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COMPARING ENERGY EFFICIENCY AND STABILITY OF LED AND FLUORESCENT LIGHTS ON MARITIME TRAINING SHIPS

PERBANDINGAN EFISIENSI ENERGI DAN STABILITAS LAMPU LED DAN FLUORESEN PADA KAPAL LATIH MARITIM

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ABSTRACT

Lighting efficiency is vital for energy management and sustainability aboard maritime vessels. This study aims to examine the comparative energy efficiency, luminous efficacy, and performance stability of light-emitting diode (LED) and fluorescent (FL) lighting systems onboard the Sultan Hasanuddin maritime training ship operated by Politeknik Ilmu Pelayaran Makassar, Indonesia. Using a quantitative experimental approach, the research combined lamp testing, shipboard lighting audits, and simulation-based analysis under actual operational conditions from June to December 2024. The results demonstrated that LED lamps achieved an average luminous efficacy of 202.4 lm/W, significantly higher than the 39.1 lm/W recorded for FL lamps. The transition to LED reduced accommodation lighting power consumption from 4,860 to 1,482 watts, with a 29.7% increase in total luminous output, while projected energy consumption fell by approximately 80.7% over the study period—indicating substantial potential for operational cost savings and emissions reductions. LED lamps also showed superior performance stability under controlled testing, maintaining consistent illumination without noticeable degradation, whereas FL lamps experienced gradual brightness decline and frequent maintenance issues. These findings suggest that adopting LED lighting on maritime training ships offers significant benefits in energy efficiency, operational reliability, and sustainability. However, because LED performance is partly based on simulation, further long-term onboard validation is recommended. The study offers practical recommendations for maritime institutions seeking to modernize shipboard lighting and contributes to broader energy efficiency goals in the maritime sector.

Keywords: energy efficiency, fluorescent lamps, LED lighting, luminous efficacy, maritime training ships

ABSTRAK

Efisiensi pencahayaan memiliki peran penting dalam meningkatkan manajemen energi dan keberlanjutan pada kapal maritim. Penelitian ini bertujuan untuk mengkaji perbandingan efisiensi energi, *luminous efficacy*, serta stabilitas kinerja sistem pencahayaan *light-emitting diode* (LED) dan fluoresen (FL) pada kapal latih maritim Sultan Hasanuddin yang dioperasikan oleh Politeknik Ilmu Pelayaran Makassar, Indonesia. Dengan pendekatan kuantitatif eksperimental, dilakukan pengujian lampu, audit pencahayaan di kapal, dan analisis berbasis simulasi yang dilakukan pada kondisi operasional nyata dari bulan Juni hingga Desember 2024. Hasil menunjukkan bahwa lampu LED mencapai rata-rata *luminous efficacy* sebesar 202,4 lm/W, jauh lebih tinggi dibandingkan dengan 39,1 lm/W pada lampu FL. Peralihan ke sistem LED menurunkan total konsumsi daya pencahayaan akomodasi dari 4.860 watt menjadi 1.482 watt, disertai peningkatan total keluaran cahaya sebesar 29,7%. Selama periode enam bulan, proyeksi konsumsi energi menurun sekitar 80,7%, yang menunjukkan potensi besar untuk penghematan biaya operasional dan pengurangan emisi. Selain itu, lampu LED menunjukkan stabilitas kinerja yang lebih unggul dalam kondisi pengujian terkendali, dengan mempertahankan tingkat pencahayaan yang konsisten tanpa degradasi yang berarti, sedangkan lampu FL mengalami penurunan kecerahan secara bertahap dan sering memerlukan perawatan. Temuan ini menunjukkan bahwa penerapan pencahayaan LED pada kapal latih maritim memberikan manfaat signifikan dalam hal efisiensi energi, keandalan operasional, dan keberlanjutan. Namun, mengingat kinerja LED sebagian didasarkan pada simulasi, validasi jangka panjang di kapal secara langsung tetap direkomendasikan. Studi ini memberikan rekomendasi praktis bagi institusi maritim yang ingin memodernisasi sistem pencahayaan kapal dan berkontribusi pada upaya yang lebih luas untuk mencapai tujuan efisiensi energi di sektor maritim.

