firstly, reducing operating hours to 6 h per day and adopting a lower tariffed compresses annual savings linearly and pushes payback upward, whereas higher utilization (10 h per day) and higher tariff pull payback downward. With capital cost variation included the PAY spans approximately 1.17 to 3.96 years for 20W_LED, 1.13 to 3.82 years for 10W_LED and 1.01 to 3.38 years for 9W_LED, demonstrating that the retrofit remains under 4 years even under conservative combinations. A 10-year discounted cashflow check further confirms robustness, where under the tested range of discount rates and tariff escalation scenarios, the combined 10-year net present savings remain positive and substantial, ranging from RM 51,847 for lower bound case to RM 423,136 for upper-bound case, with a baseline case NPV of RM 183,184 (Table 14). Overall, the sensitivity results show that the retrofit is primarily driven by hours of use and electricity price (both scale savings directly), while discount rate and LED unit cost modulate, but do not overturn the economic viability over a 10-year planning horizon.

Table 8. Comparative LCC analyses 20W_LED and 36W_TLD.

Variables	**Value**	**Unit**
Power of LED Lamps	20	Watts
Unit price of LED lamps	60	Ringgit
Power of existing lamps	36	Watts
Unit price of existing lamps	10	Ringgit
Number of lights	1168	Lamp(s)
Operating hours (per day)	8	Hours
Number of days of operation (per year)	365	Days
Energy cost/kWh	0.5	Ringgit
Calculations	**Existing system**	**LED**
Electrical costs		
- Electrical load of lamp(s)	42,048	23,360
- Annual operating hours (hours)	2920	2920
- Annual energy consumption (kWh)	122,780.16	68,211.2
- Saving electricity (kWh)	0	54,568.96
- Energy total cost (per year)	RM 61,390.08	RM 34,105.6
- Save on Electricity bills (per year)	RM 0.00	RM 27,284.48
Capital requirements		
- Purchase requirements Cost	RM 11,680.00	RM 70,080
- Installation cost per unit	RM 2.00	RM 1.00
- Installation costs	RM 2336	RM 1168
- Total capital investment requirements	RM 14,016	RM 71,248
- Net investment requirement	RM 0.00	RM 57,232
Maintenance requirements		
- Lamp lifespan (operating hours)	15,000	50,000
- Need to be replaced (per year)	227.37	68.2112
- Replacement costs (per year)	RM 2273.7	RM 4092.67
- Installation cost per new unit	RM 2.00	RM 1.00
- Maintenance costs (per year)	RM 454.74	RM 68.21
- Total maintenance costs (per year)	RM 2728.44	RM 4160.88
- Maintenance saving (per year)	RM 0.00	−RM 1432.48
Return on investment (ROI) results		
- Total operating cost (per year)	RM 64,118.52	RM 38,266.48
- First year total savings	RM 0.00	RM 25,852
- Payback period (year)	n/a	2.21
- More than 10 years LED (ROI)	RM 0.00	RM 83,084

Table 9. 10-year period LCC calculation for 20W_LED (cumulative).

Year	r	PWF	Maintenance Cost (RM)	EC (RM)	LCC (RM)
2017	0.07	1	4160.88	34,105.6	0
2018	0.07	1.08	4474.06	36,672.69	112,394.75
2019	0.07	1.16	4810.82	39,433.00	156,638.57
2020	0.07	1.24	5172.93	42,401.07	204,212.57
2021	0.07	1.34	5562.29	45,592.55	255,367.41
2022	0.07	1.44	5980.95	49,024.25	310,372.61
2023	0.07	1.55	6431.13	52,714.25	369,517.99
2024	0.07	1.66	6915.20	56,681.99	433,115.18
2025	0.07	1.79	7435.70	60,948.37	501,499.24
2026	0.07	1.92	7995.37	65,535.88	575,030.50
2027	0.07	2.07	8597.17	70,468.69	654,096.36

Table 10. Comparative LCC analyses 10W_LED and 18W_TLD.

