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Enhancing Energy Efficiency in Industrial Warehouses Using Life Cycle Cost Analysis (LCCA)

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Abstract. Industrial warehouses use inefficient lighting systems that occupy a significant portion of energy consumption and operating expenses. The aim of this study is to attain higher energy efficiency and reduce the lighting cost by replacing conventional high-pressure mercury vapor (HPL-N) lamps with LEDs in a warehouse environment. The study employs the Life Cycle Cost Analysis (LCCA) methodology to evaluate long-term cost-effectiveness and save energy. Data were collected using literature review, field surveys, and light simulation using Dialux software at PT XYZ warehouse in Cilegon, Indonesia, between January and June 2024. Findings reveal that the use of LED lighting, in conjunction with the optimization of the light point number, reduces energy consumption by 65%, saving 121,929.816 kWh of energy annually. Within 11 years, installation of LED saves an amount of Rp 947,683,204 compared to Rp 1,796,422,585 with HPL-N systems—an amount of 50.66% or Rp 848,739,381 saved. The results show the energy and economic benefits of the use of LED in industrial warehouses to be advantageous for national energy saving as well as satisfying light standards.

Keywords: Life Cycle Cost Analysis (LCCA), Industrial Energy Optimization, Sustainable Lighting, LED Retrofit, Industrial Lighting, LED Optimization.

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1. Introduction

The rising global demand for electricity presents tremendous threats to industrial processes, as inefficient energy utilization results in excessive operational costs and ineffective use of resources [1]. As social welfare enhancement and population growth drive consumption, energy supply is also being threatened by unsustainable utilization practices [2]. This discrepancy is especially true in Indonesia, whose industrial electricity consumption has seen a notable increase [3], clearly showing that efficient energy-saving provisions are much needed [4]. One such provision is lighting systems, which have an important role to play in industrial environments such as warehouses. PT. XYZ, a flour mill in Cilegon, is a good example. The use of the conventional high-pressure fluorescent (HPL-N) lamps in the plant means high energy expenditure [5], and the average electricity use always increases in 2023. HPL-N lamps are inherently inefficient, as they only convert 35% of electrical energy to visible light while losing the remaining 65% as heat [6]. For comparison, new LED lighting systems produce up to 80% energy in the form of light and only 20% in the form of heat [6], with possible energy savings of 40–70% [7], all while meeting Indonesia's industrial lighting standard of 100–250 lux[7].

The current study aims to assess the possibility to derive actual energy and cost saving for PT. XYZ with the use of LED lighting using a Life Cycle Cost Analysis (LCCA). It answers two key research problems: first, does the implementation of LED systems meet the LCCA needs for economic viability in the long run? Two, what is the probable size of savings that PT. XYZ can realize? Through analyzing HPL-N and LED systems methodically from cradle to grave, i.e., initial investment, operating cost, and maintenance needs, this study assigns quantitative value to the benefits of replacing the lighting system.

Though LED benefits are well reported, there are few studies that have evaluated them in the context of industrial warehouses with an integrated LCCA and lighting simulation approach [8]. This study introduces a new application of Dialux simulation to ensure proposed LED replacement options meet lighting performance specifications.

The move towards energy-saving LED lighting poses PT. XYZ with several benefits, including reduced electricity costs, reduced maintenance expenses through the extended use of LEDs, and reduced carbon footprint through reduced energy usage [9]. Success at PT. XYZ would be replicable as a blueprint for other industrial buildings facing the same challenges, hence contributing to national energy conservation efforts and further fortifying the economic rationale for the utilization of green technology [4].

Life Cycle Cost Analysis (LCCA) is a significant approach to quantifying initial and ongoing building system costs of ownership based on the total cost incurred from acquisition to disposal [10]. The approach spans the entire system lifetime from the time of commissioning to de-commissioning and therefore offers a true analysis of its economic worth [11]. Contemporary applications of LCCA extend beyond merely in financial terms to accommodate environmental impacts, e.g., CO_2 emissions, under increased regulatory pressure aimed at sustainability in infrastructure development [12].

LCCA is flexible across broad application project size, from individual components to entire facilities, as an over-view planning tool for cost savings and assessment of the environment impacts [13]. The method allocates costs into two broad categories: initial, i.e., start-up, and future, e.g., operation, maintenance, and terminal end-of-life final disposal costs [10]. Specific care must be taken while estimating significant costs—those with heavy effects on comparison alternatives—especially capital replacements and terminal values near the terminus of a system's economic life [14]. By emphasizing lifecycle costs of ownership, Life Cycle Costing takes away from traditional single-minded emphasis on initial costs [15].

