COMPARATIVE COST-BENEFIT ANALYSIS OF ENERGY EFFICIENT LIGHTING IN RETROFIT BUILDINGS

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Electrical and Electronic Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"COMPARATIVE COST-BENEFIT ANALYSIS OF ENERGY-EFFICIENT LIGHTING IN RETROFIT BUILDINGS"** was prepared by **LIOW SHII YIN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Electrical and Electronic Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Lighting retrofits aim to reduce energy consumption and environmental impact while providing better lighting quality. Challenges in retrofitting include the retrofit method and the economic feasibility assessment before actual implementation. This research is aimed to study the lighting quality, economic and environmental benefits of retrofitting the existing conventional lighting with energy-efficient lighting in a high-rise building. In the preliminary study, three cases with different light sources in compliance with MS 1525, SIRIM and JKR standards were modelled to study lighting qualities such as illuminance level, uniformity and lighting power intensity. The results showed that energy-efficient lighting and good lighting quality are compatible. Several factors need to be considered when selecting the LED for retrofitting, including luminous flux and polar curve. In the comprehensive study, five cases with different degrees of LED retrofitting were modelled compliant with the standards to study the energy efficiency and cost-effectiveness. The findings showed that retrofitting using a higher percentage of LEDs gives more savings in terms of life cycle cost, electricity consumption and CO_2 emission. Retrofitting with 100% LEDs can provide up to 20% net saving and save up to 34.7% in electricity consumption and CO_2 emissions per year. In cases where lighting systems are not 100% retrofitted with LEDs, priority is given to replacing longer-running inefficient light sources to maximize the net saving. By retrofitting from the long operating hours to the short operating hours, the net saving can achieve 6.7% to 8.4% higher than vice versa. Moreover, retrofitting using a longer lifespan LED should consider first because it results in more net saving, and the net saving of a 50,000-hour-life LED system can be as high as 20%. The sensitivity analyses showed that the change in LED prices is unlikely to negate the net saving of the retrofit systems. When the discount rate increases by 20% and the electricity tariff reduce by 45%, the lower percentage of LED retrofit becomes more preferred than the higher percentage of LED retrofit.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Buildings account for 33% of the total world annual energy consumption (IEA, 2021), and lighting is one of the highest proportions, about 30% of the total electricity. With the rapid population growth and electricity consumption, coupled with climate change, policymakers and international organizations start to encourage consumers to use energy-efficient light sources in new building lighting system designs and also in lighting retrofits. This is also one of the ways to achieve Goal 7 of the Sustainable Development Goals adopted by the United Nations in 2015, which focuses on energy efficiency and conservation.

Lighting retrofit is the replacement of existing light systems with more advanced and efficient systems which aim to reduce energy consumption, environmental impact and operating cost while providing better illumination and user experience. According to FMLink (n.d.), the operating cost accounts for 90% of the life cycle cost of a building. If the systems (i.e. lighting, HVAC etc.) are not properly designed or inefficient, users need to pay more unnecessary operating costs.

One of the challenges in retrofitting is the evaluation of the economic feasibility of the proposed solution before the real implementation. Investors and owners face difficulties in making decisions due to unclear future forecasts, lack of confidence in the expected investment returns and sometimes they are underfunded. Therefore, it is important to propose methods to retrofit that able to maximize the saving under different conditions. A complete economic feasibility study of the proposed retrofit solution is essential but simple economic analysis such as simple payback is not appropriate as it excludes the system operating conditions, inflation rate etc. For this reason, life cycle cost analysis (LCCA) is needed in assessing the feasibility of a lighting retrofit project and sensitivity analyses also need to determine the most affected parameters before choosing the best lighting solution for the retrofit project.

1.2 Importance of the Study

The luminous efficiency of LEDs in the residential market has exceeded 100 lumens per watt (lm/W), which has increased by 6-8 lm/W per year since 2010 (IEA, 2020). However, LED penetration rates in the markets are still uneven. Relatively speaking, sales of lighting replacements are usually lower than sales for new buildings.

The benefits of LED in terms of energy and cost-saving have been proven by many researchers, and it is foreseeable that LED lights will completely change the lighting practice and market shortly. Therefore, to encourage the use of energy-efficient light sources, it is important to let investors understand the financial benefits and importance of lighting retrofits with the use of high-efficiency light sources. Thus, this research will investigate the potential of replacing existing lighting sources with energy-efficient lighting sources in economic and environmental aspects. More research is focusing on designing a retrofit lighting system with good lighting quality, high economic benefit and small environmental impact which will help the decision-makers consider the effective integration of energy-saving technologies.

1.3 Problem Statement

Despite that the efficiency of LEDs has improved by 60% until now, many existing users still use conventional light sources such as CFLs, Incandescent lamps etc. According to Elliott, C. & Lee, K. (2020), the usage of LED for downlighting has doubled to 44.8% (from 2016 to 2018), but conventional lighting sources still account for more than 50% of the installation. Many investors and property owners face difficulties in making correct decisions on whether to retrofit because of unclear impacts and also risks in future. Therefore, research on retrofit methods and evaluation of the appropriateness and cost-effectiveness of the lighting retrofit has become imperative. The research aims to fill the gap in this field and also help to verify the benefits attached to LED lighting products.

1.4 Aim and Objectives

This research aims to study the lighting quality, economic and environmental benefits of retrofitting the existing conventional lighting with energy-efficient lighting in a high-rise building. The objectives of the study included:

i. To design lighting systems of the building compliant with the Malaysian Standard using efficient and inefficient light sources.
ii. To analyse the potential energy savings of retrofitting inefficient lighting systems with energy-efficient lighting systems.
iii. To investigate the environmental impacts of utilizing inefficient and efficient light sources.
iv. To investigate the cost-effectiveness of retrofitting inefficient lighting systems with energy-efficient lighting systems.

1.5 Scope and Limitation of the Study

This research focuses on the energy efficiency and cost-effectiveness of retrofitting conventional lighting to energy-efficient lighting. DIALux was used for lighting design and simulation throughout this study. In the preliminary study, three lighting systems with several types of light sources were modelled compliant with the MS 1525, SIRIM and JKR standards to study the luminaire performance, such as illuminance level, uniformity and lighting power intensity. In the comprehensive study, five cases with different degrees of LED retrofit were modelled compliant with the standards. Electricity consumption and climate impact were analysed to determine the potential energy-saving and impact on the environment. LCCA was used to determine the cost-benefit of the retrofits. Sensitivity analysis was carried out to investigate the uncertainty parameters.

The limitation of this study is the lighting control techniques such as dimming and motion sensors are not considered. The lighting system is assumed to be turned on all the time during operation hours. LCCA in this study does not consider the maintenance cost for general maintenance, such as ballast replacement for CFL, cleaning, broken fixture replacement etc. Another limitation is user comfort as it cannot be simulated in software. Even if there are predefined standards for the lighting design, a difference between the actual luminaire performance and the simulation output may exist.

1.6 Contribution of the Study

Retrofitting existing buildings to address the long-term challenges of climate change and resource constraints is becoming increasingly important. Rapid advances in solid-state lighting (SSL) technology have truly restructured the global lighting industry with great emphasis on enormous potential savings. Research and development in the field of energy-efficient lighting retrofits can significantly reduce global electricity consumption and carbon dioxide emissions. Therefore, it is necessary to strengthen the concept of energy-saving lighting retrofit through publicity and education. Research investigating the methods or ways to have a lighting retrofit that maximises energy efficiency and cost savings even under underfunded conditions will help investors and owners consider the basis for the effective integration of energy-efficient technologies such as LEDs.

1.7 Outline of the Report

The project is divided into six chapters, with each chapter addressing a different topic of the required research.

Chapter one introduces the background of the project, such as the current issues and the aim and objectives of the study. The scope and limitations of the study aid the direction of the project. The findings will bring significant benefits to energy efficiency, emission reduction and cost-effectiveness of lighting retrofits in buildings.

Chapter two presents the literature review of various lighting technologies in terms of performance and environmental impact. The chapter also introduces the concept of lighting retrofits, including the benefits and process. Consideration and standards for lighting system design will also be covered. Lastly, previous research on LCCA, including the benefits and reasons that LCCA as economic evaluation tools for lighting retrofit will be discussed.

Chapter three covers the overall research methodology, in which the project is divided into two studies: the preliminary study and the comprehensive study. The chapter further presents the building information and the use of DIALux to model standards-compliant lighting systems.

Chapter four presents the details of the preliminary study – luminaire analysis. The lighting system models and analysis results for all cases will be discussed.

Chapter five outlines the details of the comprehensive study, including lighting systems modelling, climate impact and electricity consumption analysis. The second part discusses the economic analysis, including the application of LCCA in accessing the economic feasibility of the retrofits. The third part covers sensitivity analysis that is used to determine the most affected parameters in the LCCA.

Chapter six summarizes the entire study, presenting the conclusions of this project and recommendations for future work to improve the research objectives.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review of lighting technology, lighting retrofit, lighting design and LCCA will be discussed. The possibility and advantages of retrofitting lighting for energy efficiency, financial and environmental applications will also be discussed by reviewing other research studies. In addition, standards and guidelines for lighting design and the rationale of LCCA as a decision-making tool for lighting retrofit projects will also be discussed.

2.2 Lighting Technology

From the invention of incandescent lamps to the transition to compact fluorescent lamps (CFL) and the current LEDs with solid-state lighting (SSL), lighting technology has developed rapidly, especially in terms of energy efficiency. It is important to have a deeper understanding of the extent to which the current lighting technology suppresses the existing lighting technology. The following subsections illustrate the comparison between traditional and LED lighting technology on the performance and environmental impacts.

2.2.1 Performance

LEDs are known for their longer lifespan than all other artificial lighting sources, with an average of 50,000 hours lifespan. This is in sharp contrast to the 2,000 hours lifespan of incandescent bulbs and 10,000 hours of CFLs. Table 2.1 shows the lifespan of three types of light bulbs. The comparison shows that the LED light bulb has a lifespan of 15,000 hours, which is 15 times more than the incandescent bulb, and roughly two times the life of the CFL bulb.

In terms of energy efficiency, LED has a great advantage over incandescent and CFL. According to the E27 LED light bulb datasheet by QEOS LED (2021), the luminous efficacy of a 4.75 W LED bulb is equivalent to an 18 W CFL or 60 W incandescent light bulb as shown in Table 2.1. Simply said, with less than half of the wattage, LED bulbs can produce the same brightness as CFL and incandescent lamps. This is because the wattage to light and heat output conversion is highly efficient in LED as compared to conventional light sources. According to EPA (2021), 90% of energy in incandescent bulbs and 80% of energy in CFLs are released as heat.

Table 2.1: Lifespan and Equivalent Wattage of Three Types of Light Bulbs (Panasonic, n.d.) (RS Malaysia, 2021) (Qeos LED, 2021).

Light Sources	**Incandescent Light**	**CFL**	**LED**
Lifespan	1,000 hours	8,000 hours	1,5000 hours
Wattage Equivalent	60W	18W	4.75W
Lumen Output	800lm	850lm	800lm

2.2.2 Environmental Impact

LED with higher energy efficiency and longer lifespan can reduce the overall electricity consumption, thereby reducing the CO_2 emissions from electricity generation. According to a study by IHS Markit (2017), the use of LEDs for building interior and exterior has reduced nearly 570 million tons of CO_2 emissions. The Climate Group (2021) also predicts that by changing to energy-efficient LED technology globally, more than 1.4 billion tons of CO_2 and the construction of 1,250 power stations can be avoided. On the other hand, energy-inefficient CFLs cannot be instant-on, and their lifespan may also be degraded due to frequent switching. This caused them to be always turned on by the user even when not in use. This will further add to the amount of wasted energy, thereby increasing energy generation followed by CO_2 emissions.

Moreover, LEDs are considered the safest lighting solutions as they do not contain hazardous substances like mercury in CFLs. Exposure to the mercury neurotoxin used in CFLs is highly toxic and may cause gastrointestinal diseases and memory loss (EPA, 2021). The mercury used in CFLs also makes the disposal and recycling process challenging. In contrast, the components of an LED such as glass, metal components etc are recyclable and can be disposed of as ordinary household waste. LEDs incorporated with phosphor or organic materials are also harmless to the environment.

2.3 Lighting Retrofit

The term *retrofit* in buildings is defined as the process of modification or reconstruction of systems. In lighting retrofit, only the lighting system is modified or redesigned to meet the specific requirements.

2.3.1 Review of Lighting Retrofit

Bossysen et al. (2021) propose a model to investigate the impact of changing fluorescent lights with efficient LEDs in South African schools. The result showed that 21% to 39% of energy can be saved and 80 to 180 kg of CO_2 emission per day can be reduced. Islam et al. (2019) analyzed the case of replacing current inefficient lighting technologies with LED lighting technologies in Kazakhstan. The study describes the cost-effectiveness and energy efficiency of these lighting retrofits, which provide huge opportunities for investors. The proposed solution also gradually reduced CO_2 emissions by approximately 3 million tons. Gavioli et al. (2015) presented a study on the impact of lighting retrofitting using dimming controls on energy efficiency, lighting quality and user satisfaction. Three different scenarios were studied: retrofitting with LEDs with inbuilt active dimming control, LEDs without dimming controls and an old lighting system. The results show that by retrofitting using efficient lamps without inbuilt dimming controls, 38% energy savings can be achieved. The energy-saving of using effective lamps with active dimming control is even higher, which can save up to 68%. In addition, the user's satisfaction was improved as the retrofitted luminosity parameters are much higher than the minimum requirements of standards and the original system. Moadab et al. (2021) also reported that through the suitable use of smart lighting solutions, more than 50% of energy consumption can be saved as compared to non-smart systems.

The aforementioned studies have demonstrated the different methods and benefits of lighting retrofits. However, in addition to considering emission reductions, energy savings and cost savings, good lighting quality is also important and meeting the standard requirements is mandatory. Poor lighting quality affects not only visual effects but also affects personal safety. However, none of the studies showed that their designs met the lighting quality standards of their respective countries. Moreover, the retrofitting in a high-rise building has not been reported. As mentioned earlier, buildings account for 33% of the world's total annual energy consumption, and lighting is one of the highest, accounting for about 30% of total electricity. Therefore, expanding the scope of research into these areas can prompt investors or owners to consider the huge benefits that lighting retrofits can bring to them.

2.3.2 Building Retrofit Process and Decision Making

Building retrofit generally starts with an energy audit, as the retrofit may only include a simple replacement of the existing system or may involve a complete redesign of the system (Belany, et al., 2021). The energy audit process determines the energy consumption of the existing system and proposes energy-saving methods by combining technically feasible solutions with economic and other organizational considerations (Dzobo, et al., 2018).

Decisions must be made among all retrofit options by comparing and ranking energy retrofit alternatives based on several criteria as shown in Figure 2.2. Health/human criteria related to interior comfort are used more frequently as compared to social indicators. Environmental criteria are considered by measuring the reduction in energy consumption and CO_2 emissions. Economic assessments are usually used to support the decision-making process as they provide measurable and direct parameters to quantify the cost-effectiveness of each option and allow the economic viability of interventions to be assessed. Economic assessment methods such as LCCA are used to assess the economic viability of retrofit projects, considering all costs incurred during the life of the building (Ruggeri, et al., 2020).

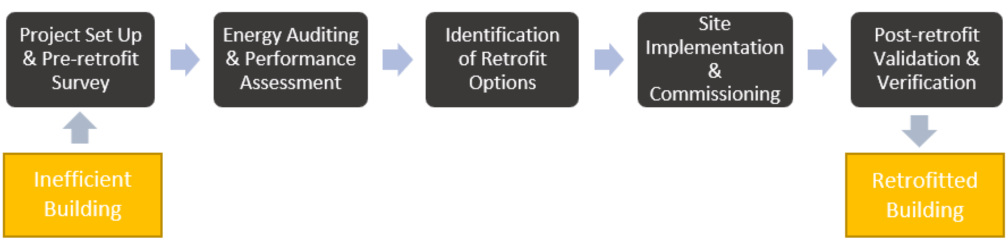


Figure 2.1: Building Retrofit Process.

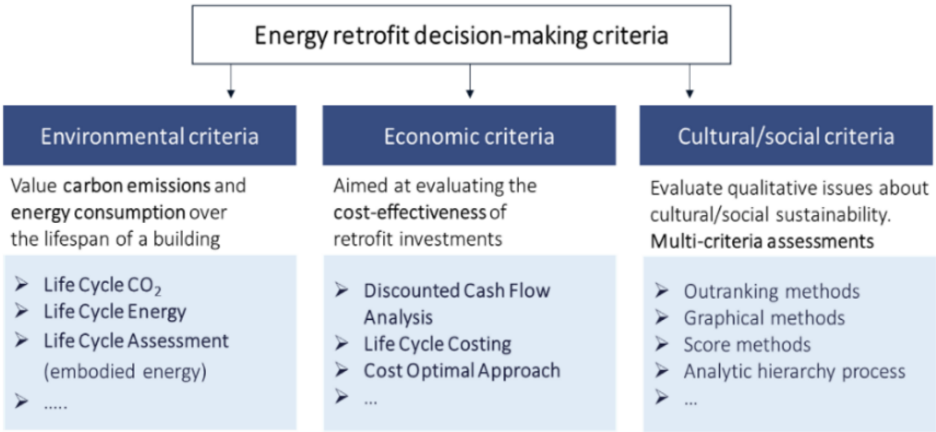


Figure 2.2: Building Retrofit Decision-Making Criteria and Assessment (Ruggeri, et al., 2020).

2.4 Lighting Design

A good lighting design is important for any workplace because lighting has biological and physical effects that can greatly affect a person. It can affect user comfort, emotion, focus, productivity and also workplace safety. The following subsections illustrate the terminology of lighting and some of the criteria and standards in lighting design. Table 2.2 shows the basic parameters that are important in a lighting system.

Table 2.2: Basic Parameters used in Lighting (ZUMTOBEL, 2013).

Parameter	Description	Unit
Luminous Flux	The amount of light emitted by a light source.	Lumens [lm]
Luminous Intensity	The amount of luminous flux radiated per solid angle in a particular direction.	Candela [cd] = [lm/sr]
Luminous Efficacy	The ratio of luminous flux to the power consumed by the luminaire.	Lumens per Watt [lm/W]
Illuminance	The quantity of luminous flux falling on a unit area.	Lux [lx] = [lm/m2]
Luminance	The brightness of a surface or object that is perceived by the eye from a specific direction.	Candela per square lumen [Cd/lm^2]

2.4.1 Design Consideration

The subsections below illustrate some criteria to be considered when designing a lighting system.

2.4.1.1 Illuminance Level

The illuminance level should be designed according to the difficulty of the task, age and the visual quality of uses. The maintained illuminance levels for different applications are specified in the MS1525 as shown in Table 2.5.

2.4.1.2 Uniformity of Illuminance

Uniformity is the ratio of the minimum to the average illuminances in a specified area. Uniformity affects the ability to perceive and control the environment. Low uniformity can cause a sudden interruption in the user experience because the lighting level drops and may cause visual discomfort. For public areas such as streets, car parks and corridors, poor uniformity makes end-users feel unsafe. The minimum uniformities are specified in the Code of Practice by SIRIM as shown in Table 2.3.

Table 2.3: Minimum Uniformity by the SIRIM Code of Practice.

Minimum Uniformity	**Applications**
0.7	• Task illuminance
0.5	• Immediate surrounding areas illuminance • Background illuminance

2.4.1.3 Glare

Glare is the visual sensation caused by the light intensity in the field of view being greater than the light intensity adapted to the eyes. A higher luminance value is the direct cause of glare. The measured parameter of glare – Unified Glare Rating (UGR) should be as low as possible to minimize the effect of glare. The UGR limits are not specified in the MS 1525 so the code of practice by SIRIM can be used as a reference guide as shown in Table 2.5.

2.4.1.4 Colour Rendering

Colour rendering is considered based on the task and the appearance of the workplace during lighting design. Colour Rendering Index (CRI) measures the ability of a light source to display the colour of an object compared to natural light sources. Higher CRI provides better colour rendering compared to the optimum reference light. The maximum CRI value is 100. CRI values over 80 are good enough. The minimum CRI for different tasks and applications are specified in the MS1525 as shown in Table 2.5.

Figure 2.3 shows the labelling of a T5 fluorescent tube. The three-digit number (i.e. 840) in the red box is the colour code that describes the lighting quality. The first digit indicates colour rendering (i.e. 8XX means the CRI is greater than 80). The second and third digits indicate the colour temperature of the light (i.e. X40 means the colour temperature is 4000 K).