Variables	**Value**	**Unit**
Power of LED Lamps	10	Watts
Unit price of LED lamps	30	Ringgit
Power of existing lamps	18	Watts
Unit price of existing lamps	5	Ringgit
Number of lights	438	Lamp(s)
Operating hours (per day)	8	Hours
Number of days of operation (per year)	365	Days
Energy cost/kWh	0.5	Ringgit
Calculations	**Existing system**	**LED**
Electrical costs		
- Electrical load of lamp(s)	7884	4380
- Annual operating hours (hours)	2920	2920
- Annual energy consumption (kWh)	23,021.28	12,789.6
- Saving electricity (kWh)	0	10,231.68
- Energy total cost (per year)	RM 11,510.64	RM 6394.8
- Save on Electricity bills (per year)	RM 0.00	RM 5115.84
Capital requirements		
- Purchase requirements Cost	RM 2190	RM 13,140
- Installation cost per unit	RM 2.00	RM 1.00
- Installation costs	RM 876	RM 438
- Total capital investment requirements	RM 3066	RM 13,578
- Net investment requirement	RM 0.00	RM 10,512
Maintenance requirements		
- Lamp lifespan (operating hours)	15,000	50,000
- Need to be replaced (per year)	85.26	25.5792
- Replacement costs (per year)	RM 426.3	RM 767.376
- Installation cost per new unit	RM 2.00	RM 1.00
- Maintenance costs (per year)	RM 170.52	RM 25.58
- Total maintenance costs (per year)	RM 596.82	RM 792.95
- Maintenance saving (per year)	RM 0.00	−RM 196.13
Return on investment (ROI) results		
- Total operating cost (per year)	RM 12,107.46	RM 7187.75
- First year total savings	RM 0.00	RM 4919.71
- Payback period (year)	n/a	2.14
- More than 10 years LED (ROI)	RM 0.00	RM 15,431.71

Table 11. 10-year period LCC calculation for 10W_LED (cumulative).

Year	r	PWF	Maintenance Cost (RM)	EC (RM)	LCC (RM)
2017	0.07	1	792.95	6394.80	0
2018	0.07	1.08	852.63	6876.13	21,306.76
2019	0.07	1.16	916.81	7393.69	29,617.26
2020	0.07	1.24	985.82	7950.20	38,553.28
2021	0.07	1.34	1060.02	8548.60	48,161.908
2022	0.07	1.44	1139.81	9192.05	58,493.76
2023	0.07	1.55	1225.60	9883.92	69,603.28
2024	0.07	1.66	1317.85	10,627.87	81,549.00
2025	0.07	1.79	1417.04	11,427.82	94,393.86
2026	0.07	1.92	1523.70	12,287.98	108,205.53
2027	0.07	2.07	1638.39	13,212.88	123,056.80

An important driver of these savings is the extended lifespan of LED technology. While fluorescent and CFL lamps require frequent replacement (15,000 h for fluorescent tubes and 10,000 h for CFLs), LED typically last 30,000 to 50,000 h. In Block L, where lamps operate an average of 2920 h annually, LED tubes can last up to 17 years, substantially reducing maintenance and replacement costs. Indeed, Table 8 illustrates that the annual maintenance costs for the LED retrofit fall by nearly 50% compared with the baseline fluorescent system. This benefit is particularly significant for multi-storey academic buildings, where lamp replacement incurs not only material and labour costs but also disruption to lecture halls and laboratories.

Table 12. Comparative LCC analyses 9W_LED and 18W_CFL.

Variables	Value	Unit
Power of LED Lamps	9	Watts
Unit price of LED lamps	20	Ringgit
Power of existing lamps	18	Watts
Unit price of existing lamps	5	Ringgit
Number of lights	225	Lamp(s)
Operating hours (per day)	8	Hours
Number of days of operation (per year)	365	Days
Energy cost/kWh	0.5	Ringgit
Calculations	**Existing system**	**LED**
Electrical costs		
- Electrical load of lamp(s)	4050	2025
- Annual operating hours (hours)	2920	2920
- Annual energy consumption (kWh)	11,826	5913
- Saving electricity (kWh)	0	5913
- Energy total cost (per year)	RM 5913	RM 2956.5
- Save on Electricity bills (per year)	RM 0.00	RM 2956.5
Capital requirements		
- Purchase requirements Cost	RM 1125	RM 4500
- Installation cost per unit	RM 2.00	RM 1.00
- Installation costs	RM 2250	RM 4500
- Total capital investment requirements	RM 3375	RM 9000
- Net investment requirement	RM 0.00	RM 5625
Maintenance requirements		
- Lamp lifespan (operating hours)	10,000	30,000
- Need to be replaced (per year)	65.70	21.9
- Replacement costs (per year)	RM 328.5	RM 438
- Installation cost per new unit	RM 2.00	RM 1.00
- Maintenance costs (per year)	RM 131.4	RM 21.9
- Total maintenance costs (per year)	RM 459.9	RM 459.9
- Maintenance saving (per year)	RM 0.00	−RM 0
Return on investment (ROI) results		
- Total operating cost (per year)	RM 6372.9	RM 3416.4
- First year total savings	RM 0.00	RM 2956.5
- Payback period (year)	n/a	1.9
- More than 10 years LED (ROI)	RM 0.00	RM 8581.5

Table 13. 10-year period LCC calculation for 9W_LED (cumulative).