LCCA needs at least two options for comparison purposes, the most economically sound option being designated in accordance with lowest lifecycle cost within the framework of constant economic conditions [14]. As a supporting method, the payback period (PP) method calculates the time needed to pay back initial investments as benefits generated by the project [16]. Relabeled as the period at which total cash inflows match total outflows, PP sheds light on capital recovery efficiency [17] to aid investment turnover analysis [18]. While helpful for short-term recovery analysis, PP is unable to substitute for LCCA because it disregards the long-term cost behavior that is the biggest concern of economic appraisal to the greatest degree [19].

Table 1. Summary article related

No.	Article Title	Method	Research Results
1	Prasetiono, E., Mandagie, K. L., & Bhirawa, W. T. (2021). Analysis of Energy Efficiency Improvement & Lighting Cost Reduction in High Rise Buildings Using Life Cycle Cost Analysis (LCCA). JURNAL TEKNIK INDUSTRI, 7(2) [20].	LCCA	This study used the LCCA method to compare two recommended lamp alternatives: CFL and LED. The results showed that LED was selected to replace CFL, yielding a cost saving of IDR 297,051,982 over 5 years and an energy saving of 73,569.6 kWh per year at The Peak at Sudirman apartment.
2	Purnamasari, L. (2012). Life Cycle Cost Analysis of Using Energy-Saving Lamps at the Faculty of Engineering UI. Universitas Indonesia [21].	LCCA	This study checked the power of lamps and calculated energy savings using the LCCA method on three lamp types: TL, CFL, and LED. The result indicated that LED replaced TL with a cost saving of 11% and energy saving of 87% compared to the TL lamps used in the Faculty of Engineering UI buildings.
3	Syam, S., Kurniati, S., & Effendi, J. (2020). Efficiency Analysis of Using Energy-Saving Lamps and Electronic Ballasts on Fluorescent Lamps. Elektrika Borneo, 6(1), 1–7 [22].	Literature Review & Experiment	Energy-saving lamps require a higher initial cost than regular lamps, but in daily operation they are more economical, resulting in energy savings of between 20%–80%.
4	Purwanti, I., Poerwanto, P., & Wahyuni, D. (2013). Analysis of Lighting Effects on Eye Fatigue of Operators in the Control Room of PT. XYZ. Jurnal Teknik Industri USU, 3(4), 219509 [23].	Descriptive Correlational	The study concluded that the lighting levels in the production control room of PT. XYZ do not meet the standards set by the Indonesian Ministry of Health Decree No. 1405/MENKES/SK/IX/02.
5	Jannah, F. R., Sahri, M., Ayu, F., & Winarno, B. (2022). Analysis of the Relationship Between Lighting Systems and Eye Fatigue in Office Workers. Jurnal Ilmiah Wahana Pendidikan, 8(13), 118–127 [24].	Analytical Observational	Measurement of lighting intensity at 11 points showed that 84.6% did not meet lighting standards. Eye fatigue measurements showed that 84.6% of employees experienced eye fatigue. The analysis indicated a strong relationship between the lighting system and eye fatigue.
6	Belany, P., Hrabovsky, P., & Kolkova, Z. (2021). Combination of Lighting Retrofit and Life Cycle Cost Analysis for Energy Efficiency Improvement in Buildings [13]. Energy Reports, 7, 2470–2483.	LCCA	Data from life cycle cost analysis was obtained through calculations. The results of measurements were compared with LCCA data to determine the accuracy of the analysis. The final objective was to evaluate its suitability for modernization, retrofit, new lighting system design, and improving energy efficiency in buildings.
7	Kale, N. N., Joshi, D., & Menon, R. (2016). Life Cycle Cost Analysis of Commercial Buildings with Energy Efficient Approach. Perspectives in Science, 8, 452–454 [25].	LCCA	This study considered two educational buildings as case studies. Their life cycle costs were calculated under existing conditions and under an energy-efficient approach using the net present value method.
8	Roja, R. (2021). Life Cycle Cost Analysis of Anak Air Padang Type A Terminal Building. Universitas Andalas [26].	LCC	The calculation results showed the following cost components for the Anak Air Padang Type A Terminal building: initial cost IDR 70,279,648,604.02 (29.39%), operational cost IDR

No.	Article Title	Method	Research Results
			132,640,280,100.43 (55.42%), maintenance cost IDR 35,131,399,213.12 (14.68%), and demolition cost IDR 1,270,016,390.89 (0.53%). Contracted operational costs were higher than non-contracted ones by 0.49% or IDR 1,175,842,425.34.