Figure 2.3: Labelling of a T5 Fluorescent Tube (ZUMTOBEL, 2013)

2.4.1.5 Colour Temperature/ Colour Appearance

Colour appearance is the lamp chromaticity of the light it emits, which is characterized by Correlated Colour Temperature (CCT). Figure 2.4 illustrates the visual colour of the lighting at different CCT values. The selection of CCT for lighting should consider the illuminance, environment and application.

Table 2.4: Colour Appearance of Different CCTs and the Applications.

Light Appearance	CCT (Kelvin)	Colour Appearance	Application
Warm white (WW)	Up to 3300K	Orange yellow	Ambient lighting, Decorative lighting
Neutral white (NW)	3300 – 5300K	White	Task lighting, Bathroom lighting
Cool white (CW)	From 5300K	Bluish	Task lighting, Display lighting

Figure 2.4: Colour Appearance at Different CCT Values (Lumega, 2017).

2.4.1.6 Maintenance Factor (MF)/ Light Loss Factor (LLF)

The MF or LLF is the ratio of the luminous flux emitted by the light source at a given time during its service life and its initial luminous flux. MF depends on the maintenance characteristics of lights, lamps, environment and maintenance, as shown in equation (2.1). Figure 2.6 shows the standard maintenance factor for general applications. The accurate maintenance factor can be computed using equation (2.1) based on data given by the manufacturer, or reference tables provided in the CIE standard. The designed lighting system should provide maintained illuminance throughout its service life. According to SIRIM, the calculated MF shall not be less than 0.80.

$$MF = RSMF \times LLMF \times LMF \times LSF \tag{2.1}$$

Where
MF = Maintenance Factor, -
RSMF = Room Surface Maintenance Factor, -
LLMF = Lamp Lumen Maintenance Factor, -
LMF = Luminaire Maintenance Factor, -
LSF = Lamp Survival Factor, -

RSMF is the reduction in reflectivity due to dirt and dust build-up on the surface of a room. LMF is the reduction in light output of a luminaire due to dirt and dust build-up on the luminaire. LLMF is the reduction in light output due to lamp ageing/degradation. LSF is the reduction in light output due to lamp failure. If the lamp is replaced immediately, the LSF will be 1. Figure 2.5 shows the effect of RSMF(a), LMF(b) and LLMF(c) on illuminance levels.

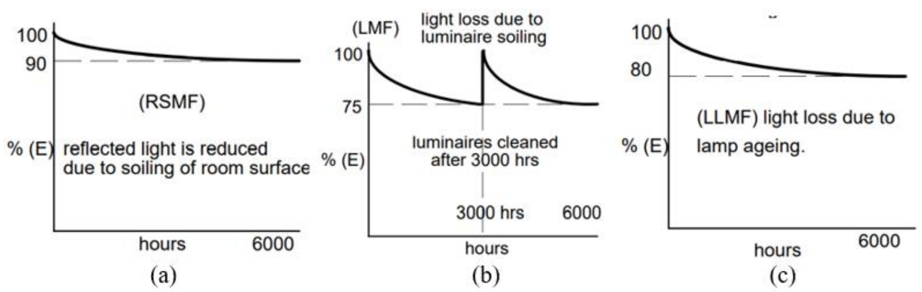


Figure 2.5: Effect of RSMF(a), LMF(b) and LLMF(c) on Illuminance Levels (Kelly & O'Connell, n.d.).

Ambient condition	Maintenance interval recommended	Working areas	Reference maintenance factor
Very Clean (**VC**)	3 years	Cleanrooms, data centres, assembly workstations for electronic components	0.80
Clean (**C**)	3 years	Offices Schools	0.67
Normal (**N**)	2 years	Shops Laboratories Restaurants Warehouses Assembly bays	0.57
Soiled (**S**)	1 year	Steel works Chemical plants Foundries Welding shops Grinding shops Wood processing	0.50
According to CIE – volume 97, “Maintenance of indoor electric lighting systems”, as at 2005			

Figure 2.6: Nominal MF for Different Conditions (ZUMTOBEL, 2013).

2.4.2 Malaysia Standard and Code of Practice for Lighting Design

There are some standards and guidelines on lighting design released by the government agencies in Malaysia, including Malaysia Standard 1525 (MS1525), SIRIM Code of Practice, JKR standards etc. In these guidelines, the criteria for lighting quality such as illuminance level (Lux level), minimum CRI and UGR limit are mentioned.

Besides lighting quality, energy efficiency also became a concern in the lighting design, especially after the introduction of sustainable development. Therefore, MS1525 also provides the limit for lighting power intensity (LPI) for a lighting system.

Table 2.5 below summarises the three different guidelines for some general building area lighting. The illuminance requirements of the three guidelines are roughly similar. Generally, the most stringent one should be followed, but sometimes may be subject to the workplace environment and requirements.

Table 2.5: Lux Level, Minimum CRI and UGR Limit of Three different Standards for Some General Building Areas.

General Building Area	MS 1525			SIRIM Standard			JKR Technical Guide
	Lux level	Min. CRI	Max. LPI (W/m^2)	Lux level	Min. CRI	UGR limit	Lux level
Corridors, Passageways	100	40	5	100	40	28	100
Interior walkway, Carpark	100	40	5	75	40	28	50
Stairs	100	40	5	150	40	25	100
Escalators, Travellators	150	40	6	150	40	25	100
Entrance, Lobbies, Waiting rooms	100	60	5	100	60	22	100
Inquiry/ Reception desk	300	80	11	300	80	22	300
Infrequent reading and writing	200	80	8	-	-	-	150
General offices, Shops, Stores reading and writing	300 – 400	80	14	300 – 500	80	19	500
Canteens	200	80	8	200	80	22	300
Rest room	150	80	8	100	80	22	100 – 150
Kitchen	150 – 300	80	11	500	80	22	300
Bathroom	150	80	6	200	80	25	100
Toilet	100	60	5	200	80	25	150
Bedroom	100	80	5	-	-	-	50

2.5 Life Cycle Cost Analysis (LCCA)

The major challenge in retrofitting is the economic feasibility study of the retrofit solution before real implementation. Investors face difficulties in making decisions due to high initial costs, unclear future forecasts etc. Simple economic study such as the simple payback method is not suitable as it excludes the system operating conditions, time value of money, profitability after payback etc. These limitations can be eliminated with the use of LCCA.

2.5.1 Life Cycle Analysis (LCA) and LCCA

LCA is the ancestral method to evaluate the environmental impact of a product or service through its life cycle which helps in decision-making on the sustainable design of products and processes, thereby reducing the usage and release of non-renewable or toxic material and the overall environmental impact. With the LCA, the necessary parameters and the operation and maintenance strategy of the product or service can be obtained and defined (Belany, et al., 2021). Nowadays, large-scale engineering projects such as power plants, and civil infrastructure are also important in sustainable development to improve energy efficiency and minimize pollution. Therefore, environmental and economic analysis throughout the project's lifetime is necessary. However, LCA itself is not enough for the evaluation as it excludes economic aspects. Therefore, LCCA comes from this, which considers all the costs throughout the life cycle of the buildings or isolated building systems, as shown in Figure 2.7.

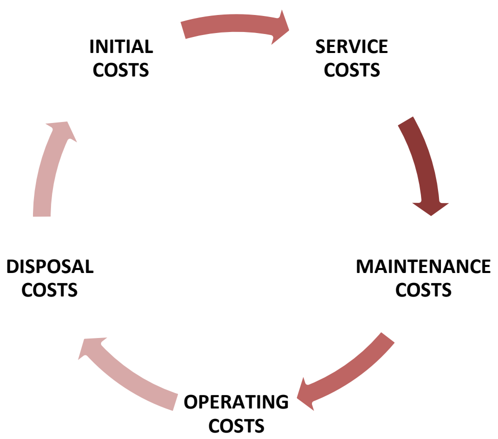


Figure 2.7: Cost Components in Life Cycle Cost.

2.5.2 LCCA in Building Retrofit

Through LCCA, the consumption development and life cycle cost curves of various solutions of the system can be determined with high precision, providing investors with more insight before implementation. The forecast results can provide better solutions for retrofits to improve the energy efficiency of the building while maximizing savings and financial returns. Presenting financial benefits such as NPV, IRR and cash flow with life cycle costs will help persuade investors to invest in retrofit projects, because they will understand the expected development in the next few years, thereby reducing investment risk.

Hajare & Elwakil (2020) explored the potential of LCCA as a green building solutions assessment tool by performing energy simulations for different solutions in their study. The authors emphasize the integration of energy modelling, energy simulation tools and LCCA during the design phase can provide more accurate outcomes. Belany et al. (2021) verifies the accuracy of LCCA on real retrofitted lighting systems in buildings. Overall, the average result error between the practical results and LCCA is only approximately 4.5%.

Moreover, LCCA considers individual operating parameters therefore the economic behaviour of the system over the years is possible to be determined accurately. In the entire life cycle of the system, each part of the system will affect the performance and LCC of the system (i.e. quality and service life of a single component). A low initial cost retrofitted system may not be the most beneficial as it may have lower quality components that will lead to earlier failure and frequent maintenance, which will increase the cost of replacement and maintenance. On the other hand, a system with a higher initial investment and high quality and efficient components can operate longer and more efficient, thereby reducing the total cost of maintenance and operation. The study by Bossysen et al. (2021) on lighting retrofit at schools in South Africa showed that buying the cheapest lights could prove to be the costliest decision over the life cycle because the investment cost differs from the LCC. Therefore, the life cycle concept is important because the outcome will be more realistic if the relevant information of each part of the system is considered.

In addition, the environmental impact can be determined through LCCA by determining the consumption during the life cycle of the retrofit system, thereby previewing the amount of greenhouse gases released during the life cycle. Reducing carbon footprint is a key area of Sustainable Development Goal 13, which can address climate change in order to control the rise in global temperature to well below the pre-industrial level of 2°C in this century, as stated in the 2015 Paris Agreement. In this context, LCCA provides a way to find the best solution to minimize greenhouse gas emissions. In the study of Coyle (2015), LCCA was used to evaluate Passive Houses to assess the suitability and optimization of the deep retrofit of Irish houses. Passive House is an extremely energy-efficient building standard that also promotes comfortable, affordable and ecological at the same time. The results also show that through extensive retrofit to the Passive House standard, the carbon dioxide emissions can be reduced by nearly 90%.

LCCA is the most suitable evaluation tool for building retrofit because it provides information on financial benefits, consumption development, energy efficiency and environmental impact under different investment scenarios, which facilitates decision-making. However, the results of LCCA can be affected by the uncertainty of LCC, including system operating time, inflation and discount rate, price changes and the average value between individual product prices, energy prices, additional losses, etc (Pérez & Cabeza, 2017) (Belany, et al., 2021). Therefore, uncertainty assessments such as sensitivity analysis are needed to carry out before the final decision.

CHAPTER 3

METHODOLOGY AND DIALUX SIMULATION

3.1 Introduction

The methodology is illustrated in the flowchart in Figure 3.1. The research flow is as shown in the following: site information, model development, luminaires analysis, energy analysis, economic analysis, and sensitivity analysis. The research project will be carried out in two phases, the preliminary study, and the comprehensive study. The flows for both phases are as follows:

i. Chapter 4 discusses the preliminary study where various lighting designs with different light sources of the common corridor on the 8th floor were simulated and evaluated through luminaires analysis.
ii. Chapter 5 discusses the comprehensive study for all the common areas of high-rise buildings and included sensitivity analysis after performing the energy and economic analyses.

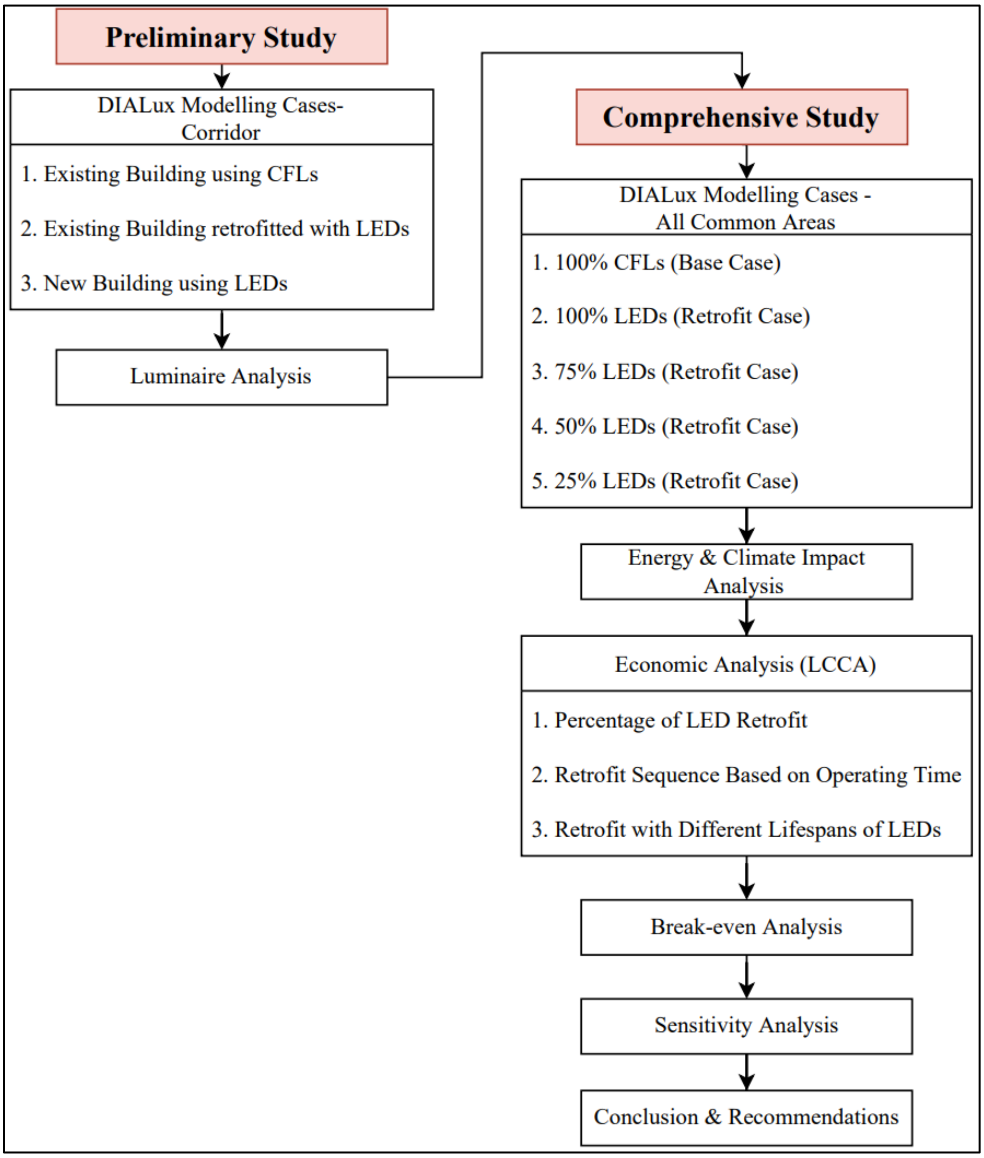


Figure 3.1: Methodology Flow Chart for Final Year Project.

3.2 DIALux Simulation

The studies were performed by modelling a residential building which is in Persiaran Medini Sentral 1, 79250, Nusajaya, Johor. This residential building consists of 41 floors with a total floor area of 187600m^2. The details of the building description are shown in Table 3.1.

Table 3.1: Building Description.

Floor Level	Floor Type	Floor-to-floor Height (m)	Floor Area (m^2)
LF & GF	Retail	7.5	19840
1F-5F	Carpark Podium	3.0	11700
6F	Carpark Podium	4.0	11700
7F	Amenities	7.0	11700
8F-39F	Tenant	3.1	2840
40F	M&E, Rooftop	5.4	2840

Common areas were considered in both primary and comprehensive studies. Common areas are those parts of a building that are generally available to all occupants, such as hallways, stairs, playgrounds, lobbies, parking lots, and entertainment areas. Table 3.2 shows the classifications of the common areas in the building.

The site was modelled using DIALux Evo software with imported CAD drawings as reference. Different types of light sources were found on the manufacturer's website or using LUMsearch. Figure 3.2 shows the light placement and arrangement methods in DIALux. The luminaires were placed automatically by selecting different types of arrangements based on the spaces and then adjusted manually to achieve the illuminance level and uniformity in accordance with the standards. The requirement of uniformity is 0.5 according to SIRIM standards whereas the required illuminance levels vary for different spaces as shown in Table 3.2.

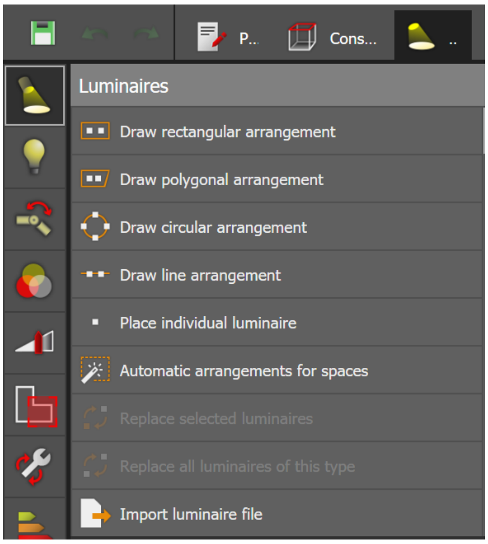


Figure 3.2: Light Placement and Arrangement Methods in DIALux.

In DIALux, the illuminance levels were measured on the work plane, which was determined according to the function of the space as shown in Table 3.2. Work plane height is the horizontal plane measured from the floor that spans the entire room and represents the typical height of a desk or work surface. The CCTs were set according to the environment and application as shown in Table 3.2.

Moreover, the MF is set to 0.8 according to the SIRIM standard to ensure that the illuminance level can be maintained during the service life. The MF is considered because the illuminance level will drop after a period of use due to the luminaire factors such as lamp degradation, failure and dust and dirt build-up; environmental factors such as reduced reflectivity due to dirt and dust build-up on room surfaces.

Finally, DIALux software will calculate the illuminance level, uniformity, and lighting power intensity and generate a report for reference. Value charts, isolines and false colour rendering of the calculation surface (work plane) can also be investigated using DIALux after the calculation. The illuminance level and uniformity of each space are required to meet the standards.

Table 3.2: Work Plane Height, Illuminance Level and CCT for All Common Areas in the Building.

Classification	**Common Area**	**Work Plane Height (m)**	**Min. Illuminance Level (lux)**	**CCT (K)**
Semi-enclosed/ Semi-open Space	• Carpark	0	100	3000
Connecting Space	• Corridor, • Lift lobby, • Service lift lobby			
	• Stairs	Treads & Landings		
Facilities				
Composite Space	• Multipurpose Room	0.8	300	4000
	• AV Room		200	
	• Function room			
	• Family party room			
	• Indoor Lounge		100	3000
	• Jacuzzi	0	150	
	• Sauna/ Steam Bath/ Shower Room			
Standard Space	• Gymnasium	0.8	300	4000
	• In-door Golf Room			
	• Squash Room			
	• Table Tennis Room			
	• Public toilet	0	100	

CHAPTER 4

PRELIMINARY STUDY

4.1 DIALux Modelling

The corridor area of the 8th floor, which is one of the typical floors for tenants was chosen for the preliminary case studies. The layout plan of the 8th floor is shown in Figure 4.1. The green shaded area is the corridor area, which was used to perform the case study. The enlarged figure and measurement (in mm) of the corridor area can be found in Figure 4.2. The 3D model of the corridor is shown in Figure 4.3.

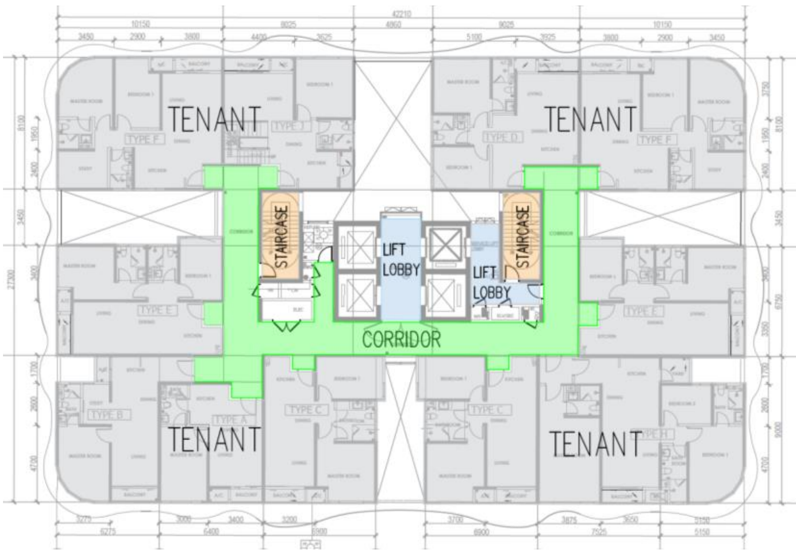


Figure 4.1: 8th Floor Layout Plan of the Building.