Kata kunci: efisiensi energi, kapal latih maritim, lampu fluoresen, *luminous efficacy*, pencahayaan LED

INTRODUCTION

The transition to energy-efficient technologies has become a central focus across various industries, including the maritime sector. In particular, advancements in lighting technologies such as light-emitting diodes (LEDs) have brought substantial benefits in terms of energy savings, operational reliability, and reduced environmental impact (Van Der Zee *et al.* 2022; Yang *et al.* 2022). Unlike traditional fluorescent (FL) lamps, LEDs offer higher luminous efficacy and longer operational lifespans, making them a strategic choice for enhancing energy management systems, especially in confined and energy-intensive environments like ships (Sulkhani *et al.* 2014; Qian *et al.* 2021).

In maritime operations, energy efficiency is crucial not only for reducing fuel consumption and operational costs but also for supporting international efforts to minimize greenhouse gas (GHG) emissions and align with standards set by the International Maritime Organization (IMO) (Yeremenko 2022). Although lighting represents a smaller proportion of total onboard energy use compared to propulsion, heating, or pumping systems (Kim and Choi 2023; Uyan *et al.* 2023), it remains an important factor due to the continuous operation of accommodation, navigation, and safety lighting systems. Improving lighting efficiency, therefore, presents an accessible yet often overlooked opportunity to enhance overall vessel sustainability.

Previous comparative studies have consistently demonstrated the superior performance of LED lighting over fluorescent and neon alternatives, with findings reporting up to 80% reductions in energy consumption (Kazemi *et al.* 2018; Zhang *et al.* 2023). However, specific research examining the application of LED lighting within the context of maritime training ships remains limited. Training ships, such as those operated by maritime academies, are uniquely demanding environments, requiring reliable, high-quality illumination for extended periods to support educational, operational, and navigational activities.

The core problem that motivates this study is the absence of empirical, ship-specific evidence on whether replacing fluorescent lighting with LEDs in maritime training vessels can deliver measurable improvements in energy efficiency, lighting stability, and operational sustainability. While LEDs are widely promoted as efficient, the practical benefits and potential challenges of their use in training ships, which function under distinctive operational and educational conditions, have not been systematically examined.

This study addresses this problem by systematically comparing the energy efficiency, luminous efficacy, and performance stability of LED and fluorescent (FL) lighting systems aboard the Sultan Hasanuddin maritime training ship, operated by Politeknik Ilmu Pelayaran (PIP) Makassar, Indonesia. In addition to energy considerations, the study also acknowledges the importance of lighting quality for supporting crew performance, safety, and visual comfort in maritime training environments. Fluorescent lighting systems are commonly associated with issues such as flicker, gradual lumen depreciation, and lower color rendering quality, which may contribute to visual fatigue and reduced work comfort during prolonged operational activities.

Through direct measurement of illumination intensity, power consumption analysis, and longitudinal observation over seven months, the research seeks to provide empirical evidence on both the technical performance and practical implications of transitioning to LED lighting in maritime training settings. Ultimately, the findings aim to inform energy management strategies while also supporting improvements in onboard working conditions and more sustainable operational practices within the maritime education sector.

METHODS

This study adopts a comparative quantitative research approach to evaluate the energy efficiency, luminous efficacy, and performance stability of light-emitting diode (LED) and fluorescent (FL) lighting systems onboard the Sultan Hasanuddin maritime training ship. The research was conducted over a period of seven months, from June to December 2024, under actual operational conditions to capture realistic patterns of lighting usage, energy consumption, and performance.

During the seven-month study period (June–December 2024), the ship continued to operate with its existing fluorescent (FL) lighting system. Illumination stability, brightness degradation, and maintenance events (e.g., flickering or replacements) were directly recorded through routine monitoring on board. For the LED system, direct operational measurements were not carried out for seven months, since LEDs were not yet installed across the vessel. Instead, the luminous efficacy and power consumption of representative LED lamps (10 W and 20 W) were experimentally measured under controlled conditions. These values were then used to construct a full-ship simulation, where the number of required LED fixtures, total power consumption, and predicted energy use over seven months were calculated using the standardized formulas described earlier.

This means that FL lamps were observed in real time for seven months, while LED lamps were assessed through a combined approach of controlled testing and seven-month simulation. The comparative analysis, therefore, represents actual FL performance versus projected LED performance under equivalent operating conditions.