The novelty of this study compared to existing studies is the optimization of mercury vapor lamp (HPL-N) replacement by highbay lighting using Life Cycle Cost Analysis (LCCA) method, specifically used in industrial building areas such as warehouses. The study employs DIALux simulation to ensure that the renewal of lighting meets the required level of illumination. The testing is conducted based on the Minister of Health Regulation No. 70 of 2016 on industrial occupational health environment standards and requirements [27].

2. Methods

This study employed the Life Cycle Cost Analysis (LCCA) to compare and analyze energy efficiency and cost savings of conventional HPL-N lamps compared to LED lights in PT. XYZ's warehouse in Cilegon. Information was gathered by documenting existing lamp details (number, type, power rating, and lifetime), field surveys for verification of utilization patterns (12 hours/day), and Dialux simulations to ensure recommended LED lighting meeting Indonesian Ministry of Health lighting standards (100–250 lux). The 12-hour usage pattern was based on direct observation of daily warehouse operations at PT. XYZ.

Dialux Evo computer software was used to simulate the lighting design and intensity of the proposed LED system. The simulations took into account warehouse size, the mounting position of the luminaire, surface reflectivity, and photometric information of the selected LED models. The results were cross-checked with the existing lighting condition and national lighting standard for validity and conformity.

Electricity rates (IDR 1,450/kWh) and lamp prices were sourced from PT. XYZ's distributor. The selected electricity tariff reflects the actual rate charged to PT. XYZ as confirmed by their Engineering Department. LCCA analysis covered initial investment, operating costs (energy consumption), maintenance, and replacement over a duration of 11 years at present value.

The 11-year cost comparison period was selected to align with the HPL-N lamp ballasts' operating life (approximately 40,000 hours) to create a total cost comparison for one complete system life cycle. Lamp lives were taken from the manufacturer information and typical industrial use patterns (12 hours per day). HPL-N lamps, rated for 6,000 hours, have to be replaced several times during that period, while LED Highbay lamps have a life of more than 50,000 hours, the entire period without replacement. There was no discount rate applied because the 11-year period with its certain cash flows allowed for direct comparison independent of inflation and financial discount. This keeps things simple and still gives useful insight into long-term cost-effectiveness.

The energy saving was determined by an annual comparison of kWh consumption between the HPL-N and the LED systems, while cost savings were compared in payback period and total lifecycle cost.

3. Results and Discussion

3.1. Data collection

Data concerning stock lamps in the warehouse are the number of lamp units on hand and in use at PT. XYZ, installed lamp units' power capacity, period of usage, and specific brands used by the company.

The data collection process in PT. XYZ comprises detailed records of types of lamp units and supporting specifications commonly applied to the Cilegon Warehouse, together with the unit price and associated Lux (lighting) levels, which will subsequently serve as standards for evaluating the potential of energy saving.

Table 2. Data on Light Points and Types

No	Lighting Type & Specification	Unit (Pcs)	Total Wattage (W)
1	HPLN 125 W (Non-LED)	140	21,882
2	HPLN 250 W (Non-LED)	66	20.625
	Total	**206**	**42,507**

Table 2 presents data on the quantity and type of luminaries used by PT. XYZ in Cilegon. The lighting types are HPLN (High-Pressure Mercury Vapor Lamps) with wattages of 125 Watts and 250 Watts. The quantity of HPLN lamp units in use is 206. The wattage values include ballast losses based on real usage.

3.2. Lamp Lifespan and Operating Parameters

Table 3 summarizes the estimated operational lifespan of both the lamps and their supporting components, based on manufacturer specifications and actual usage patterns (12 hours/day).

Table 3. Operational Lifetimes of Lighting Components

Specification	Quantity	Lifetime (hours)	Equivalent Years
HPLN 125W	140	6.000	1,67 years
HPLN 250W	66	6.000	1,67 years
Ballast HPLN 125W	140	40.000	11,11 years
Ballast HPLN 250W	66	40.000	11,11 years

Note: These figures directly impact the total replacement cost during the 11-year evaluation period.

3.3 Data Retrieval from PT. XYZ (Lighting distributor)

After learning the amount and what kind of lamps are installed in the PT. XYZ Warehouse in Cilegon, the second important data is concerned with the price of every kind of lamp. The data were asked directly to PT. XYZ, which also acts as a distributor of lighting products.