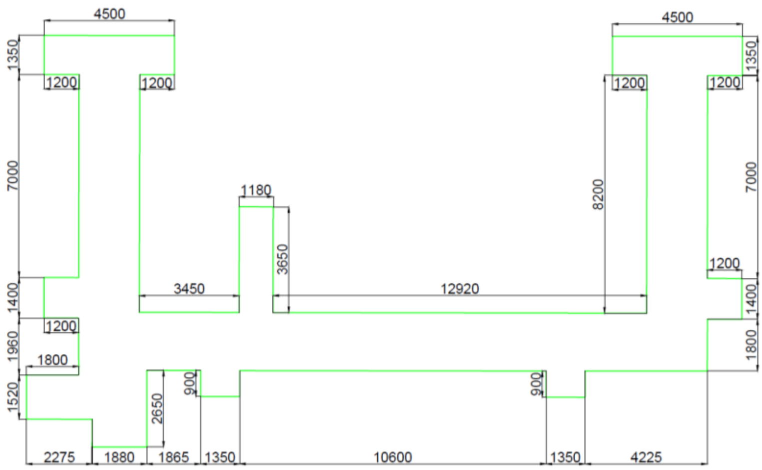


Figure 4.2: 2D Model of the Corridor (in mm).

Figure 4.3: 3D Model of the Corridor in DIALux Evo.

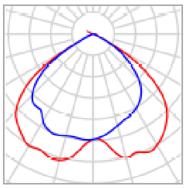
Three scenarios with different light sources were considered in this study and the details of each case study will be described in the following chapter. The scenarios are as follows:

Case 1: Existing Building Installed with Energy Inefficient Lighting System.
Case 2: Existing Building Retrofitted with Energy Efficient Lighting System.
Case 3: New Building Installed with Energy Efficient Lighting System.

4.1.1 Case 1: Existing Building Installed with Energy Inefficient Lighting System

The lighting system for the existing building was designed using energy inefficient CFL, and the details of the luminaires are shown in Table 4.1. The location of luminaries was adjusted to meet the lighting quality requirement in MS 1525, SIRIM, and JKR standards. Besides the illuminance level and uniformity mentioned in Table 2.5, the maximum lighting power intensity (LPI) is 5 W/m^2 under MS1525. The tabulated results for simulated illuminance level, uniformity and lighting power intensity are shown in Table 4.2.

Table 4.1: Details of Luminaire used in Case 1.

Base Case	**Case 1**
Types of Luminaires	BS 33-FL-14112
Abbreviation	28W CFL Bulb
Luminous Flux (lm)	1449
Luminous Efficacy (lm/W)	52
Power Rating (W)	28
Polar Curve	

According to Figure 4.4, a total of 14 lighting points were designed and the distance between each lighting point is in the range of 2.1 m to 4.2 m. As a rule of thumb, the fixtures are placed equidistant from each other, and the spacing is determined by dividing the ceiling height by two. For example, if the ceiling is 3.1m, the spatial distance between each lighting point is 1.55 m. This is to ensure that the illuminance variation (i.e. uniformity) of the entire working plane is acceptable. Since the corridor is an irregular polygon, it is difficult for the fixtures to be spaced 1.55 m apart and equidistant from each other. However, the designed lighting system achieved the illuminance level of 109 lx and uniformity of 0.49 with the least number of lighting points as shown in Table 4.2. Therefore, the distance between lighting points of 2.1 m to 4.2 m is acceptable.

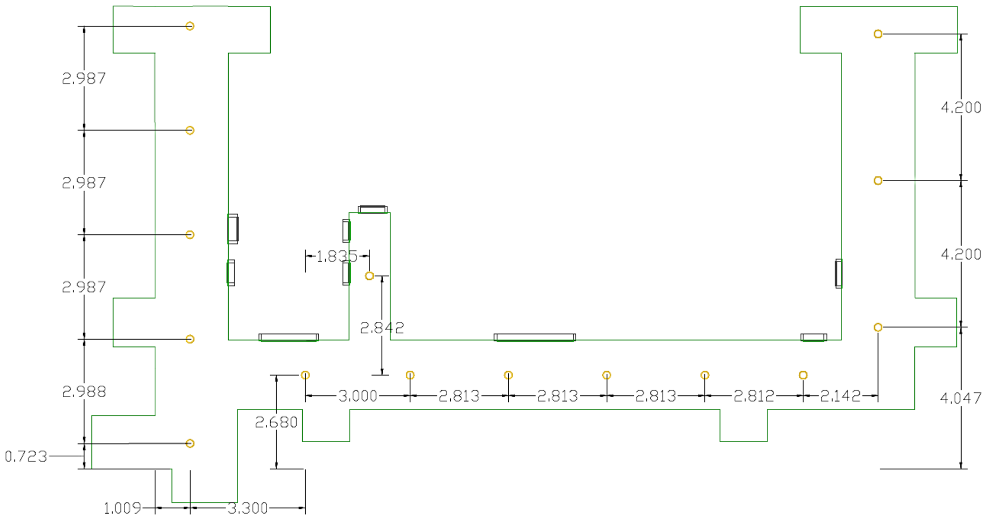


Figure 4.4: Placement of Luminaires in Case 1 (in meter).

Figure 4.5 shows the ray-tracing model located lower-left corner of the corridor lit by all lamps. The brightness of the entire area is acceptable, and there is no sudden drop of brightness on the work plane between the two lighting points.

Figure 4.5: 3D Simulation Model in Case 1.

Figure 4.6 shows the isolines and value charts which illustrate the illuminance level at a particular point of investigation of the calculated lighting system. The illuminance level on the work plane is in a range from 60 to 150 lx. The difference in range affects the uniformity as uniformity is the ratio of the minimum illuminance to the average illuminance levels. If the range is wider, the uniformity decreases, which means that the light distribution is uneven. Based on Table 4.2, the lighting system has a good uniformity of 0.49, which is very close to the 0.5 required by SIRIM. Furthermore, the LPI in Case 1 is 3.86 W/m^2, which is within the limit of MS 1525. LPI of 3.86 W/m^2 means that 3.86 W is consumed per unit floor area of illuminated space.

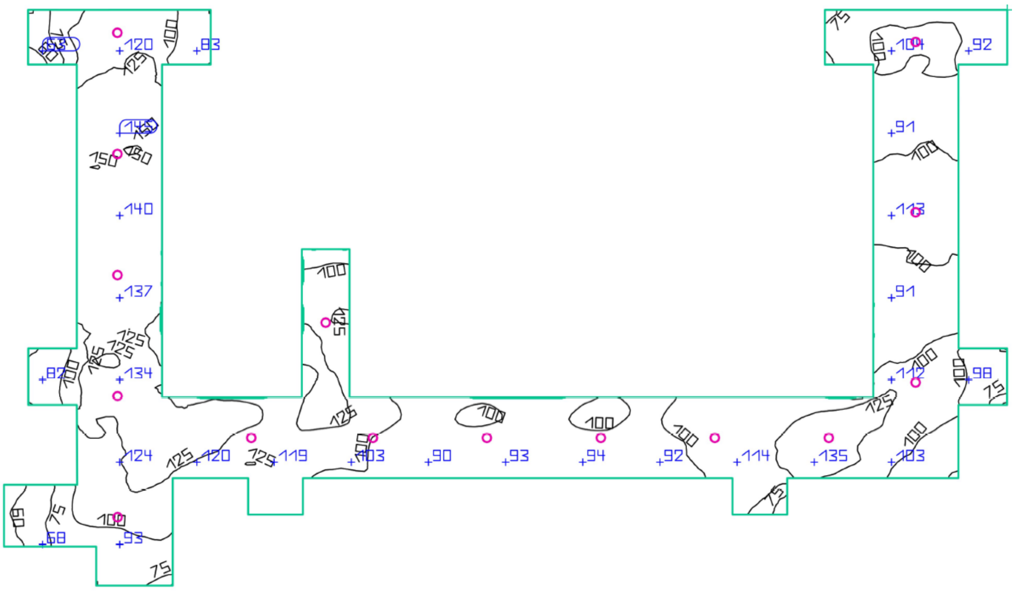


Figure 4.6: Isolines and Value Chart on the Work Plane in Case 1.

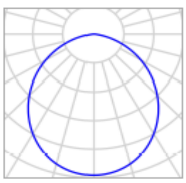
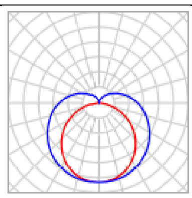
Table 4.2: Summary of DIALux Simulation Results in Case 1.

Base Case	**Case 1**	
Type of Luminaire (-)	28W CFL Bulb	
Luminous Flux (lm)	1449	
No. of Luminaires (-)	15	
Total System Power (W)	420	
	Standard **[MS1525, JKR & SIRIM]**	**Simulated**
Illuminance Level (lx)	100	109
Uniformity (-)	0.5	0.49
LPI (W/m^2)	5 (Max)	3.86

4.1.2 Case 2: Existing Building Retrofitted with Energy Efficient Lighting System

Case 2 is the lighting retrofit of Case 1 with energy-efficient lighting sources (i.e. the LED). Case 2 is further refined into Case 2(a) and Case 2(b), using two different types of LEDs with different specifications such as model, rating, and luminous flux for the retrofit design. The location of luminaires is fixed as in Case 1, only the light source is changed. Two case studies with different LED light sources were simulated to achieve the standard requirement. The final light sources selected for two retrofit designs which are Case 2(a) and Case2(b) are shown in Table 4.3. The tabulated simulation results for average illuminance level, uniformity and lighting power intensity are shown in Table 4.4.

Table 4.3: Details of Luminaires used in Case 2.

Retrofit Cases	**Case 2(a)**	**Case 2(b)**
Types of Luminaires	DN296B LED15S-6500 PSU WH	MasterConnect LEDtube InstantFit T8 14T8/48-3000
Abbreviation	13W LED Downlight	14W LED Tube
Luminous Flux (lm)	1500	2000
Luminous Efficacy (lm/W)	110	142
Power Rating (W)	13	14
Polar Curve		

The luminaires' placements are illustrated in Figure 4.7 (Case 2(a)) and Figure 4.8 (Case 2(b)). The spacing between the lighting points is the same as in Case 1, with a range of 2.1 m to 4.2 m. Based on Table 4.4, the retrofit Case 2(a) and 2(b) can maintain the illuminance level of 110 and 105 lx respectively, which meet the requirement in standards.

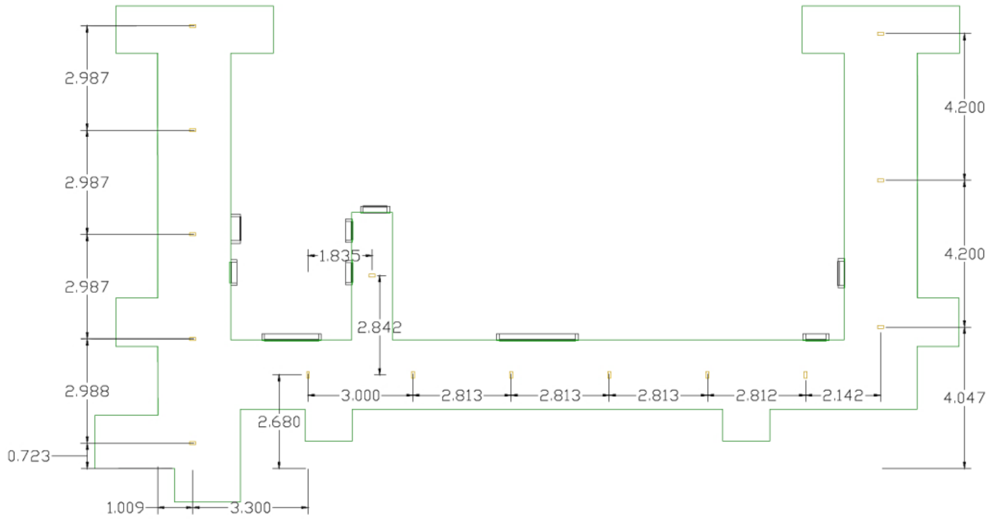


Figure 4.7: Placement of Luminaires in Case 2(a) (in meter).

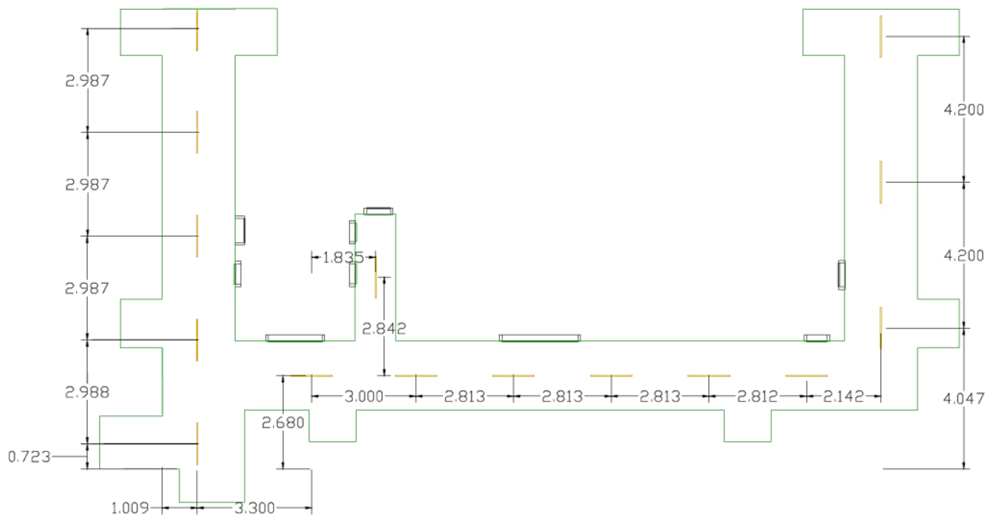


Figure 4.8: Placement of Luminaires in Case 2(b) (in meter).

The ray-tracing model of the lower-left corner of the corridor is shown in Figure 4.9 (Case 2(a) and Figure 4.10 (Case 2(b)). The brightness of the entire area for both cases is acceptable, and there is no sudden huge drop of brightness on the work plane between the two lighting points. It can be seen that the light distribution in Case 2(b) is wider than in Case 2(a) because there is a huge drop between the two lighting points near the ceiling as shown in Figure 4.9. This can be proved by the polar curve of the light source used as in Table 4.3. The polar curve of the 14W LED Tube used in Case 2(b) is wider, which means that the distributed light coverage is bigger.

Figure 4.9: 3D Simulation Model in Case 2(a).

Figure 4.10: 3D Simulation Model in Case 2(b).

Based on the isolines and value charts shown in Figure 4.11 and Figure 4.12, the illuminance level is in the range of 50 to 155 lx for Case 2(a) and 74 to 156 lx for Case 2(b). Since the difference between the minimum and maximum values for Case 2(a) is larger, the uniformity is only 0.42, which is lower than 0.48 in Case 2(b) as shown in Table 4.4. This means that the light distribution in Case 2(a) is not as good as in Case 2b, this also matches with the previous discussion on the ray-tracing model in Figure 4.9 and Figure 4.10.

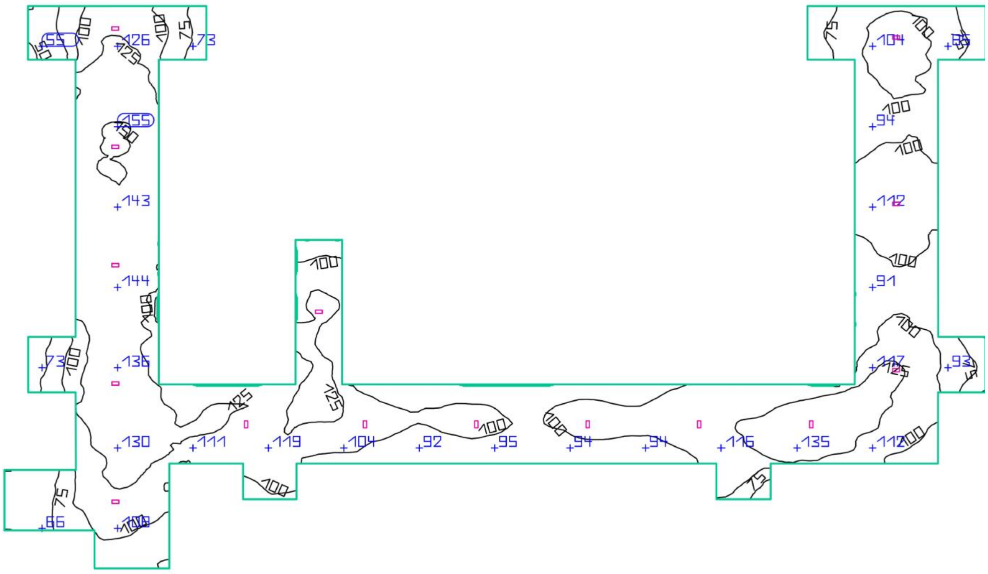


Figure 4.11: Isolines and Value Chart on the Work Plane in Case 2(a).

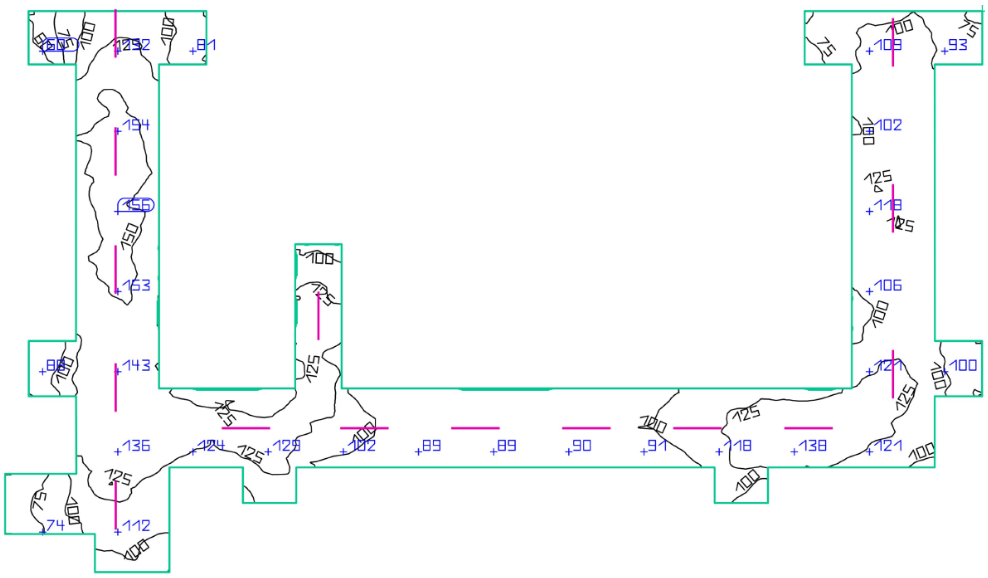


Figure 4.12: Isolines and Value Chart on the Work Plane in Case 2(b).

Furthermore, the LPIs for both cases are within the limit in MS 1525. However, the LPI of Case 2(a) (1.85 W/m^2) is lower than Case 2(b) (1.93W/m^2). This means that the lighting system in Case 2(a) consumed less power per unit floor area of illuminated space.

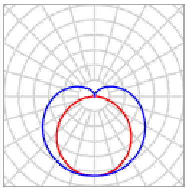
Table 4.4: Summary of DIALux Simulation Results in Case 2.