Year	r	PWF	Maintenance Cost (RM)	EC (RM)	LCC (RM)
2017	0.07	1	459.90	2956.50	0
2018	0.07	1.08	494.52	3179.03	12,673.55
2019	0.07	1.16	531.74	3418.31	16,623.60
2020	0.07	1.24	571.76	3675.61	20,870.97
2021	0.07	1.34	614.80	3952.27	25,438.03
2022	0.07	1.44	661.07	4249.75	30,348.85
2023	0.07	1.55	710.83	4569.62	35,629.30
2024	0.07	1.66	764.33	4913.57	41,307.21
2025	0.07	1.79	821.86	5283.41	47,412.48
2026	0.07	1.92	883.72	5681.09	53,977.29
2027	0.07	2.07	950.24	6108.69	61,036.22

Overall, both payback and LCC analyses clearly demonstrate that the LED retrofit in Block L is economically viable, with return achieved in under three years and long-term savings exceeding RM 350,000 when aggregated across all lamp types. Importantly, these benefits accrue even under conservative assumptions about electricity tariff escalation and discount rates.

Table 14. Sensitivity analysis results matrix for LED retrofit.

Scenario	Operation Hour (h/day)	Tariff (RM/kWh)	Discount, r (%)	Escalation, g (%)	Capital Cost Variation (%)	1-Year Savings (RM/Year)	PAY (Year)	10-Year NPV
Lower bound	6	0.45	10	0	+20	22.766	3.87	51,847
Low use	6	0.50	7	2	0	25,296	2.90	119,046
Baseline	8	0.50	7	2	0	33,728	2.18	183,184
High use	10	0.50	7	2	0	42,160	1.74	247,323
Higher tariff	8	0.60	7	2	0	40,473	1.81	234,495
Low discount rate	8	0.50	5	2	0	33,728	2.18	209,546
Upper bound	10	0.60	5	5	-20	50,592	1.16	423,136

3.5. Emission Reduction

Beyond financial considerations, lighting retrofits have significant implications for environmental sustainability. This section quantifies the emissions reduction potential of replacing fluorescent and CFL lamps in Block L and LEDs.

Table 6 showed that replacing the existing lighting systema with LEDs yields an electricity saving of 44.7%, equivalent to approximately 70,810 kWh annually. This figure aligns with the projected cumulative reduction shown in Table 7, where annual electricity consumption declines from 158,410 kWh in 2017 to 87,600 kWh in 2027, representing an absolute saving of 70,810 kWh per year once the retrofit is fully implemented. To translate energy savings into emission reductions, the emission factor listed in Table 3 was applied. The EM for each gas emitted from power generation annually is listed in Table 15. From the data the possible cumulative gas reduced can achieve 130,285 kg of CO_2, 408 kg of SO_2, 275 kg of NO_x and 106 kg of CO for 10 years period.

Table 15. Forecast of electricity consumption of Block L lighting replacement scheme, percentage of resource used for power generation in Malaysia and possible gas emission.

Year	Total (kWh)	Coal (%)	Petroleum (%)	Gas (%)	Hydro (%)	CO_2 (kg)	SO_2 (kg)	NO_x (kg)	CO (kg)
2017	158,410	24.9	1.1	42.0	32.1	83,174	609	269	41
2018	151,329	26.2	1.0	41.2	31.6	81,111	607	266	39
2019	144,248	27.5	1.0	40.6	30.9	79,131	605	263	37
2020	137,167	29.0	1.0	40.0	30.0	77,198	603	260	36
2021	130,086	30.3	1.0	39.3	29.4	74,742	595	254	34
2022	123,005	31.7	0.9	38.7	28.7	72,221	585	249	32
2023	115,924	33.1	0.9	38.0	28.0	69,522	572	242	30
2024	108,843	34.5	0.9	37.4	27.3	66,645	558	234	28
2025	101,762	35.9	0.8	36.7	26.6	63,589	540	226	26
2026	94,681	37.2	0.8	36.1	25.9	60,356	520	216	24
2027	87,600	38.6	0.8	35.4	25.2	56,944	497	206	22

These reductions are not only statistically significant but also environmentally meaningful. For context, the CO_2 savings alone are equivalent to offsetting the annual emissions of over 550 passenger vehicles (assuming 4.75 tonnes CO_2/year per vehicle [43]). This illustrates the scale of environmental benefit achievable through relatively modest retrofitting actions.