Table 4. Prices and Lamp Specifications

No	Specification	Quantity	Unit Price (USD)	Lifetime
				Hours
	Lighting			
1	HPLN 125W	140	4,387	6.000
2	HPLN 250W	66	12,903	6.000
	Support			
1	Ballast HPLN 125W	140	12,581	40.000
2	Ballast HPLN 250W	66	17,742	40.000

Complete specifications of LED lamps, with particular reference to the OSRAM brand in comparison with HPLN lamps, are given in Figure 1.

Figure 1. Lamp Specifications

Spesifikasi					
No	Data	Existing	Existing	OSRAM	OSRAM
1	Type	Highbay with HPLN 125W	Highbay with HPLN 250W	GINOLED GL-HO-E 80W-865 L60X60	GINOLED GL-HO-E 120W-865 L60x60
2	Power Consumption (Watt)	156 W	313 W	83	125
3	Voltage	115-135V	125-145V	220-240VAC	220-240VAC
4	Beam Angel	-	-	60^ox 60^o	60^ox 60^o
5	Color Temperature	4200K	4100K	6500K	6500K
6	CRI	46	45	80	80
7	Index Protection	-	-	IP65	IP65
8	System lumen output (lm)	6200lm	12700lm	11.000Lm	16.500Lm
9	System Efficacy (lm/w)	50lm/W	51lm/W	143 lm/W	143 lm/W
10	Life Time	6000hr	6000hr	50.000Hrs	50.000Hrs
11	Warranty	-	-	3 Years	3 Years

3.4 State Electricity Tariff

Based on information provided by the Engineering Department Manager of PT. XYZ Cilegon, the normal electricity rate for PT. XYZ Cilegon is IDR 1,450 per kWh or USD 0.094 per kWh.

3.5. Calculation Life Cycle Cost Analysis

Electricity Consumption (EC)

The total energy consumed is applied to determine the variation in energy requirements when existing lights are replaced by LED Highbay lamps in PT. XYZ Cilegon. Energy consumption per type of lamp—HPLN and LED Highbay—is categorized. According to data amassed on the subsequent pages, the total number of LED Highbay units (both 80W and 120W) is 206. If replacement is done, there will be an installation of the same number of 206 units. Operating time is 12 hours per day.

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$$EC_{HPLN125} = (N\ x\ W\ x\ OH) / 1000 = (140\ x\ 156{,}3\ x\ 12\ x\ 30\ x\ 12) / 1000 = 94.530{,}24\text{Kwh}$$

$$EC_{HPLN250} = (N\ x\ W\ x\ OH) / 1000 = (66\ x\ 312{,}5\ x\ 12\ x\ 30\ x\ 12) / 1000 = 89.100\text{Kwh}$$

Total annual energy consumption of HPLN lamps (125W and 250W) is 189,030.24 kWh.

$$EC_{LEDE80} = (N\ x\ W\ x\ OH) / 1000 = (140\ x\ 82{,}8\ x\ 12\ x\ 30\ x\ 12) / 1000 = 50.007{,}44\text{Kwh}$$

$$EC_{LEDE120} = (N\ x\ W\ x\ OH) / 1000 = (66\ x\ 124{,}7\ x\ 12\ x\ 30\ x\ 12) / 1000 = 35.554{,}46\text{Kwh}$$

The yearly energy consumption of LED Highbay lamps of 80W and 120W stands at an estimated 71,108.924 kWh.

Table 5. HPLN calculation

No	Specification	Quantity	Price per Unit	Total Price	System Wattage	Total kW	Electricity Cost			Lifetime (Hours)
							5 Years	7 Years	10 Years	
	Lighting									
1	HPLN 125W	140	USD 4.39	USD 614.19	125	17.50	USD 29,467.74	USD 41,254.84	USD 58,935.48	6,000 (1.67 years)
2	HPLN 250W	66	USD 12.90	USD 851.61	250	16.50	USD 27,783.87	USD 38,897.42	USD 55,567.74	6,000 (1.67 years)
	Support									
1	Ballast HPLN 125W	140	USD 12.58	USD 1,761.29	31.3	4.38	USD 7,366.94	USD 10,313.71	USD 14,733.87	40,000 (11.11 years)
2	Ballast HPLN 250W	66	USD 17.74	USD 1,170.97	62.5	4.13	USD 6,945.97	USD 9,724.35	USD 13,891.94	40,000 (11.11 years)
	Lighting	206		USD 1,465.81	**TOTAL**	**42.50**	**USD 71,564.52**	**USD 100,190.32**	**USD 143,129.03**	
	Support	206		USD 2,932.26						
	Total Proposal Cost	412		USD 4,389.06						

Table 5 shows the cost breakdown for HPLN lamps, including lamp prices, electricity fees, and life. The replacement cost is indicated at USD 4,398.06, and electricity fees within a 5,7, and 10 years span are included in the table.