Retrofit Cases	**Case 2(a)**	**Case 2(b)**
Type of luminaires	13W LED Downlight	14W LED Tube
Lamp Luminous flux (lm)	1500	2000
No. of Luminaires	15	15
Total System Power (W)	195	210
Illuminance Level (lx) [MS1525 & JKR]	100	
Simulated Illuminance Level (lx)	110	115
Uniformity [SIRIM]	0.5	
Simulated Uniformity	0.42	0.48
Max. LPI (W/m^2) [MS 1525]	5	
Simulated LPI (W/m^2)	1.85	1.93

4.1.3 Case 3: New Building Installed with Energy Efficient Lighting System

The lighting system for a new building was designed with the use efficient light source (i.e. the LEDs) instead of the inefficient light source (i.e. the CFLs) as in Case 1. Table 4.5 shows the luminaire type used in this case and its details. The placement of luminaries was adjusted to meet the standard requirements: illuminance level of 100 lx, lighting power intensity within 5 W/m^2 and uniformity of 0.5.

Table 4.5: Details of Luminaire used in Case 3.

New Building Design	**Case 3**
Types of Luminaires	MasterConnect LEDtube InstantFit T8 14T8/48-3000
Abbreviation	14W LED Tube
Luminous Flux (lm)	2000
Luminous Efficacy (lm/W)	142
Power Rating (W)	14
Polar Curve	

The final placement of the luminaire with measurement is shown in Figure 4.13. A total of 13 lighting points were designed and the distance between each illuminating point is in the range of 2.5 m to 4.2 m. Based on the result in Table 4.6, the designed lighting system achieved the illuminance level of 102 lx, which met the standard requirement.

The ray-tracing model at the lower-left corner of the corridor is shown in Figure 4.14. The brightness of the entire area is good, and there is no sudden drop of brightness on the work plane between the two lighting points.

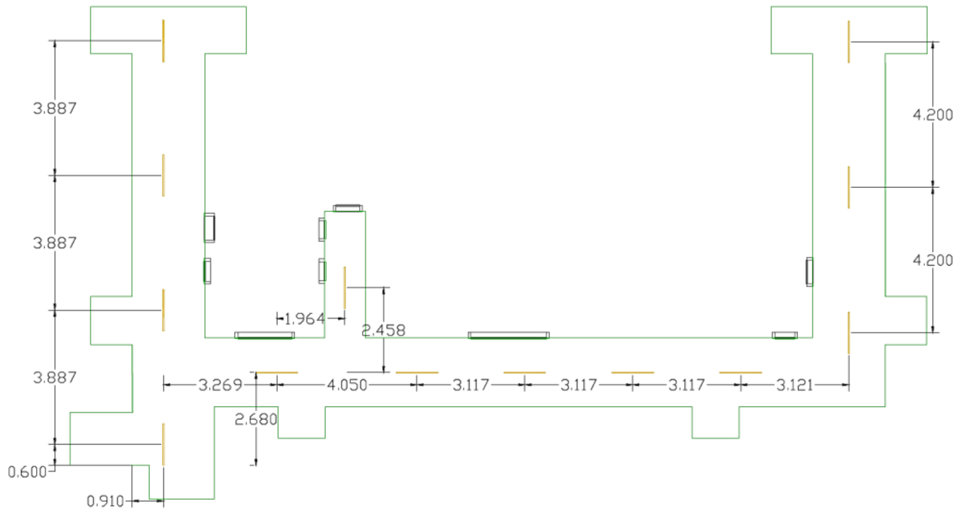


Figure 4.13: Placement of Luminaires in Case 3 (in meter).

Figure 4.14: 3D Simulation Model in Case 3.

Based on the isolines and value charts in Figure 4.15, the illuminance level on the work plane is in a range from 68 to 130 lx and the uniformity is 0.51 (based on Table 4.6), which met the requirement of 0.5 in the SIRIM standard. Furthermore, the LPI in Case 3 is 1.67 W/m^2 according to Table 4.6, which is far from the limit of MS 1525 (5 W/m^2). A lighting power intensity of 1.67 W/m^2 means that 1.67 W is consumed per unit floor area of illuminated space.

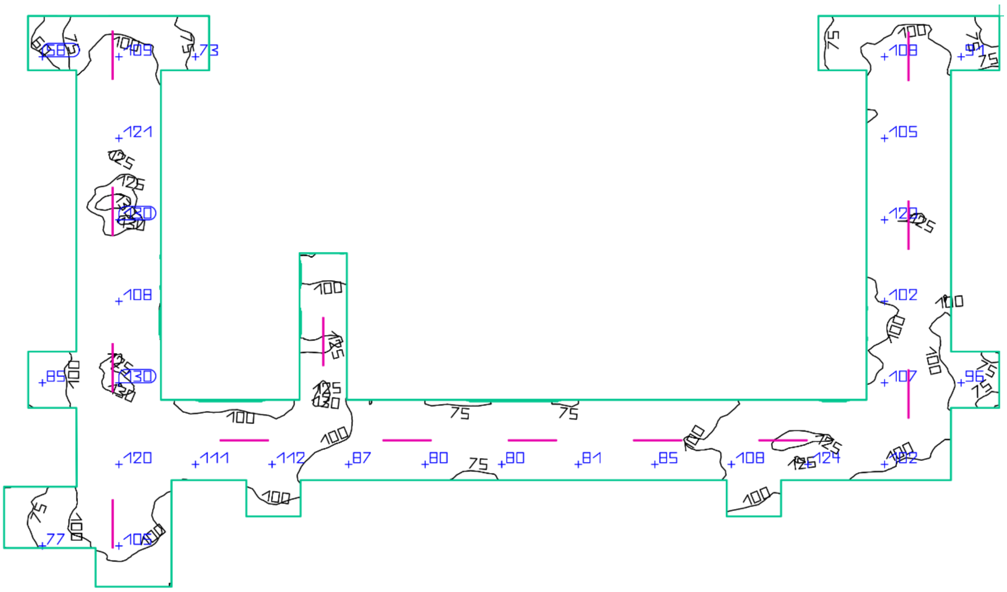


Figure 4.15: Isolines and Value Chart on the Work Plane in Case 3.

Table 4.6: Summary of DIALux Simulation Results in Case 3.

New Building Design	**Case 3**	
Type of Luminaire	14W LED Tube	
Lamp Luminous Flux (lm)	2000	
No. of Luminaires	13	
Total System Power (W)	182	
	Standard **[MS1525, JKR & SIRIM]**	**Simulated**
Illuminance Level (lx)	100	102
Uniformity	0.5	0.51
LPI (W/m^2)	0.5 (Max)	1.67

4.2 Comparative Luminaires Analysis for All Cases

Table 4.7 shows the summary results for all cases. Based on Figure 4.16, the illuminance levels for all cases exceed the 100 lux that is required by standards. Case 2b has the highest illuminance level of 115 lux because the 14W LED Tube has a wider polar curve and a high luminous flux of 2000lm, as shown in Table 4.4. Luminous flux is a measure of the total amount of visible light emitted by a lamp. Luminous flux is often a criterion of light bulb comparison because it will affect the illuminance levels. This is validated in Table 4.7 that for the same number of luminaires, higher luminous flux gives a higher illuminance level.

Table 4.7: Summary of DIALux Simulation Results for All Cases.

	Base Case	**Retrofit Cases**		**New Building**
	Case 1	**Case 2(a)**	**Case 2(b)**	**Case 3**
Type of luminaire	28W CFL Bulb	13W LED Downlight	14W LED Tube	14W LED Tube
Lamp Luminous Flux (lm)	1449	1500	2000	2000
No. of Luminaires	15	15	15	13
Total System Power (W)	420	195	210	182
Illuminance level (lx) [MS1525, JKR & SIRIM]	100			
Simulated Illuminance Level (lx)	109	110	115	102
Uniformity [SIRIM]	0.5			
Simulated Uniformity	0.49	0.42	0.48	0.51
Max. LPI (W/m^2) [MS 1525]	5			
Simulated LPI (W/m^2)	3.86	1.85	1.93	1.67

For the maintained uniformity, Case 2(a) has the lowest uniformity because the polar curve of 13W LED Downlight has the smallest coverage, therefore the light level might slightly drop in between two lighting points, causing the reduction in uniformity. On the other hand, the uniformity in Case 3 is the highest even if the illuminance level is not the highest. Despite that Case 2(b) and Case 3 use the same type of LED, the placement and number of luminaires are different. More lighting points (15 points) in Case 2(b) will result in a reduction in spacing between lighting points, which may cause some light to be concentrated on a specific point, resulting in extremely high illuminance at that point. This will cause the difference between the minimum illuminance and maximum illuminance to become larger, and the uniformity will decrease.

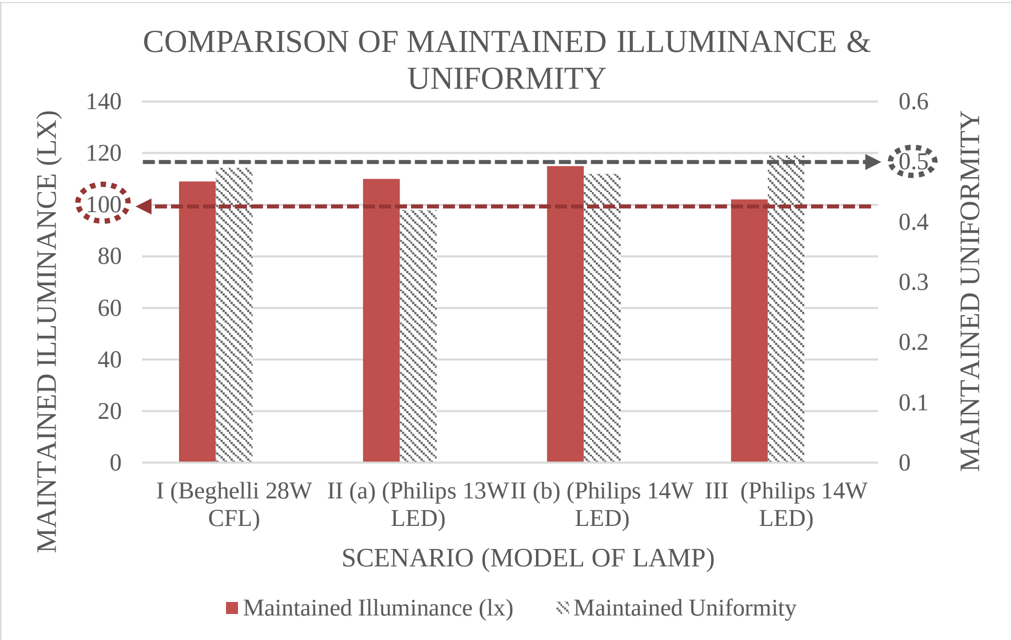


Figure 4.16: Comparison of Maintained Illuminance and Uniformity for All Cases.

Based on Figure 4.17, the power consumption (420 W) and the number of luminaires (15 points) of Case 1 are the highest among all cases because the inefficient 28W CFL bulb has the highest power rating and lowest luminous efficacy. Luminous efficacy is the ratio of luminous flux to power, which measures how efficiently a light source produces visible light. Higher luminous efficacy means the light source is more energy efficient. Therefore, the light source used in Case 1 is considered as least efficient.

For retrofit Case 2, with the same number of fittings as in Case 1, the total power consumption is only 50% of that of Case 1. This huge reduction is due to the retrofit using energy-efficient LED that can achieve the same illuminance level with lesser power consumption. When comparing cases 2a and 2b, the power consumption for both retrofit systems is similar as the lamp powers are almost the same (13W in Case 2(a) and 14W in Case2(b).

The power consumption in Case 3 is the lowest among all cases, with a value of 182 W due to lesser lighting points (13 points). The good thing about a new building that is directly used LED for lighting system design is that the required luminaires to achieve the illuminance level and uniformity can be varied, unlike the retrofit building that has fixed the number of lighting points.

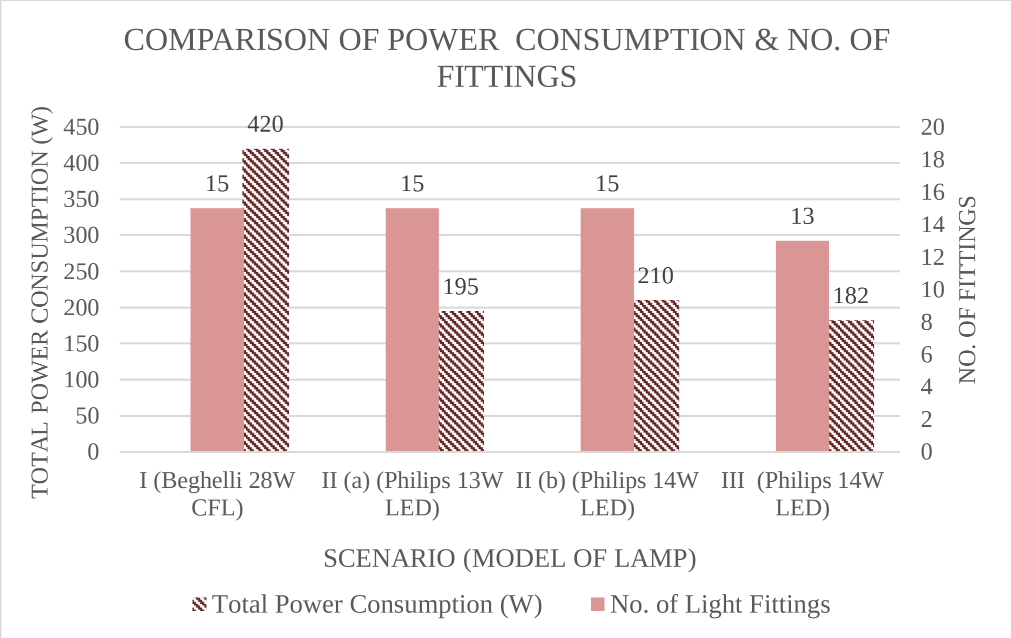


Figure 4.17: Comparison of Power Consumption and No. of Luminaires for All Cases.

Based on Figure 4.18, the LPI of Case 1 is the highest of all cases, valued at 3.86 W/m^2. LPI is the power consumed by lighting installations per unit floor area of illuminated space. The system power of Case 1 is the highest (420W), causing more power to be received by a surface per unit area as compared to others.

With the use of LED for retrofit and new design, the LPI is reduced almost by 50% for Cases 2a, 2b and 3 as compared to Case 1. With Case 3 is the lowest among all cases, with a value of 1.67 W/m^2. For the LED and CFL that have similar luminous flux, the power rating for LED is far less than the

CFL, which can be supported by Table 2.1. This is because LED has higher efficiency in wattage to light and heat output conversion as compared to conventional light sources (Qeos LED, 2021). It shows that using energy-efficient LED can gradually reduce the power consumption, which thereby reduces the LPI because LPI is measured in W/m^2. Under the illuminance level requirement by the standards, using LED to retrofit will not exceed the LPI limits.

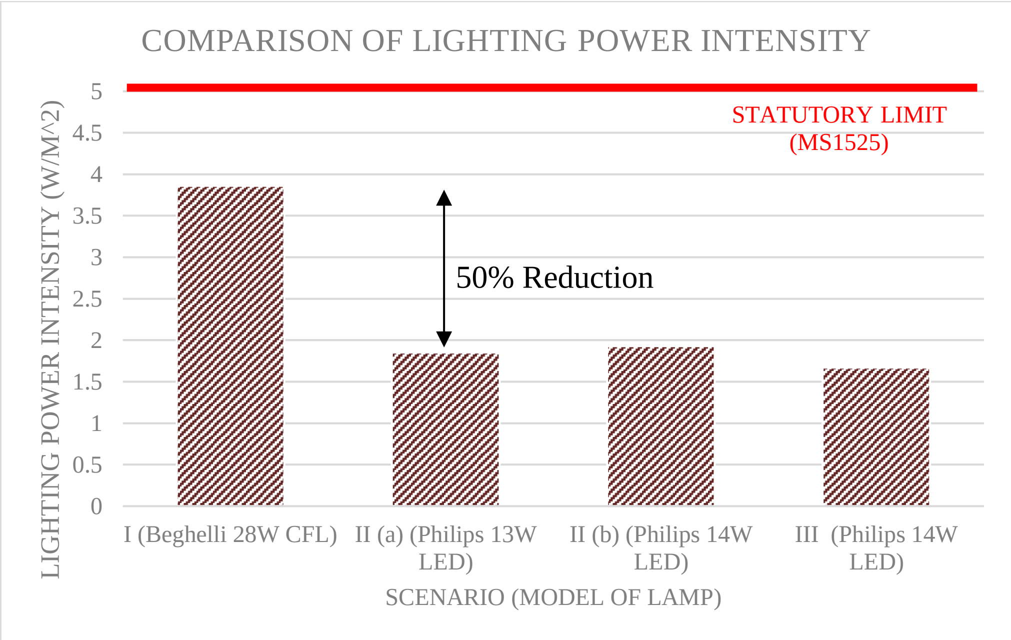


Figure 4.18: Comparison of LPI for All Cases.

In a nutshell, since the number and the location of luminaires in the existing lighting system are fixed, retrofit design for the lighting system has to compensate for these issues. Therefore, choosing the right luminaires for retrofit is important to ensure the energy-efficient can be achieved and at the same time the lighting quality can also be maintained as follow the standards.

Based on the above discussion, when choosing luminaires for retrofit, luminous flux has to be as close as or higher than the existing luminaires because lower luminous flux will reduce the illuminance level. To ensure a good uniformity, luminaires with a wider polar curve are preferred except for applications that use decorative lights, spotlights etc. Moreover, as long as under the illuminance level and uniformity requirement by the standards, using LED to retrofit will not exceed the LPI limits.

CHAPTER 5

COMPREHENSIVE STUDY

5.1 DIALux Modelling

All the common areas in the building were modelled in DIALux software. Figure 5.1 and Figure 5.2 show the typical layout and the 3D model of the car park area, respectively. In this comprehensive study, several types of CFLs and LED luminaires were used in modelling to achieve the required illuminance level. Table 5.1and Table 5.2 show the type of CFLs and LEDs that were used in this comprehensive study, respectively.

Figure 5.1: Typical Layout Plan of the Car Park Area.

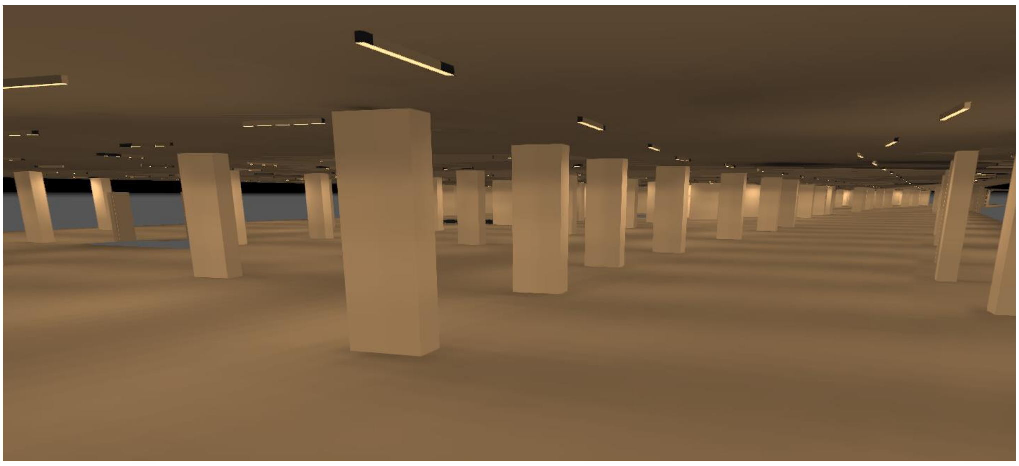


Figure 5.2: 3D model of the Car Park Area in DIALux.

Table 5.1: Type of CFLs Used in Modelling.

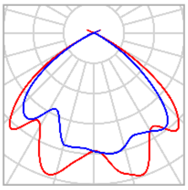
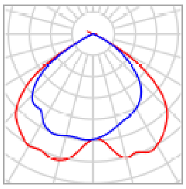
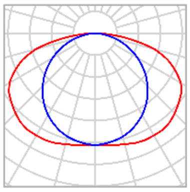
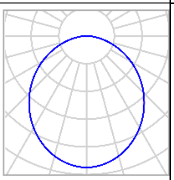
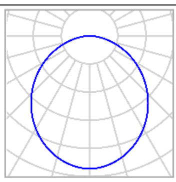
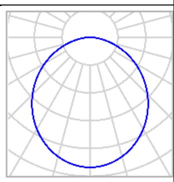
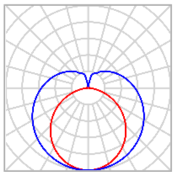
Types of Luminaires	BS 33-FL-14111	BS 33-FL-14112	TMS022 UK 1XTL-D36W HFS +GMS022R
Abbreviation	17W CFL Bulb	28W CFL Bulb	36W CFL Tube
Luminous Flux (lm)	1015	1449	3250
Luminous Efficacy (lm/W)	59.7	52	74.3
Power Rating (W)	17	28	36
Lifespan (h)	20000	20000	20000
Polar Curve			

Table 5.2: Type of LED Luminaires Used in Modelling.