The Sultan Hasanuddin training ship, operated by Politeknik Ilmu Pelayaran (PIP) Makassar, served as the research site (the vessel is shown in Figure 1). As a 1,200 gross tonnage (GT) vessel, the ship is equipped with multiple decks, including the Bridge Deck, Crew Deck, Main Deck, and Bottom Plan, each with specific lighting needs for accommodation, educational, and navigational purposes. A detailed audit of the ship's existing lighting systems was performed, utilizing the ship's official electrical layout diagrams to document the number of lighting points, lamp wattages, and the spatial arrangement of fixtures across different compartments. The deck layout of the ship is illustrated in Figure 2.

To facilitate the comparative analysis, the study employed both 10-watt and 20-watt FL and LED lamps. These lamps were tested using standardized light fittings and a lux meter to measure illumination at a distance of 1 meter in a controlled environment, eliminating external light interference. Electrical power consumption was measured using a calibrated digital power meter. All lamps were tested three times, and average values were recorded to enhance the reliability of the results. The measurement procedure focused on measuring lux values, calculating lumen output, and determining the luminous efficacy of each lighting type using standardized formulas. The following formulas were applied to quantify lamp performance and comparative energy efficiency:

Lumen Output

$$Lumen\ Output\ (LM) = Illuminance\ (lux) \times Area\ (m^2)$$

Luminous Efficacy

$$Lumen\ Efficacy\left(\frac{lm}{W}\right) = \frac{Lumen\ Output\ (LM)}{Power\ Consumption\ (W)}$$

Daily Power Consumption

$$P_{daily} = \sum_{i=1}^{n}(W_i \times N_i) \times H$$

where Wi is lamp wattage, Ni is the number of lamps, and H is the average operating hours per day.

Figure 1. Sultan Hasanuddin maritime training ship used as the study site for onboard lighting evaluation.

Figure 2. Deck layout of the Sultan Hasanuddin maritime training ship showing bridge, crew, main, and bottom levels.

Monthly and Seven-Month Consumption

$$P_{month} = P_{daily} \times D, P_{6months} = \sum_{j=1}^{6} P_{monthly,j}$$

Total Lumen Output

$$L_{total} = \sum_{i=1}^{n} (LumenOutput_i \times N_i)$$

The key tools and materials used during the study are summarized in Table 1.

Following lamp testing, a shipboard survey was conducted to document the current lighting installation. The total number of FL lamps in each deck was recorded, along with the cumulative power consumption. Based on the measured luminous efficacy of the tested LED lamps, the number of LEDs required to achieve equivalent or better illumination in each area was calculated. Subsequently, a simulation of a full LED replacement scenario was created, adjusting for both the number of fixtures and total wattage required to maintain or improve illumination levels throughout the vessel.

Energy consumption calculations were performed under the assumption that lighting systems operate for approximately 12 hours per day, particularly in accommodation and navigation areas where lighting remains active throughout the night. The monthly and total seven-month energy consumption for both the existing FL lighting system and the simulated LED system was computed. These calculations allowed for the estimation of potential energy savings, percentage reductions in consumption, and anticipated operational cost benefits.

Data analysis primarily involved descriptive statistical techniques, including mean comparisons, percentage reduction calculations, and energy cost estimations. Lighting intensity data, luminous efficacy, and power consumption values were cross-validated against theoretical benchmarks found in previous studies (Qin *et al.* 2009; Pattison *et al.* 2018) to ensure consistency and validity. To enhance the robustness of the findings, measurements were conducted in stable environmental conditions, instruments were calibrated, and repetitive testing was performed to minimize measurement errors.

This methodology provided a comprehensive and empirical basis to assess the comparative performance of LED and FL lighting systems onboard a maritime training vessel, offering actionable insights for future decisions regarding energy management improvements in similar maritime education contexts.

RESULTS AND DISCUSSION

Lamp testing was conducted to directly measure the luminous efficacy and light intensity of both fluorescent (FL) and light-emitting diode (LED) lamps at two different wattages, 10 W and 20 W, under controlled conditions. Each lamp was positioned one meter away from a calibrated lux meter sensor in a dark environment to eliminate ambient light interference. The experimental setup for measuring illumination intensity is shown in Figure 3. The luminous flux (lumen output) was calculated based on measured lux values, and luminous efficacy was then derived by dividing lumen output by power consumption (W). The test results are summarized in Table 2.