Table 6. LED calculations

No	Specification	Quantity	Price per Unit	Install Price per Unit	Total Price	System Wattage	Total kW	Electricity Cost			Lifetime (Hours)
								5 Years (18,000 hours)	7 Years (25,200 hours)	10 Years (36,000 hours)	
	Lighting										
1	OSRAM GINOLED GL-HO-E 80W-865 L60X60 IP65 (11,000 lm)	140	USD 112.58	-	USD 15,760.60	82.8	11.59	USD 19,518.42	USD 27,325.75	USD 39,036.54	50,000 (13.89 years)
2	OSRAM GINOLED GL-HO-E 120W-865 L60x60 IP65 (16,500 lm)	66	USD 125.08	-	USD 8,255.21	124.7	8.23	USD 13,862.06	USD 19,406.88	USD 27,724.12	50,000 (13.89 years)
	Support										
1	No Ballast	-	-	-	-	**TOTAL**	**19.824**	**USD 33,380.48**	**USD 46,732.67**	**USD 66,760.96**	
2	No Ballast	-	-	-	-						
	Lighting	206			USD24,015.81						
	Installation Cost	-									
	Total Proposal Cost	206			USD24,015.81						

Table 6 gives the cost structure of LED Highbay lamps, such as lamp costs, electricity consumption, and lifespan. The initial cost is USD 24,015.81 and expected electricity costs within 5,7, and 10 years also listed in the table.

Table 7. HPLN and LED calculation results

Review	5 Years		7 Years		10 Years		Notes
	Non-LED (USD)	**LED (USD**	**Non-LED (USD)**	**LED (USD)**	**Non-LED (USD)**	**LED (USD)**	
Price	0.00	24,015.81	0.00	24,015.81	0.00	24,015.81	Initial Investment
Spare Parts Cost	4,397.42	0.00	5,863.23	0.00	8,794.84	0.00	Parts Replacement Cost (Year 2, etc.)
Electricity Cost	71,564.52	33,380.48	100,190.32	46,732.67	143,129.03	66,760.96	Electricity Consumption Cost
Total Cost	75,961.94	57,396.29	106,053.55	70,748.48	151,923.87	90,776.77	Initial + Spare Parts + Electricity Cost
Annual Operating Cost	15,192.39	6,676.10	15,150.51	6,676.10	15,192.39	6,676.10	Avg. Parts & Electricity Cost per Year

Table 7 juxtaposes the lamp price, electricity cost, and replacement expense of HPLN and LED Highbay lamps during the 5,7, and 10 years lifespan. While the initial cost of LED Highbay lamps is also greater than that of HPLN lamps, the net operating expense of operating LED Highbay lamps is still more economical when all the cost elements are considered.

Table 8. Comparison Results of HPLN and Highbay LED Lamps

Product	Before (Conventional)	After (LED)
Quantity (pcs)	206	206
Total Energy Consumption (kW)	42,500	19,824
Operational Cost per Year (USD)	15,192	6,676
Reduction of Total Energy Consumption From Non LED to LED	**53%**	
Operational Cost Savings per Year (USD)	8,516	
Operational Cost Savings per Month (USD)	710	
Lighting Investment (USD)	24,016	
Payback Period (Years)	2.82	

4. Conclusion

After doing extensive computations and analysis for power suitability and selecting replacement lamps for the installed HPLN units, the following conclusions are drawn. Based on the Life Cycle Cost Analysis (LCCA) method, cost-effectiveness is the primary consideration for deciding between the two lamp types. The operating cost of the HPLN lamps is USD 15,192 annually, and that of the Highbay LED lamps is USD 6,676 annually. Therefore, the Highbay LED is the most appropriate option for PT.

XYZ Cilegon, which is firstly and most importantly due to its extended operating life—five HPLN life cycles are equivalent to a single LED life cycle. Secondly, Highbay LED lamps are more ecologically friendly, as HPLN lamps still contain mercury. The Highbay LED lamps achieve a 53% energy consumption saving compared to HPLN lamps, as calculated in Table 8, which represents 22,676 kWh of annual energy saving for PT. XYZ Cilegon.

Author Contributions

Pratama Jaya conceived and planned the study, conducted data collection and analysis, and wrote the first manuscript under the supervision of Taufik. Taufik added conceptual input, checked the methodology for validity, and provided critical manuscript revisions. The authors have read and approved the final manuscript and are fully responsible for the validity of the research.

Data Availability

The datasets used in this study are available at Zenodo repository https://zenodo.org/records/15628038

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