Types of Luminaires	DN027C LED12/WW D175	DN027C LED15/WW D200	DN027C LED20/WW D225	MASTER LEDtube 1200mm HO 26W 830 T5
Abbreviation	14W LED Downlight	17W LED Downlight	22W LED Downlight	26W LED Tube
Luminous Flux (lm)	1200	1500	2000	3600
Luminous Efficacy (lm/W)	85.7	88.2	90.9	138.5
Power Rating (W)	14	17	22	26
Lifespan (h)	50000	50000	50000	50000
Polar Curve				

Five scenarios with different degrees of lighting retrofit were considered in this study as shown in Table 5.3. Case 1 is a base case for an existing inefficient lighting system. Different types of CFLs with different power ratings and models were used in the modelling to achieve the required illuminance level in MS1525. There is a total of 8,206 CFLs in all common areas of the building.

Case 2 to Case 5 are the retrofits of the base case (Case 1), with different degrees of retrofit in each case. The retrofit lighting systems were modelled by replacing the different amounts of the existing CFLs with different types of LED lamps with different power ratings and models to achieve the required illuminance level in the MS1525. The total number of luminaires is maintained as 8206 lamps for all cases. The details of the distribution of luminaires for each retrofit case are described in Table 5.4 to Table 5.8.

Table 5.3: Five Cases with Different Degree of Lighting Retrofit.

Case	Description	No. of CFLs	No. of LEDs
1	Existing Lighting System Installed with 100% CFL	**8206**	**-**
2	Retrofitted Lighting System Installed with 100% LED	**-**	**8206**
3	Retrofitted Lighting System Installed with 75% LED + 25% CFL	**2051**	**6155**
4	Retrofitted Lighting System Installed with 50% LED + 50% CFL	**4103**	**4103**
5	Retrofitted Lighting System Installed with 25% LED + 75% CFL	**6154**	**2052**

Table 5.4: Distribution of Luminaires for Case 1 (100% CFL).

Common Area	Daily Operation Hours (h)	Lamp Lifespan (month)	Type of Lamps	No. of CFLs	No. of LEDs	Retrofit with LED
Corridor	14	47	28W CFL Bulb	1963	-	-
		47	36W CFL Tube	79	-	
Stairs	24	27	28W CFL Bulb	1056	-	-
Lift Lobby/Service Lift Lobby	14	47	28W CFL Bulb	462	-	-
		47	17W CFL Bulb	456	-	
Car Park	14	47	36W CFL Tube	3764	-	-
Toilet (F/M/D)	17	39	17W CFL Bulb	15	-	-
		39	28W CFL Bulb	48	-	
Jacuzzi/Sauna/Steam Bath/ Shower Room	17	39	28W CFL Bulb	85	-	-
Mail Room	24	27	28W CFL Bulb	23	-	-
In-door Golf/Squash/ Table Tennis	17	39	28W CFL Bulb	89	-	-
Gym	17	39	28W CFL Bulb	40	-	-
Multipurpose Room	14	47	28W CFL Bulb	38	-	-
Function Room	14	47	28W CFL Bulb	37	-	-
Family Party Room	14	47	28W CFL Bulb	16	-	-
Indoor Lounge	17	39	28W CFL Bulb	18	-	-
AV Room	14	47	28W CFL Bulb	17	-	-
Total No. of Luminaires (CFL+LED)				8206	0	**8206**

Table 5.5: Distribution of Luminaires for Case 2 (100% LED).

Common Area	**Daily Operation Hours (h)**	**Lamp Lifespan (month)**	**Type of Lamps**	**No. of CFLs**	**No. of LEDs**	**Retrofit with LED**
Corridor	14	119	17W LED Downlight	-	1963	✓
		119	26W LED Tube	-	79	
Stairs	24	69	14W LED Downlight	-	1056	✓
Lift Lobby/Service Lift Lobby	14	119	17W LED Downlight	-	432	✓
		119	22W LED Downlight	-	30	
		119	14W LED Downlight	-	456	
Car Park	17	98	26W LED Tube	-	3764	✓
Toilet (F/M/D)	17	98	14W LED Downlight	-	19	✓
		98	17W LED Downlight	-	44	
Jacuzzi/Sauna/Steam Bath/ Shower Room	24	69	17W LED Downlight	-	85	✓
Mail Room	17	98	17W LED Downlight	-	23	✓
In-door Golf/Squash/ Table Tennis	17	98	17W LED Downlight	-	89	✓
Gym	14	119	22W LED Downlight	-	40	✓
Multipurpose Room	14	119	17W LED Downlight	-	38	✓
Function Room	14	119	17W LED Downlight	-	37	✓
Family Party Room	17	98	22W LED Downlight	-	16	✓
Indoor Lounge	14	119	17W LED Downlight	-	18	✓
AV Room	14	119	22W LED Downlight	-	17	✓
Total No. of Luminaires (CFL+LED)				0	8206	**8206**

Table 5.6: Distribution of Luminaires for Case 3 (75% LED + 25% CFL).

Common Area	**Daily Operation Hours (h)**	**Lamp Lifespan (month)**	**Type of Lamps**	**No. of CFLs**	**No. of LEDs**	**Retrofit with LED**
Corridor	14	119	17W LED Downlight	-	1963	✓
		119	26W LED Tube	-	79	
Stairs	24	27	28W CFL Bulb	1056	-	
Lift Lobby/Service Lift Lobby	14	47	28W CFL Bulb	462	-	
		47	17W CFL Bulb	456	-	
Car Park	14	119	26W LED Tube	-	3764	✓
Toilet (F/M/D)	17	98	14W LED Downlight	-	19	✓
		98	17W LED Downlight	-	44	
Jacuzzi/Sauna/Steam Bath/ Shower Room	17	98	17W LED Downlight	-	85	✓
Mail Room	24	69	17W LED Downlight	-	23	✓
In-door Golf/Squash/ Table Tennis	17	98	17W LED Downlight	-	89	✓
Gym	17	39	28W CFL Bulb	40	-	
Multipurpose Room	14	47	28W CFL Bulb	38	-	
Function Room	14	119	17W LED Downlight	-	37	✓
Family Party Room	14	119	22W LED Downlight	-	16	✓
Indoor Lounge	17	98	17W LED Downlight	-	18	✓
AV Room	14	119	22W LED Downlight	-	17	✓
Total No. of Luminaires (CFL+LED)				2051	6155	**8206**

Table 5.7: Distribution of Luminaires for Case 4 (50% LED + 50% CFL).

Common Area	**Daily Operation Hours (h)**	**Lamp Lifespan (month)**	**Type of Lamps**	**No. of CFLs**	**No. of LEDs**	**Retrofit with LED**
Corridor	14	47	28W CFL Bulb	1963	-	
		47	36W CFL Tube	79	-	
Stairs	24	27	28W CFL Bulb	1056	-	
Lift Lobby/Service Lift Lobby	14	47	28W CFL Bulb	462	-	
		47	17W CFL Bulb	456	-	
Car Park	14	119	26W LED Tube	-	3764	✓
Toilet (F/M/D)	17	98	17W CFL Bulb	15	-	
		98	28W CFL Bulb	48	-	
Jacuzzi/Sauna/Steam Bath/ Shower Room	17	98	17W LED Downlight	-	85	✓
Mail Room	24	27	28W CFL Bulb	23	-	
In-door Golf/Squash/ Table Tennis	17	98	17W LED Downlight	-	89	✓
Gym	17	98	22W LED Downlight	-	40	✓
Multipurpose Room	14	119	17W LED Downlight	-	38	✓
Function Room	14	119	17W LED Downlight	-	37	✓
Family Party Room	14	119	22W LED Downlight	-	16	✓
Indoor Lounge	17	98	17W LED Downlight	-	18	✓
AV Room	14	119	22W LED Downlight	-	17	✓
Total No. of Luminaires (CFL+LED)				4103	4103	**8206**

Table 5.8: Distribution of Luminaires for Case 5 (25% LED + 75% CFL).

Common Area	**Daily Operation Hours (h)**	**Lamp Lifespan (month)**	**Type of Lamps**	**No. of CFLs**	**No. of LEDs**	**Retrofit with LED**
Corridor	14	47	28W CFL Bulb	1963	-	
		47	36W CFL Tube	79	-	
Stairs	24	69	14W LED Downlight	-	1056	✓
Lift Lobby/Service Lift Lobby	14	119	17W LED Downlight	-	432	✓
		119	22W LED Downlight	-	30	
		119	14W LED Downlight	-	456	
Car Park	17	39	36W CFL Tube	3764	-	
Toilet (F/M/D)	17	39	17W CFL Bulb	15	-	
		39	28W CFL Bulb	48	-	
Jacuzzi/Sauna/Steam Bath/ Shower Room	17	39	28W CFL Bulb	85	-	
Mail Room	24	27	28W CFL Bulb	23	-	
In-door Golf/Squash/ Table Tennis	17	39	28W CFL Bulb	89	-	
Gym	17	98	22W LED Downlight	-	40	✓
Multipurpose Room	14	119	17W LED Downlight	-	38	✓
Function Room	14	47	28W CFL Bulb	37	-	
Family Party Room	14	47	28W CFL Bulb	16	-	
Indoor Lounge	17	39	28W CFL Bulb	18	-	
AV Room	14	47	28W CFL Bulb	17	-	
Total No. of Luminaires (CFL+LED)				6154	2052	**8206**

5.2 Energy and Climate Impact Analysis

5.2.1 Analysis Method

The energy performance was analysed by computing electricity consumption in kWh/year using equation (5.1). Since the study period is 10 years, the lighting systems were assumed to be operated for 10 years, i.e., 12 months per year, 30 days per month. The daily operation hours of luminaires for all areas in the building are shown in Table 5.9.

$$E_{annual} = \frac{N \cdot W \cdot H}{1000} * \frac{30\ days}{month} * \frac{12\ months}{year} \tag{5.1}$$

Where

E_{annual} = Annual electricity consumption, kWh/year

N = Number of luminaires, -

W = Power of luminaries, W

H = Operation hour, h

Table 5.9: Operation Hours of Luminaires for All Areas in the Building.

Daily Operation Hour (h)	Building Area (-)
14	Corridor, Lift Lobby, Service Lift Lobby, Car Park, Function Room, AV Room, Multipurpose Room, Family Party Room.
17	Public Toilet, Gymnasium, In-door Golf, Squash, Table Tennis, Indoor Lounge, Jacuzzi, Sauna, Steam bath, Shower Room.
24	Stairs.

The climate impact can be analysed by calculating the annual CO_2 emission by the lighting system using equation (5.2).

$$Climate\ Impact = E_{annual} * Emission\ Factor \tag{5.2}$$

Where

Climate Impact = Annual CO_2 emission, kg CO_2/year

E_{annual} = Annual electricity consumption, kWh/year

Emission Factor = CO_2 emission factor, kg CO_2/kWh

The project is located in Peninsular Malaysia; hence, the emission factor based on the electricity generation from Peninsular Malaysia can be used. Figure 5.3 and Figure 5.4 show the CO_2 emission factors and the generation mix for Peninsular Malaysia. It can be observed that the emission factor is related to the fuel share of non-renewable (i.e., coal and gas). Figure 5.5 shows the projected capacity mix for Peninsular Malaysia, the share for the renewables is expected to rise about 14% by 2039 (Energy Commission, 2022), which means the emission factor will reduce due to the reduction in non-renewables for electricity generation. Since the study period is 10 years, the average renewables share from 2022 to 2031 will be taken, which contributes an 18% rise as compared to 2017. Therefore, regardless of the emission factor fluctuations, the average emission factor over the study period is estimated to be 18% lower than the 2017 emission factor, or 0.48 kgCO_2/kWh.

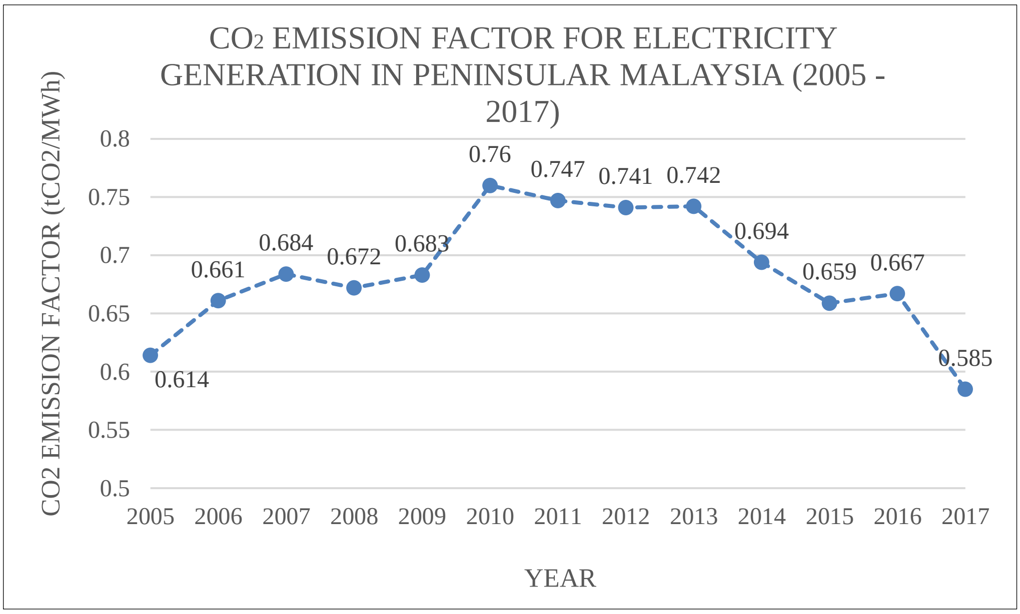


Figure 5.3: CO_2 Emission Factor for Peninsular Malaysia (2005-2017) (MGTC, 2019).

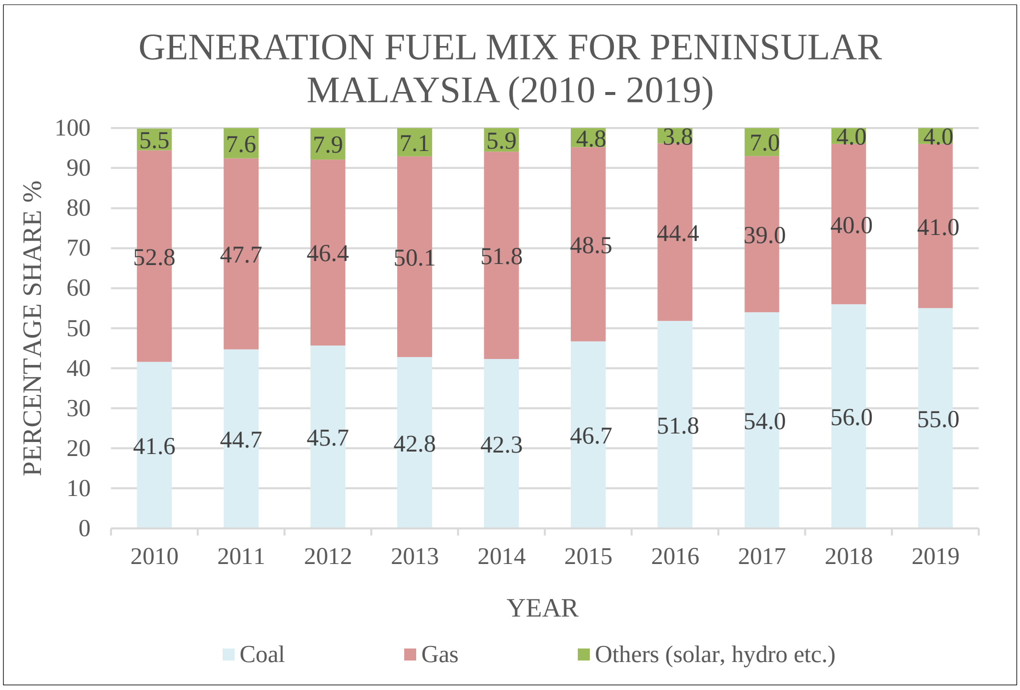


Figure 5.4: Generation Mix by Fuel (2010-2019) (Energy Commission, 2021).

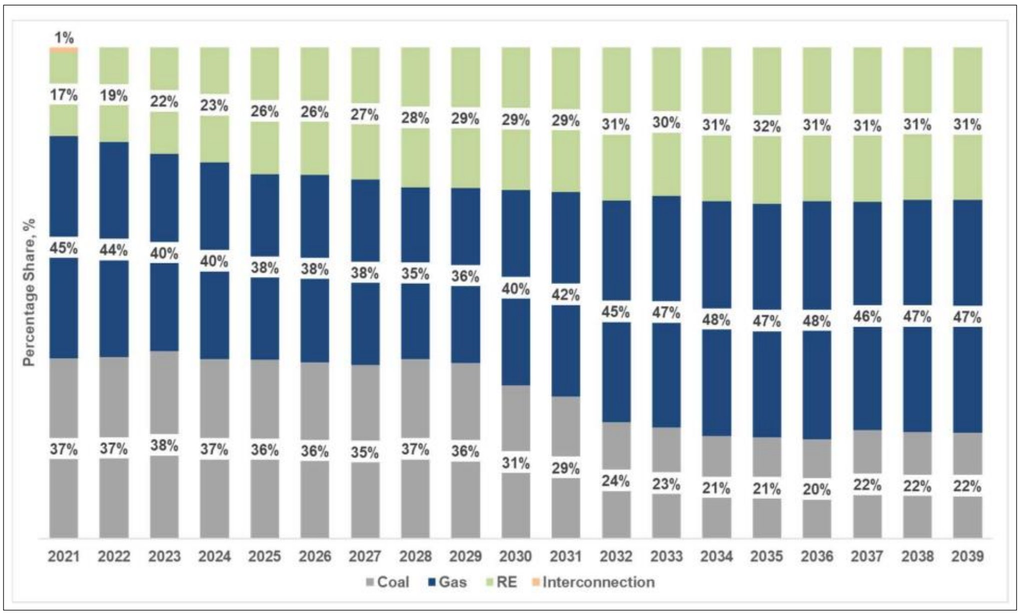


Figure 5.5: Capacity Mix by Fuel Projection (2021-2039) (Energy Commission, 2021).

5.2.2 Energy Saving and Emission Reduction Analysis

Figure 5.6 shows the comparison of annual electricity consumption and climate impact for the existing lighting system and all retrofit alternatives. The climate impact of Case 1 is the highest among all cases, with an emission of 674 tonnes of CO_2 annually. A large amount of CO_2 emission is due to the high electricity consumption of the CFL lighting system, with consumption of 1404MWh/year. Therefore, the CFL lighting system in Case 1 is considered energy inefficient and non-environmentally friendly.

For the retrofit lighting system cases, the overall trend shown in Figure 5.6 is that electricity consumption and CO_2 emission savings increase with the percentage of LED used in retrofit, with 100% LED retrofit being the highest reduction in emission and consumption. In Case 2 (100% LED system), a 35% reduction in electricity consumption and CO_2 emissions can be observed as compared to Case 1 (100% CFL System). Such huge saving is due to the use of energy-efficient light sources (i.e. LEDs) that require lesser power consumption for the same illuminance level. With less electricity being used, less electricity is generated, and thereby less CO_2 emissions.