Beyond greenhouse gases, the reductions in SO_2, NO_x and CO emissions are notable. These pollutants contribute to urban air quality degradation, with direct implications for human health. For example, NO_x emissions are precursors of ground level ozone and fine particulate matter, both of which are linked to respiratory and cardiovascular diseases. In Kuala Lumpur, where air pollution episodes are frequent, demand-side efficiency measures such as LED retrofits thus yield co-benefits extending beyond carbon mitigation, improving both environmental quality and public health outcomes [44,45].

3.6. Limitation of the Study

This study is subject to several limitations that warrant further investigation in future work. First, the analysis primarily focuses on educational buildings, where occupant behaviour, space utilization patterns and the nature of electrical appliances differ fundamentally from those of commercial buildings. As a result, the direct transferability of the findings to commercial building typologies may be limited without appropriate contextual adaption. Second, interior space characteristics can significantly require illuminance levels. These factors ultimately affect LED specification, luminaire selection and perceived visual comfort, yet they were simplified in the present analysis to maintain methodological consistency. Also, additional investigation is needed for human comfort that ultimately decided the LED specification including light colour, luminance and interior design which affect the energy consumption. Third, lighting control strategies, including occupancy sensors, daylight responsive dimming and scheduling systems, play a critical role in minimizing unnecessary lighting operation in intermittently occupied or idle spaces. The absence of advanced lighting control integration in this study may therefore lead to conservative estimates of achievable energy savings. Nevertheless, the study provides a structured and replicable workflow for luminaire retrofit assessment, cost evaluation and emissions analysis. This framework offers a practical reference for lighting retrofit initiatives in other educational facilities establishes a foundation for future studies incorporating behavioural modelling, detailed daylight analysis and intelligent lighting control systems.

4. Conclusions

The results of this research confirm that retrofitting conventional lighting systems with LED technology offers substantial economic and environmental benefits for institutional buildings, with the Faculty of Engineering, University of Malaya serving as a representative case study. Experimental analysis demonstrated that the complete replacement of existing fluorescent and CFLs with LED alternatives reduces annual lighting energy consumption by approximately 44.7%, translating into savings of 70,810 kWh compared to the baseline of 158,410 kWh recorded in the existing system. These savings correspond to an annual reduction of around 54.8 tonnes of CO_2 emissions when applying Malaysia’s official grid emission factor. Over a 10-year assessment horizon, the retrofit yields cumulative emission reductions of approximately 130,285 kg CO_2, 408 kg SO_2, 275 kg NO_x and 106 kg CO, thereby underscoring the environmental significance of the retrofit.

Financially, the LCC analysis of 3 retrofit options consistently demonstrated attractive PAY of 2.21 years (20W_LED replacement), 2.14 years (10W_LED replacement) and 1.90 years (9W_LED replacement) respectively. Over a 10-yeara assessment horizon, LEDs delivered savings exceeding RM 225,000 compared to baseline fluorescent lighting, even when accounting for higher initial capital outlays and traffic escalation. Sensitivity analysis further confirmed the robustness of these results, with payback periods remaining below 4 years across variations in operating hours, electricity tariffs, discount rates and capital cost assumption. The superior performance of LEDs is further reinforced by their durability, with service lifetimes nearly 5 times longer than quality fluorescent of CFL systems, resulting in reduced maintenance costs and operational disruptions. Beyond the quantified results, the practical advantage of LEDs lies in their compatibility with existing fixtures, as replacement requires minimal modification, typically involving only the removal of starters, thereby simplifying implementation. In a broader context, the findings demonstrate that the proposed retrofit approach and evaluation framework area scalable and transferable to other educational and institutional facilities, particularly in regions with comparable operating schedules, lighting standards and electricity tariff structures.

Nevertheless, several limitations should be acknowledged. The study focuses on educational buildings, where occupant activities, lighting usage patterns and electrical appliance profiles differ from those of commercial buildings. In addition, interior design factors such as daylight availability, window configuration, surface reflectance and occupant behaviour, as well as the integration of advanced lighting control systems, were not considered in this analysis. These aspects may influence actual lighting demand and energy saving potential and should be addressed in the future studies to further refine the applicability of the framework.

Overall, given the magnitude of cost savings, the short payback period and the significant environmental co-benefits observed, this study concludes that full-scale LED retrofits represent a robust, transferable solution for educational and institutional facilities. By proving both financial feasibility and sustainability impact in a real-world setting, the findings provide an evidence-based model that can guide similar retrofits across the region, contributing to the dual goas of lowering electricity bills and advancing national carbon reduction commitments.

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