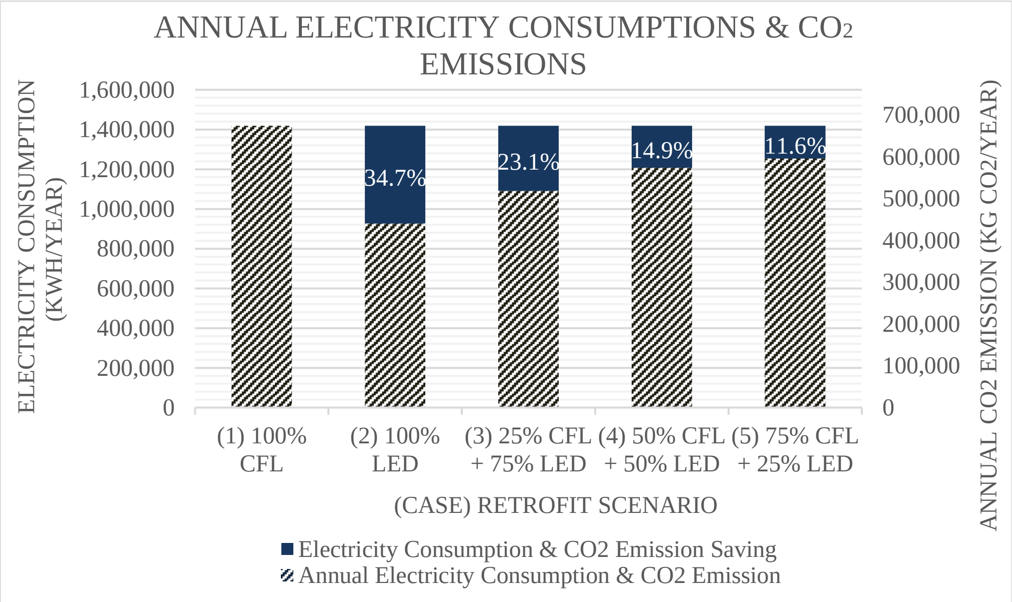


Figure 5.6: Annual Electricity Consumptions & CO_2 Emissions for All Cases.

For Case 3, 4 and 5, the retrofit lighting systems consist of mixtures of energy-efficient and inefficient light sources (i.e. LEDs and CFLs), therefore the savings in electricity consumption and CO_2 emissions cannot achieve the maximum. All retrofit systems have good performance in terms of energy consumption and climate impact. To be more environmentally friendly and energy-saving, a retrofit alternative with a higher proportion of energy-efficient light sources should be selected.

5.3 Economic Analysis

5.3.1 LCCA Method

LCCA was applied in the economic analysis to investigate the cost-effectiveness of each retrofit design alternative. In LCCA, life cycle cost (LCC) was computed by considering capital investment cost, operational cost, and replacement cost of the lighting system over a given study period (Belany, et al., 2021) as shown in equation (5.3) and all the costs were adjusted to reflect the time value of money through discounts.

$$LCC = CAPEX + \sum F_{pv} \cdot OPEX + \sum F_{pv} \cdot REPEX \qquad (5.3)$$

Where

LCC = Total LCC of the lighting system, RM

CAPEX = Capital expenditure, RM

OPEX = Operational expenditure, RM

REPEX = Replacement expenditure, RM

F_{pv} = Single value present factor, -

Equation (5.4) show the capital expenditure, which is the retrofit investment cost of the retrofit lighting system. There is no capital expenditure for the base case (100% CFL lighting system) as for optional retrofit projects in existing facilities, the base case is generally the continuation of the existing system, with no initial investment cost but high operational cost.

All the costs are quoted by assuming the retrofit lighting system uses existing lighting points, wiring switches and time-controlled switches. The luminaire costs include lamps and fittings. The installation costs include supply, delivery, installation, connection, testing and commissioning of lighting fixtures. Based on market research, the luminaire cost and installation cost for different types of lamps are shown in Table 5.10 (Kristal Maya, 2020) (JKR, 2021).

$$CAPEX = N \cdot (P_{lamp} + P_{installation}) \tag{5.4}$$

Where

CAPEX = Capital expenditure, RM

N = Number of fixtures, -

P_{lamp} = Price per lamp (include fitting), RM

$P_{installation}$ = Installation cost per lamp, RM

Table 5.10: Lamp & Installation Cost for Different Lamps (Kristal Maya, 2020) (JKR, 2021).

Lamp Model	**Lamp Cost (RM)**	**Installation Cost (RM)**
14W LED Downlight	59	25
17W LED Downlight	49	25
22W LED Downlight	69	25
26W LED Tube	68	30

Operational expenditure consists of annual electricity consumption multiplied by the TNB energy tariff rate, as shown in equation (5.5). Since the study period is 10 years, the lighting systems were assumed to be operated for 10 years, i.e. 12 months per year, 30 days per month. The daily operation hours of luminaires for all areas in the building are shown in Table 5.11. The monthly electricity consumption can be computed according to equation (5.6).

$$OPEX = E_{monthly} \cdot Tariff \cdot \frac{12\ months}{year} \tag{5.5}$$

Where

OPEX = Annual electricity cost, RM/year

$E_{monthly}$ = Monthly electricity consumption, kWh/month

Tariff = Monthly TNB electricity tariff rate, RM/kWh

$$E_{monthly} = \frac{N{\cdot}W{\cdot}H}{1000} * \frac{30\ days}{month} \quad (5.6)$$

Where

$E_{monthly}$ = Monthly electricity consumption, kWh/month

N = Number of luminaires, -

W = Power of luminaries, W

H = Operation hour, h

Table 5.11: Operation Hours of Luminaires for All Areas in the Building.

Daily Operation Hours (h)	**Building Area (-)**
14	Corridor, Lift Lobby, Service Lift Lobby, Car Park, Function Room, AV Room, Multipurpose Room, Family Party Room.
17	Public Toilet, Gymnasium, In-door Golf, Squash, Table Tennis, Indoor Lounge, Jacuzzi, Sauna, Steam bath, Shower Room.
24	Stairs.

The electricity tariff rate is based on the rate specified by TNB according to voltage level, usage profile and business activity. Since the building is a 40-story building, the supply voltage will be 11kV, which belongs to the medium voltage level by referring to Table 5.12, hence the tariff category is tariff C1 as shown in Table 5.13.

Table 5.12: Supply Voltage Level for Tariff Classification.

Voltage Level	**Supply Voltage**
Low Voltage (Single/Three Phase)	Extra Low Voltage (V ≤ 50V) Low Voltage (50V < V ≤1kV)
Medium Voltage	Medium Voltage (1kV < V ≤ 50kV)
High Voltage	High Voltage (50kV < V ≤ 230Kv) Extra High Voltage (V > 230kV)

Table 5.13: Medium Voltage General Commercial Tariff (TNB, 2022).

Tariff C1 (per month)	**Current Rate**
Each Kilowatt of Maximum Demand per Month	RM 30.30/kW
All kWh	RM 0.365/kWh
Minimum Monthly Charge = RM 600.00	

Maximum demand (MD) is the highest amount of electricity that a consumer needs in a month. The maximum demand in a building is not only contributed by lighting systems but also contributed by HVAC and other high-power appliances. Therefore, calculating MD using only lighting systems is not practical. Thus, the maximum demand charges in our study are excluded.

Replacement expenditure is the cost to replace the luminaires to maintain the functionality, which can be computed using equation (5.7). The lifespan of the luminaires affects the frequency of the light replacement throughout the life cycle of the lighting system. The LCCA study period was chosen as 10 years for investigation. Based on research on market available products, the lifespan for CFL bulbs and tubes are assumed to be 20000 hours and 50000 hours for LED downlights and tubes, respectively (Philips, 2022). Since the lamp operating hours are different for all areas in the building, the time for lamp replacement is different in each case, which is summarized in Table 5.15.

Based on market research, the replacement cost and installation cost for different types of lamps are shown in Table 5.14 (Kristal Maya, 2020) (JKR, 2021). The replacement lamp costs include lamps only. The installation costs include supply, delivery, installation, connection, testing and commissioning of lighting fixtures.

$$REPEX = N \cdot (P_{replacement} + P_{install}) \quad (5.7)$$

Where

REPEX = Replacement expenditure, RM

N = Number of lamps, -

$P_{replacement}$ = Replacement cost per lamp, RM

$P_{installation}$ = Installation cost per lamp, RM

Table 5.14: Replacement Lamp & Installation Cost for Different Lamps (Kristal Maya, 2020) (JKR, 2021).

Lamp Model	Replacement Lamp Cost (RM)	Installation Cost (RM)
28W CFL Bulb	26	25
17W CFL Bulb	12	25
36W CFL Tube	14	25
14W LED Downlight	59	25
17W LED Downlight	49	25
22W LED Downlight	69	25
26W LED Tube	43	25

Table 5.15: Lamp Replacement for All Cases.

Year	Case 1 (100% CFL)		Case 2 (100% LED)		Case 3 (75% LED + 25%CFL)		Case 4 (50% LED + 50%CFL)		Case 5 (25% LED + 75%CFL)	
	Lamp Type	**No. of Lamp**	**Lamp Type**	**No. of Lamp**	**Lamp Type**	**No. of Lamp**	**Lamp Type**	**No. of Lamp**	**Lamp Type**	**No. of Lamp**
3	28W CFL Bulb	1079			28W CFL Bulb	1056	28W CFL Bulb	1079	28W CFL Bulb	23
4	28W CFL Bulb	2813			28W CFL Bulb	540	28W CFL Bulb	2473	28W CFL Bulb	2313
	17W CFL Bulb	471			17W CFL Bulb	456	17W CFL Bulb	471	17W CFL Bulb	17
	36W CFL Tube	3843					36W CFL Tube	79	36W CFL Tube	3843
5	28W CFL Bulb	1079			28W CFL Bulb	1056	28W CFL Bulb	1079	28W CFL Bulb	23
6			14W LED Downlight	1056	17W LED Downlight	23			14W LED Downlight	1056
			17W LED Downlight	23						
7	28W CFL Bulb	331			28W CFL Bulb	1096	28W CFL Bulb	1127	28W CFL Bulb	263
	17W CFL Bulb	15					17W CFL Bulb	15	17W CFL Bulb	15
8	28W CFL Bulb	2533					28W CFL Bulb	2425	28W CFL Bulb	2033
	17W CFL Bulb	456			28W CFL Bulb	500	17W CFL Bulb	456	36W CFL Tube	3843
	36W CFL Tube	3843			17W CFL Bulb	456	36W CFL Tube	79		

Table 5.15 (Continued): Lamp Replacement for All Cases.

Year	**Case 1 (100% CFL)**		**Case 2 (100% LED)**		**Case 3 (75% LED + 25%CFL)**		**Case 4 (50% LED + 50%CFL)**		**Case 5 (25% LED + 75%CFL)**	
	Lamp Type	**No. of Lamp**	**Lamp Type**	**No. of Lamp**	**Lamp Type**	**Lamp Type**	**No. of Lamp**	**Lamp Type**	**No. of Lamp**	**Lamp Type**
9	28W CFL Bulb	1079	14W LED Downlight	19	28W CFL Bulb	1056	28W CFL Bulb	1079	28W CFL Bulb	23
			17W LED Downlight	236	14W LED Downlight	19	17W LED Downlight	192	22W LED Downlight	40
			22W LED Downlight	40	17W LED Downlight	236	22W LED Downlight	40		
10	28W CFL Bulb	280	14W LED Downlight	456	28W CFL Bulb	40	28W CFL Bulb	48	28W CFL Bulb	240
	17W CFL Bulb	15	17W LED Downlight	2470	17W LED Downlight	2000	17W CFL Bulb	15	17W CFL Bulb	15
			22W LED Downlight	63	22W LED Downlight	33	17W LED Downlight	75	14W LED Downlight	456
			26W LED Tube	3843	26W LED Tube	3843	22W LED Downlight	33	17W LED Downlight	470
							26W LED Tube	3764	22W LED Downlight	30

In LCCA, all costs incurred at different timelines must be discounted back to the present value on the base date before being incorporated into the LCC estimation to determine whether the overall savings justify the planned investment during the investment decision. In this case, replacement costs and electricity charges are most dependent on time changes in monetary value and therefore need to be discounted by a present value factor (F_{pv}), as shown in equation (5.8).

$$F_{pv} = \frac{1}{(1+D)^t} \qquad (5.8)$$

Where

F_{pv} = Present value factor, -

D = Discount rate, %

t = Number of periods, year

A discount rate is a return rate to bring future cash flows back to present value. There are two methods for setting discount rates: prescriptive and descriptive. Descriptive method is chosen for this study, in which the discount rate is based on observable and realized outcomes in society (usually market interest rates). Figure 5.7 shows the statistics on the bank lending rate for the past 10 years (2012 – 2022). The lending rate has fallen sharply from 2020 so far to support economic growth affected by the Covid-19 pandemic and MCO. According to The Star, Bank Negara may raise the interest rate in the third quarter of 2022 (ZAINUL, 2022). Therefore, the average bank interest rate (4.6%) from 2012 to 2020 will be used as the discount rate used in the LCCA study.

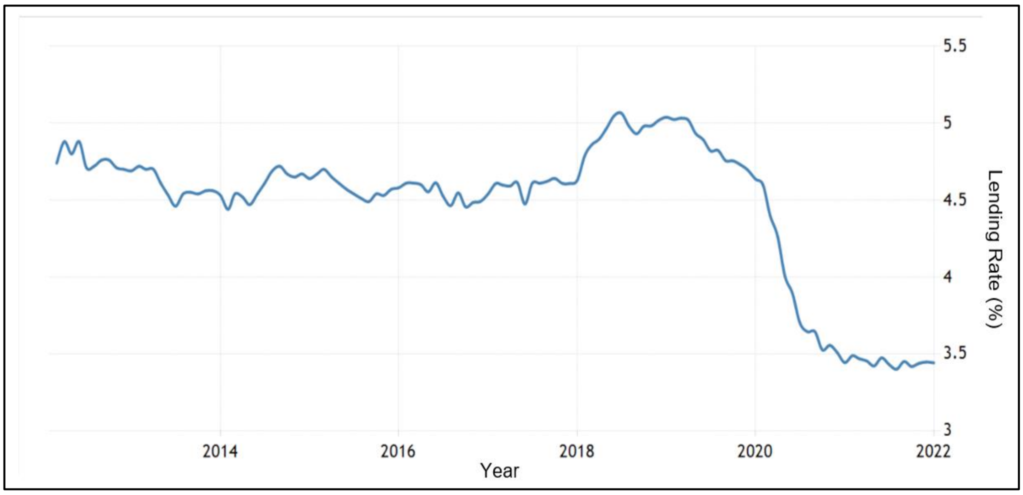


Figure 5.7: Malaysia Bank Lending Rate from 2012 to 2022 (Trading Economics, 2022).

Net Savings (NS) was chosen as a measure of the economic performance of the project evaluation. The NS for an alternative relative to a designated base case is the difference between the LCC of the alternative and the base case, which can be calculated using equation (5.9).

$$NS = LCC_{basecase} - LCC_{alternative} \tag{5.9}$$

Where

NS = Net saving for an alternative relative to the base case, RM

$LCC_{basecase}$ = Life-cycle cost of base case, RM

$LCC_{alternative}$ = Life-cycle cost of an alternative, RM

The alternative is cost-effective relative to the base case if the NS is greater than zero. This also implies that the LCC of an alternative is lower than the base case. When evaluating multiple alternatives, the alternative with the highest NS is also the alternative that has the lowest LCC.

5.3.2 Economic Analysis of Percentage of LED Retrofit

Figure 5.8 shows the total life cycle cost (LCC) of all cases, the definition of the costs is shown in Table 5.16. Based on Figure 5.8, the LCC of the base case (Case 1) with 100% CFL is the highest, followed by Case 4 with 50% LED retrofit, Case 5 with 25% LED retrofit, Case 3 with 75% LED retrofit and the lowest is in Case 2 with 100% LED retrofit. Even though Case 1 has no CAPEX, the high OPEX of the inefficient lighting system, which accounts for 86% of the LCC, results in the LCC of Case 1 being the highest of all cases, valued at RM4.70 million.

Moreover, all the retrofit alternatives are cost-effective relative to Case 1 since the NS in all cases is greater than zero. By analysing the retrofit cases from Case 2 and Case 3, the NS increase with the percentage of LEDs used in retrofitting. With a higher number of energy-efficient LEDs used in the retrofitting, lesser power is consumed for the same illuminance level, thereby reducing the OPEX and LCC eventually leading to higher NS.

The CAPEX for Case 2 is the highest, which is around 15% of the LCC, but the LCC is the lowest, with the NS can achieve up to 20%, which is the highest among all retrofit cases. Such low LCC and high NS as compared to other retrofit cases are due to the 100% use of energy-efficient LEDs that greatly reduce the OPEX by around 30% as compared to the base case, thereby leading to the lowest LCC and highest NS among all retrofit cases.

Table 5.16: Definition of the Costs used in LCCA.

Abbreviation	Definition
CAPEX	Capital expenditure
Discounted OPEX	Operational expenditure discounted by present value factor
Discounted REPEX	Replacement expenditure discounted by present value factor
NS	Net saving for an alternative relative to the base case

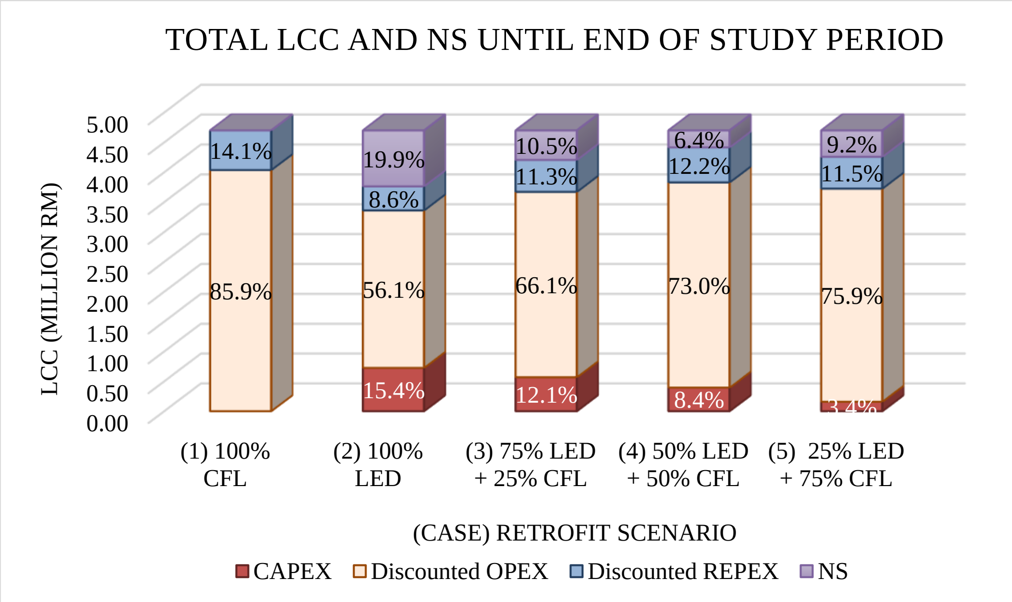


Figure 5.8: Effect of Percentage of LED Retrofit on LCC and NS.

Theoretically, the LCC of Case 4 should be lower than Case 5 because more energy-efficient light is used leading to lower OPEX. However, due to the random selection of lamps to retrofit, the inefficient luminaires with long operation hours were not chosen to be retrofitted in Case 4, and longer operation hours shorten the lamp lifespan, therefore the frequency of lamp replacement is higher, leading to higher REPEX.

Based on Table 5.17, the longest operating hours of luminaires which is 24 hours installed on stairs have shortened the life span of the lamp. This led to more replacement needed in 10 years for Case 4, doubling the REPEX as compared to Case 5. Therefore, the retrofit of luminaires for long hours of operation is a priority to reduce the replacement because normally they have a shorter lifespan. Further study on the cost-benefit analysis of retrofit sequence based on operating time will be discussed in the next subchapter.

Table 5.17: Lamp Replacement for Stairs in Case 4 and Case 5.

Stairs	**Case 4** **50% LED**	**Case 5** **25% LED**
Type of Lamps (-)	28W CFL Bulb	14W LED Downlight
No. of Lamps (-)	1,056	1,056
Operating Hours (Hours)	24	24
Life Span of Lamps (Hours)	20,000	50,000
Life Span of Lamps (Years)	2.25	5.75
No. of Replacement over 10 years (-)	4	1
REPEX for Each Replacement (RM)	39,072.00	76,032.00
Total Discounted REPEX (RM)	119,930.34	58,050.55

5.3.3 Economic Analysis of Lighting Retrofit Sequence Based on Operating Time

The previous discussion shows that the REPEX has a significant impact on the cost-effectiveness of the retrofit alternatives. Hence, the retrofit cases 3, 4 and 5 were further studied by changing the sequence of retrofits based on operating hours. Table 5.11 shows the operation hours of luminaires for different common areas.

The retrofit method was categorised into two groups which are descending order and ascending order as shown in Figure 5.9. Descending order means the areas with the longest operating hours will be chosen to be retrofit first, followed by the areas with the moderate operating hours, then the areas with the least operating hours areas. On the other hand, ascending order will consider the areas with the least operating hours first.

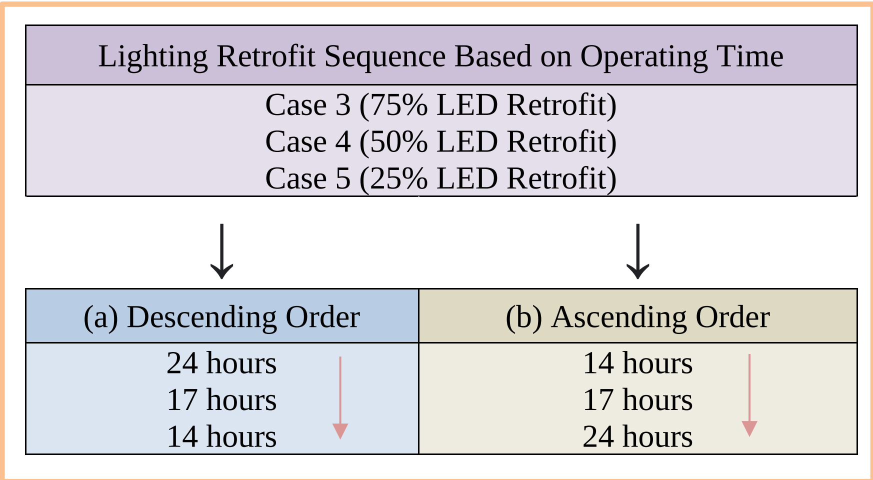


Figure 5.9: Retrofit Sequence Based on Lamp Operating Time.

Based on Figure 5.10, the retrofit cases 3(a), 4(a) and 5(a) that retrofit the areas in descending order, from the longest operating hour to the least operating hours have gained more NS as compared to those retrofit in ascending order. This is because the inefficient CFLs have a shorter initial lifespan than LEDs, coupled with the longer operating hours of the lamps which eventually result in extremely short lifespans, resulting in more frequent replacements and therefore higher REPEX. Besides that, inefficient CFLs with longer operation hours also increase the electricity consumption, leading to higher OPEX because OPEX is calculated based on kWh. This can be validated through Figure 5.10 that the REPEX and OPEX for Case 3(b), 4(b) and 5(b) are higher than Case 3(a), 4(a) and 5(a).

The CAPEX for both descending and ascending orders retrofits is similar, the difference is within 0.4%. This is because the number of LEDs retrofitted is the same according to the percentage of LED retrofit (i.e. 75%, 50% and 25%), the only difference is the lamp price that changes according to different power ratings. Therefore, it clearly shows that even with the upfront cost being the same, the way the area is chosen to be retrofitted can have a significant impact on the total NS.

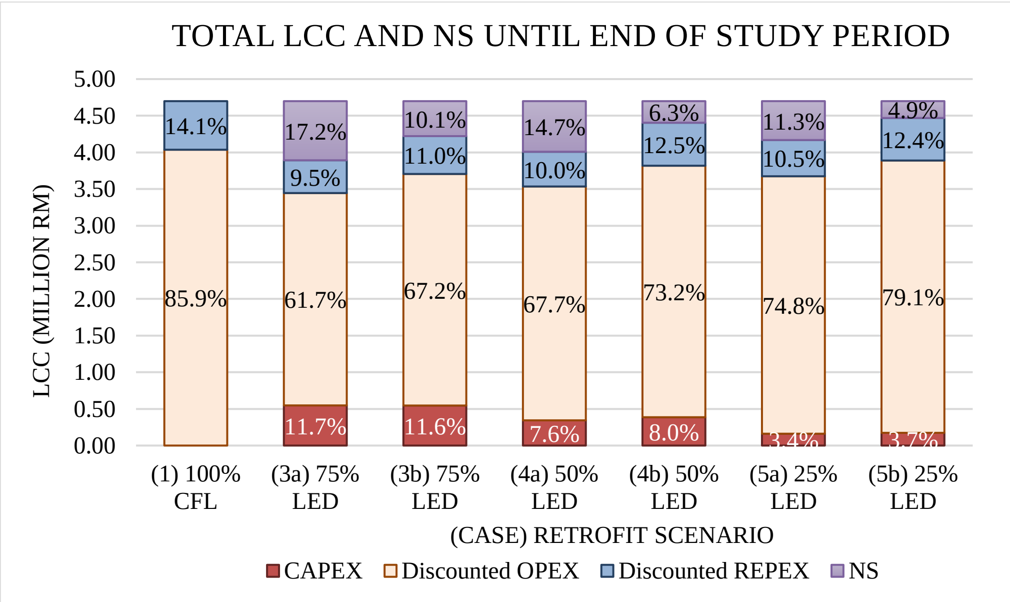


Figure 5.10: Effect of Retrofit Sequence Based on Operating Time on the LCC and NS.

Figure 5.11 shows the NS ranges for all retrofit cases based on operating hours. The NS ranged from 10.1% to 17.2% for case 3, from 6.3% to 14.7% for case 4, and from 4.9% to 11.3% for case 5. The NS range for each case is overlapping with other cases, meaning that the retrofit case can be effective or non-effective compared to other cases. For example, at a 14.7% of NS, Case 4 is preferred as compared to Case 3 because the same NS can be achieved with a lower CAPEX in Case 4. Moreover, to achieve a 10.1% of NS, Case 5 is preferred due to the lowest CAPEX among all cases. Therefore, consideration of retrofit percentage and operating time is important to ensure the cost-effectiveness of a retrofit design.

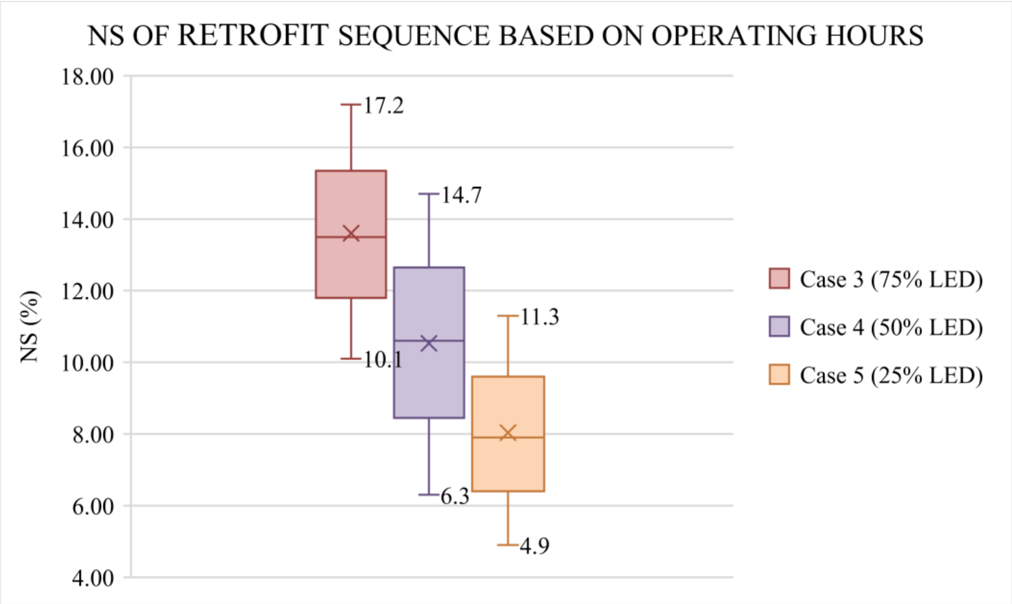


Figure 5.11: Range of NS of Retrofit Sequence Based on Operating Time.

5.3.4 Economic Analysis of Lighting Retrofit using LEDs with Different Lifespans

Besides operating hours, the lifespan of the luminaires is also one of the factors that will affect the NS. Case 2 with 100% LED retrofitted was chosen to study the effect of the lifespan of luminaires on the LCC and NS. The study was carried out by varying the LED luminaires with different lifespans and computing the LCC and NS using the LCCA method. The flowchart of the study method is shown in Figure 5.12. The LED unit price of different lifespans from different brands are surveyed and the final selection is shown in Table 5.18 and Table 5.19.

Table 5.18: LED Downlight Unit Prices with Different Lifespans and Brands.

LED Downlight	**Philips**			**Panasonic**			**Ledeon**		
Lifespan (h)	50,000			20,000			15,000		
Power Rating (W)	14	17	22	15	18	24	12	18	25
Luminous Flux (lm)	1200	1500	2000	1275	1530	2040	1100	1650	2300
Luminous Efficacy (lm/W)	85.7	88.2	30.9	85.0	85.0	85.0	91.7	91.6	92
Unit Price (RM)	49	59	69	19	23	25	9	12	21

Table 5.19: LED Tube Unit Prices with Different Lifespans and Brands.

LED Tube	**Philips**	**Mixed Brands**	
Lifespan (h)	50,000	20,000	15,000
Power Rating (W)	26	30	36
Luminous Flux (lm)	3,600	3,600	3,600
Luminous Efficacy (lm/W)	138.5	120.0	100
Unit Price (RM)	67	28	19

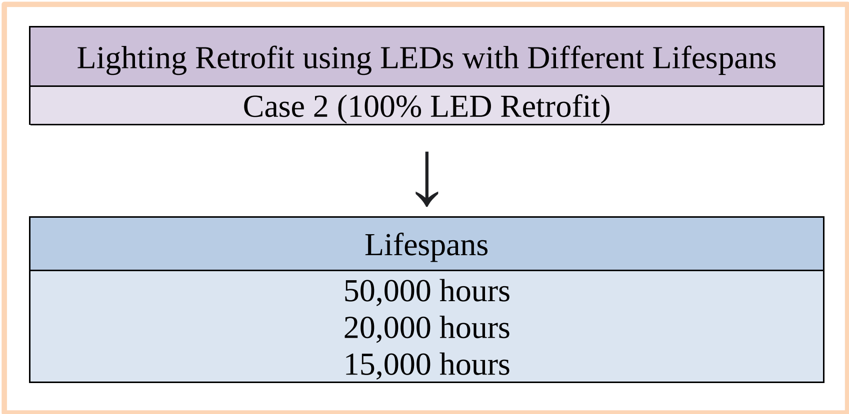


Figure 5.12: Retrofit Sequence Based on Lamp Operating Time.

Based on Figure 5.13, NS decrease with LED lifetime, which means LCC increase with the decrease in lifespan. A 15,000-hour-life LED achieves the lowest NS, which is 5.7% lower than a 20,000-hour-life LED and 11.3% lower than a 50,000-hour-life LED despite having the lowest CAPEX.

The main contribution to the high LCC is due to REPEX and OPEX. The reduction in lifespan increases the frequency of the lamp replacement, thereby increasing the REPEX. Besides, more lamp replacements also gradually increase the labour cost involved in REPEX as the labour cost per lamp is counted and fixed for all rated power LEDs.

On the other hand, a 50,000-hour-life LED has the highest CAPEX, which is 6% to 8% higher than other cases because the unit price for a longer lifespan is generally higher. However, the longer lifespan reduces the number of replacements and then REPEX, it can be seen that the REPEX for a 50,000-hour-life LED is the lowest.

Besides, as the LED lifespan shortens, the OPEX also increases. This is because the power consumption of LED tubes with different lifetimes varies greatly. Based on Table 5.19, the 15,000-hour-life and 20,000-hour-life LED are rated 10W and 4W higher than the 50,000-hour-life LED. This gradually increases the electricity consumption and OPEX. Therefore, even though the unit price for a lower lifespan is cheaper, the energy efficiency of the luminaire cannot be guaranteed.

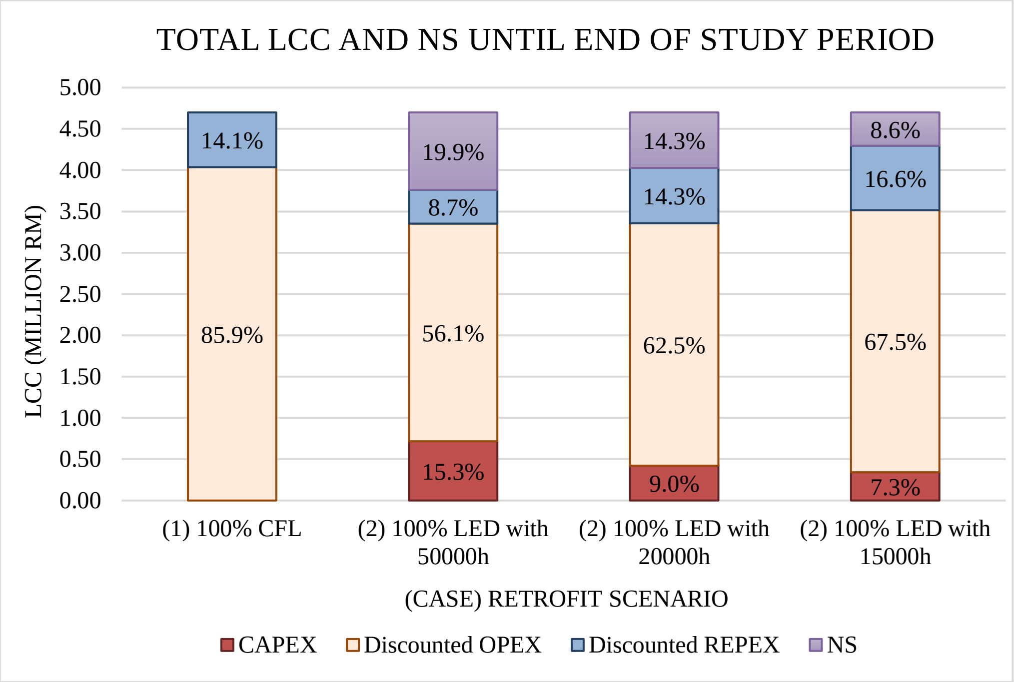


Figure 5.13: Effect of Retrofitting using Different Lifespans of Luminaires on the LCC and NS.

5.3.5 Comparative Analysis of Energy, Climate Impact and Economic

Table 5.20 to Table 5.22 present the comparative analysis of electricity consumption, climate impact and NS for all retrofit cases and the base case. According to Table 5.20, Case 2 of 100% LED retrofit is the best choice for the retrofit solution, achieving 20% NS and saving 34.7% of electricity consumption and CO_2 emissions per year.

In cases where lighting systems are not 100% retrofitted with LEDs due to being underfunded, priority is given to replacing longer-running inefficient light sources to reduce the REPEX and maximize the NS. As shown in Table 5.21, the NS of descending retrofit is 6.7% to 8.4% higher than that of ascending order. According to Table 5.22, retrofit using a longer lifespan LED should consider first because it results in more NS, and the NS of a 50,000-hour-life LED system can be as high as 20%.

Table 5.20: Comparative Analysis of Percentage of LED Retrofit.

Case	Retrofit Scenario	Annual Electricity Consumption Saving (%)	Annual CO_2 Saving (%)	NS (%)
2	100% LED	34.7%	34.7%	19.9%
3	75% LED	23.1%	23.1%	10.5%
4	50% LED	14.9%	14.9%	6.4%
5	25% LED	11.6%	11.6%	9.2%

Table 5.21: Comparative Analysis of Retrofit Sequence Based on Operating Hours.

Case	Retrofit Scenario	Retrofit Sequence Based on Operating Hours	NS (%)
3	75% LED	Descending	17.2%
		Ascending	10.1%
4	50% LED	Descending	14.7%
		Ascending	6.3%
5	25% LED	Descending	11.3%
		Ascending	4.9%

Table 5.22: Comparative Analysis of Retrofit using LEDs with Different Lifespans

Case	Retrofit Scenario	LED Lifespan (h)	NS (%)
2	100% LED	50,000	19.9%
		20,000	14.3%
		15,000	8.6%

5.4 Break-even Analysis

The break-even analysis is used to determine the point at which have to save enough to cover all of the costs. The point is the payback period (PB), which is located at the intersection between the base case and retrofit case LCC graphs. The PB determines the time required to recover initial investment costs. If the payback period is less than the study period, the project is considered cost-effective. The LCC graphs were plotted by computing the cumulative yearly LCC using equation (5.3). Since the previous section has determined the most effective method for energy-efficient retrofit, the base case and retrofit cases will model based on the selected retrofit methods as shown in Table 5.23.

Table 5.23: Retrofit Methods used for Break-even Analysis.

Case	Percentage of LED Retrofit	Retrofit based on Operating Hours	Lifespan of Luminaires
1 (Base Case)	0%	Descending Order (24h, 17h, 14h)	20,000 hours
2	100%		50,000 hours
3	75%		
4	50%		
5	25%		

Figure 5.14 to Figure 5.17 show the break-even analysis for all retrofit cases against the base case. The PB for all retrofit cases is less than 10 years, which means that all retrofit designs are cost-effective. Case 5 with 25% LED retrofit has the shortest PB, which is only 2.2 years but is not the highest NS. This is due to the initial investment of Case 5 being the lowest, therefore only requires a short period to recover back the costs.

On the other hand, among all retrofit cases, Case 2 with 100% LED retrofit has the longest PB, which is 3.4 years due to the highest initial investment, but it also has the highest NS, which can achieve up to 20% at the end of the study period. This suggests that the shortest PB is not necessarily the most cost-effective, as the payback measure ignores all costs and savings such as increased OM&R costs that may occur after the payback year, which may negate the cost-effectiveness of investment of the alternatives. Therefore, PB is useful as a rough guide for accept/reject decisions and is not recommended as a criterion for selecting among mutually exclusive or ranking independent projects.

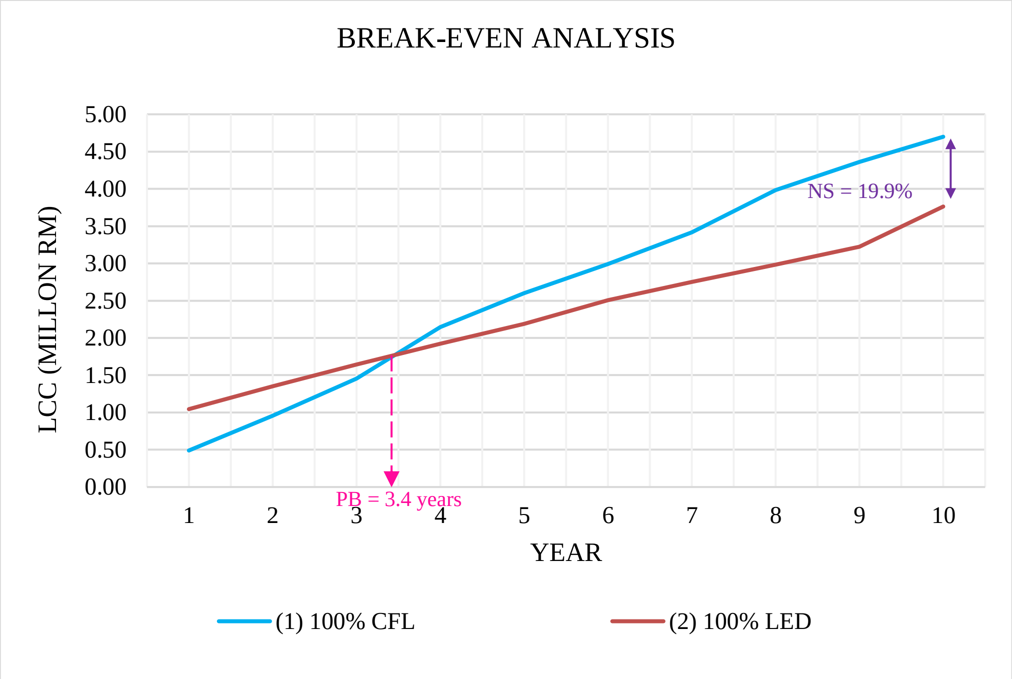


Figure 5.14: Break-even Analysis for 100% LED Lighting System.

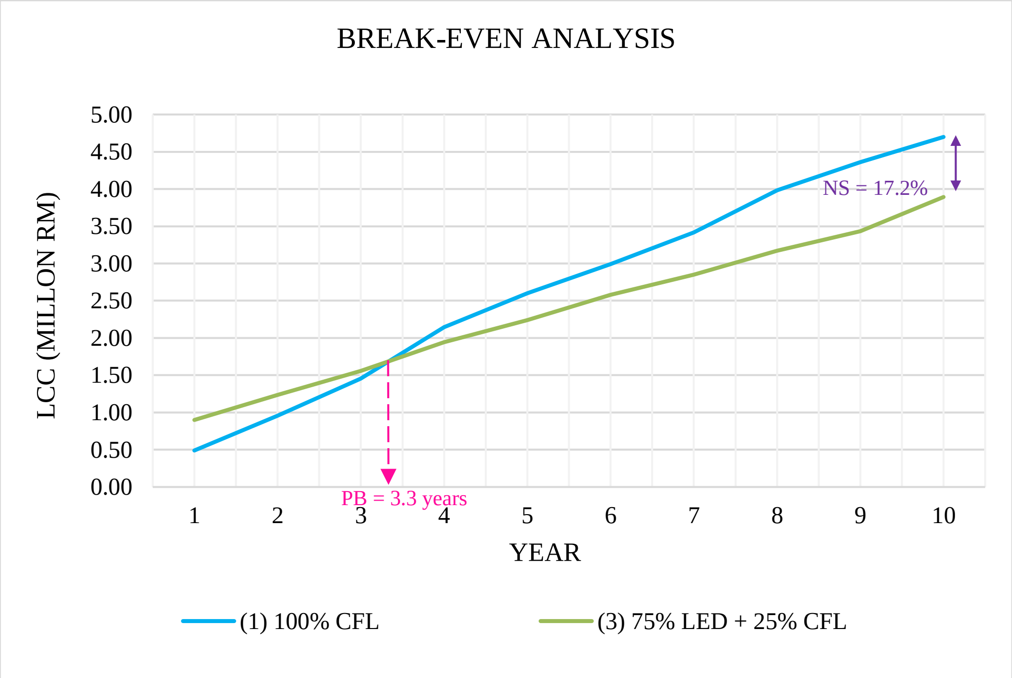


Figure 5.15: Break-even Analysis for 75% LED Lighting System.

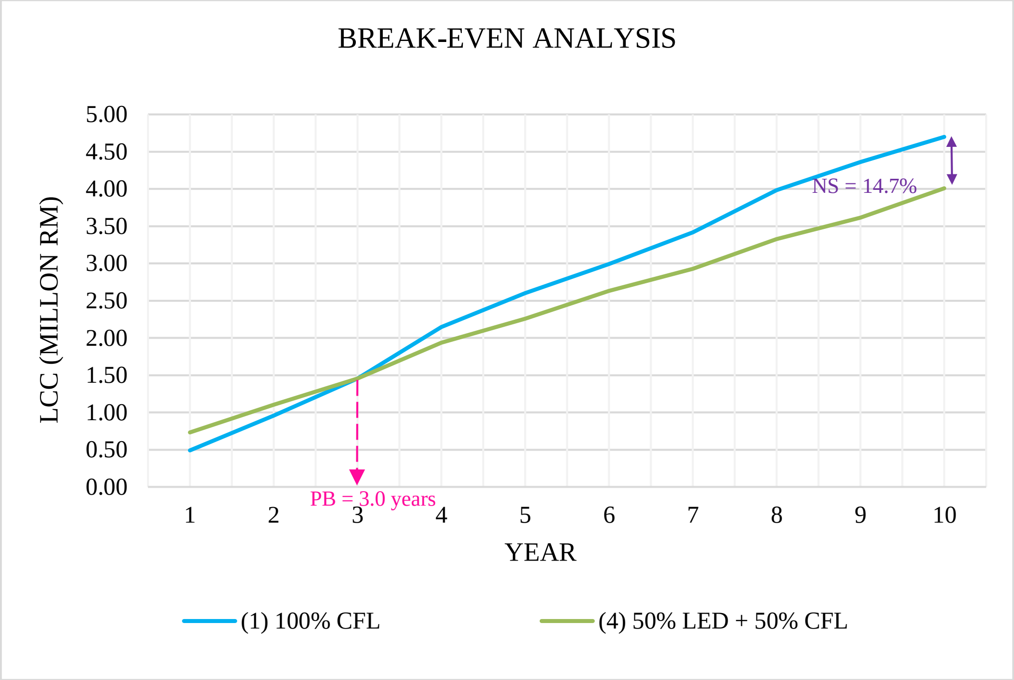


Figure 5.16: Break-even Analysis for 50% LED Lighting System.

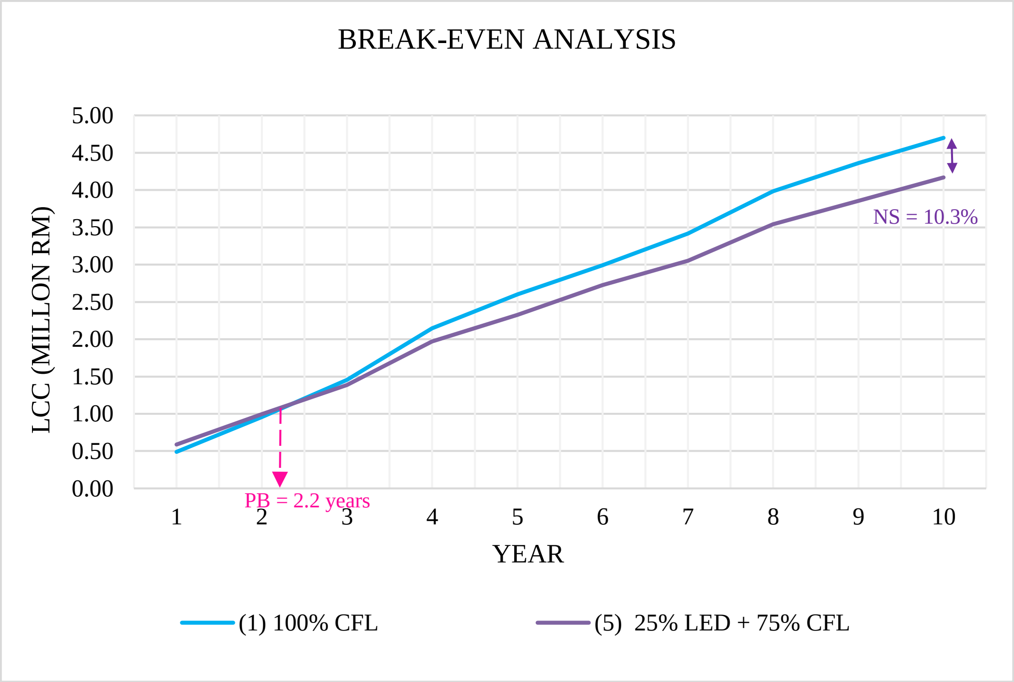


Figure 5.17: Break-even Analysis for 25% LED Lighting System.

5.5 Sensitivity Analysis

Sensitivity analysis is used to determine the criticality of the input variables and the lower and upper bounds of the LCC or any other economic evaluation metric for the alternatives. In LCCA, the cost-effectiveness of lighting retrofit depends on the expected costs and selected key economic variables such as discount rates, electricity tariffs, lamp prices etc. The sensitivity analysis was performed by taking the LCC of the base case and retrofit cases based on the selected retrofit methods as shown in Table 5.23.

5.5.1 Critical Inputs Identification

The input values critical to the LCC of the retrofit alternatives were identified by increasing the uncertain input values such as CAPEX, OPEX and REPEX as shown in Table 5.24 by a certain percentage (10% in this case) and then recalculating the LCC based on equation (5.3). Then percentage changes in the LCCs that resulted from the change in the input values were compared. Table 5.25 shows the results of critical inputs identification for all retrofit cases.

Table 5.24: CAPEX, OPEX, REPEX and LCC for All Cases.

Cost Item	Case 2 (100% LED)	Case 3 (75% LED)	Case 4 (50% LED)	Case 5 (25% LED)
CAPEX (RM)	724,983	547,903	546,409	344,161
OPEX (RM)	2,635,614	2,897,154	3,159,260	3,190,633
REPEX (RM)	402,111	447,317	516,210	473,625
LCC (RM)	3,762,708	3,892,374	4,221,878	4,008,418

Based on Table 5.25, the inputs critical to the LCC are operational expenditure (OPEX) and capital expenditure (CAPEX). A 10 % increase in OPEX increases the LCC by approximately 7 to 9% for all retrofit cases. For Case 2, a 10 % increase in CAPEX increases the LCC by around 2%. Changes in the other input values such as REPEX have a much smaller effect on LCC for all retrofit cases. In this case, the degree of uncertainty associated with the OPEX and CAPEX has to be determined.

Table 5.25: Percentage Change in LCC with a 10% Increase in the Input Variable.

Cost Item	Percentage Change in Life Cycle Cost (%)			
	Case 2 (100% LED)	**Case 3 (75% LED)**	**Case 4 (50% LED)**	**Case 5 (25% LED)**
CAPEX	1.93%	1.41%	0.86%	0.39%
OPEX	7.00%	7.44%	7.96%	8.43%
REPEX	1.07%	1.15%	1.18%	1.19%

5.5.2 Degree of Uncertainty and Feasibility Determination

The previous results show that OPEX has the largest impact on LCC, followed by CAPEX. For the same reason, in terms of net savings, the feasibility of the retrofit alternatives and the extent of NS can be determined based on the most likely highest or lowest OPEX and CAPEX. These are done by adding a certain percentage to the input variables such as discount rates, electricity tariff and lamp prices that affect these costs and concluding the degree of uncertainty.

Based on Figure 5.18, an increase in the electricity tariff rate results in an increase in NS for all retrofit alternatives, and vice versa. For every 1% increase in electricity tariff, NS increased by RM5238 for Case 5, RM8455 for Case 4, RM11390 for Case 3 and RM14005 for Case 2. Also, the higher the percentage of retrofits using LEDs, the steeper the graph, because a higher number of efficient LEDs decreases electricity consumption and is, therefore, more NS can be achieved. On the other hand, at around a 45% reduction in electricity tariff rate, the lower percentage of LED retrofit is preferred over the higher percentage of LED retrofit. If the electricity tariff decreases by 67% onwards, the NS of retrofit alternatives will become negative, leading to the choice of the base case rather than alternatives.

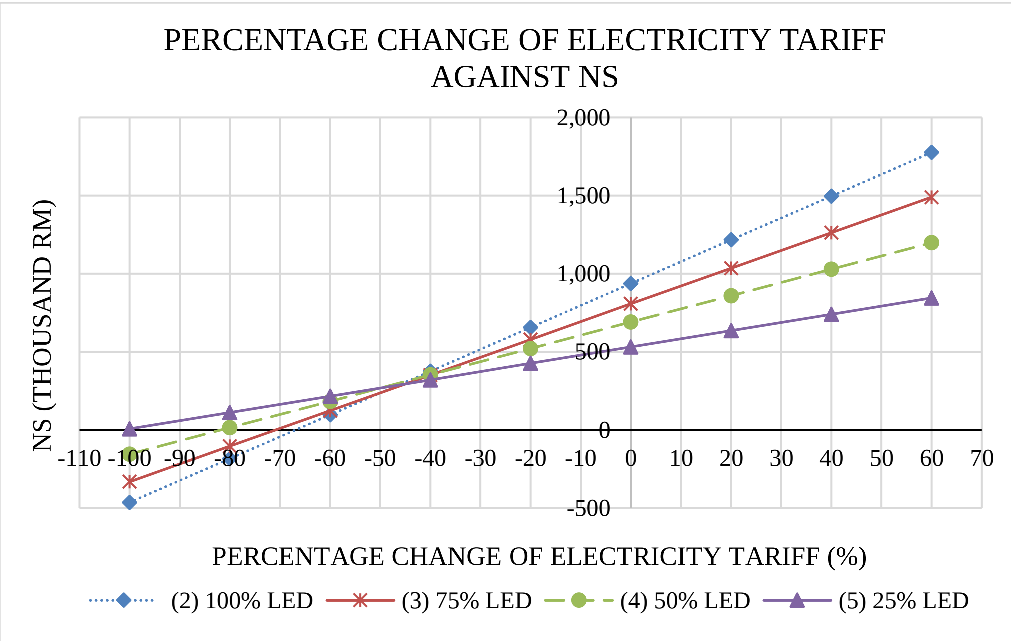


Figure 5.18: Percentage Change of Electricity Tariff against NS.

Based on Figure 5.19, an increase in the rate of change in LED prices results in a decrease in NS for all retrofit alternatives, and vice versa. For every 1% increase in LED price, NS reduces by RM 7683 for Case 2, RM 5774 for Case 3, RM 3836 for Case 4 and RM 1820 for Case 5. Also, the higher the percentage of retrofits using LEDs, the steeper the graph, which means the LED price change will greatly affect the NS. This can be shown in Figure 5.19 that at around a 70% increase in LED price, the lower percentage of LED retrofit will become more cost-effective instead of the higher percentage of LED retrofit.

However, even with the doubling of LED prices, the NS for all retrofit cases are still not negated, implying that changes in LED prices are less sensitive to NS. This is because LEDs are only involved in one-time CAPEX and non-annually REPEX. Uncertainties associated with CAPEX are generally small because CAPEX occurs at an initial stage close to the date of the study. For REPEX, the price of LEDs offering the same characteristics as retrofit cases is unlikely to rise that much in the future due to advances in technology.

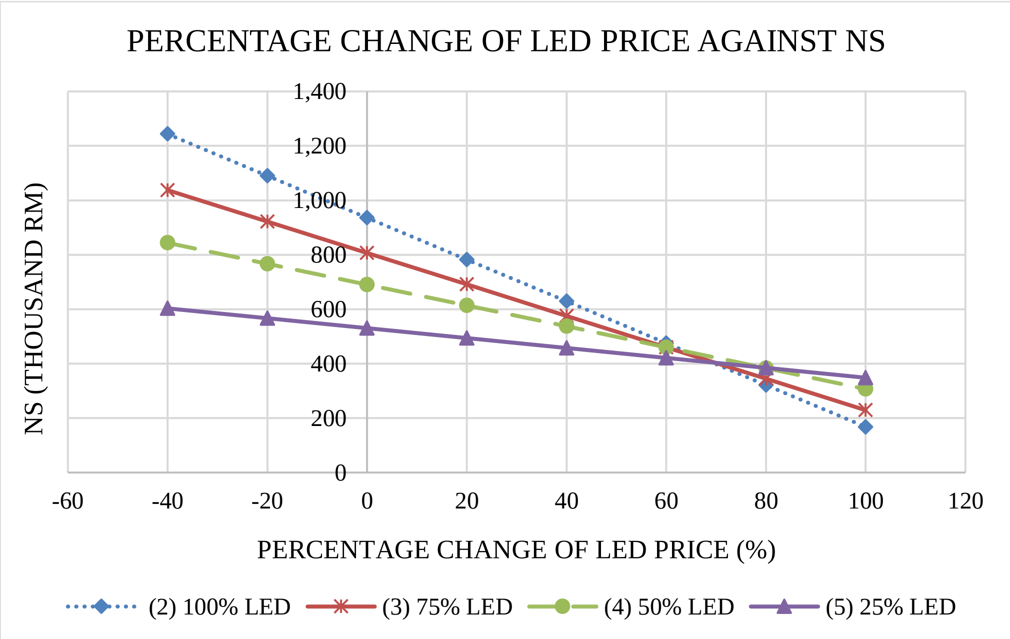


Figure 5.19: Percentage Change of LED Price against NS.

Figure 5.20 shows the effect of changing the discount rate on the NS for all retrofit alternatives. It can be seen that an increase in the discount rate results in a decrease in NS. After reaching a discount rate of approximately 27% to 50%, none of the alternatives is economically feasible. When the discount rate is below 20%, the higher percentage of LED retrofit cases is more economical. On the other hand, a lower percentage of LED retrofit cases have better NS beyond that point.

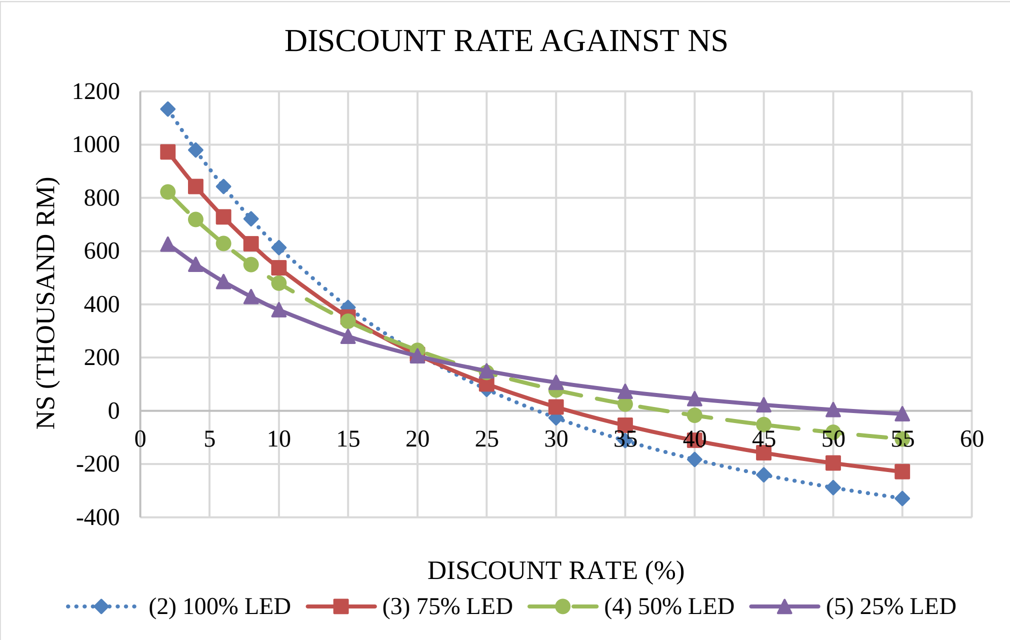


Figure 5.20: Discount Rate against NS.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The lighting quality, economic and environmental benefits of retrofitting the existing conventional lighting systems with energy-efficient lighting systems in a high-rise building were studied. Retrofit existing inefficient lighting systems with energy-efficient LEDs can maintain the required lighting quality with lesser power consumption. Several factors need to be considered when selecting the light sources for retrofitting. The luminous flux of the retrofitting light sources that are closer or higher to the existing light sources can maintain or enhance the illuminance level. A wider polar curve of the light sources enhances the uniformity, giving more even light distribution. Under the illuminance level and uniformity requirement by the standards, using LED to retrofit will not exceed the LPI limits.

For the cost-benefit analysis, retrofit using a higher percentage of LEDs gives more savings in terms of LCC, electricity consumption and CO_2 emission. Retrofitting with 100% LEDs can provide up to 20% NS and save up to 34.7% in electricity consumption and CO_2 emissions per year. In cases where lighting systems are not 100% retrofitted with LEDs, priority is given to replacing longer-running inefficient light sources to maximize the NS. By retrofitting from the long operating hours to the short operating hours, the NS can achieve 6.7% to 8.4% higher than vice versa. Moreover, retrofitting using a longer lifespan LED should consider first because it results in more NS, and the NS of a 50,000-hour-life LED system can be as high as 20%.

The benefits of lighting retrofits are known in terms of energy efficiency, climate impact control and also monetary savings. The findings are significant as they suggest methods or ways to have a lighting retrofit that maximises energy efficiency and cost savings even under underfunded conditions. Economic measures such as NS and PB can be computed using LCCA. The study also suggests that the LCCA method is preferred as a project selection tool over PB. However, the results can be influenced by several factors such as lamp prices, changes in electricity tariff, discount rates, additional losses, etc. The sensitivity analyses showed that the change in LED prices is unlikely to negate the net saving of the retrofit systems. When the discount rate increase by 20% and the electricity tariff reduce by 45%, the lower percentage of LED retrofit becomes more preferred than the higher percentage of LED retrofit.

This study does not consider user comfort as it cannot be simulated in software. Even if there are predefined standards for the lighting design, a difference between the actual luminaire performance and the simulation output may exist. Moreover, this study does not consider lighting control techniques such as dimming and motion sensors. LCCA in this study does not consider the maintenance cost for general maintenance, such as ballast replacement, cleaning, broken fixture replacement etc.

6.2 Recommendations for future work

Future research should cover constraints mentioned such as maintenance costs and other lighting system costs to predict more accurate and practical outcomes. Lighting control systems such as motion sensors and timers could be considered in research to further improve energy efficiency. Daylighting may also be considered, as it reduces the amount of time the lights are used.

Furthermore, future studies should not be limited to the percentage of LED retrofits. Different research methods can also be carried out, for example, to study the cost-effectiveness of retrofitting lighting systems on a part-by-part basis when the lifespan of the existing lighting system is reached, to determine the best retrofit year that can maximize cost savings. To make the study more realistic and in-depth, the study can be expanded beyond common areas, such as office buildings, hotel buildings, etc., as the working hours of lights in common areas are remarkably similar, and the working hours in these places often vary widely.

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