The luminous efficacy values for individual lamp ratings are shown in Table 2. Specifically, the 10 W fluorescent lamp achieved 36.7 lm/W, and the 20 W fluorescent lamp achieved 41.6 lm/W. For LED lamps, the 10 W model produced 182.1 lm/W, while the 20 W model produced 222.9 lm/W. To provide a general comparison, the results were averaged across both wattages. The average luminous efficacy recorded for the FL lamps was therefore 39.1 lm/W, while for the LED lamps it was significantly higher at 202.4 lm/W. These averages indicate that, at the lamp level, LED lamps are approximately five times more efficient than fluorescent lamps in converting electrical energy into visible light.

Table 1. Equipment and materials used for lamp testing and onboard lighting measurement.

Equipment and Materials	Specifications
Fluorescent lamps	10 W and 20 W
Light-emitting diode (LED) lamps	10 W and 20 W
Lux meter	Calibrated, high sensitivity
Digital power meter	Accurate measurement of watts consumed
Lamp fittings	Standardized for both lamp types
Stable power source	Ship generators and shore connection

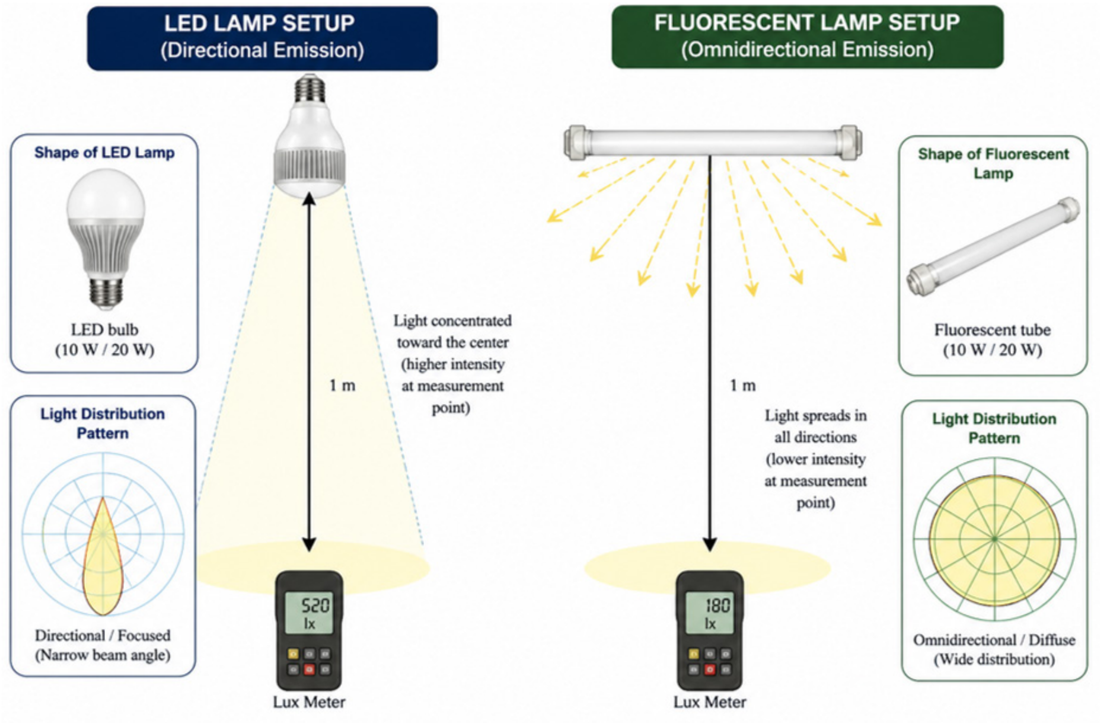

Figure 3. Experimental setup for measuring illumination intensity of LED (bulb-type, directional emission) and fluorescent (tube-type, omnidirectional emission) lamps using a lux meter at a 1 m distance.

Table 2. Measured illumination intensity, calculated lumen output, and luminous efficacy of LED and fluorescent lamps (10 W and 20 W) at a 1 m testing distance.

Lamp Type	Power (W)	Measured Lux	Calculated Lumen Output (lm)	Luminous Efficacy (lm/W)
Fluorescent (FL)	10	117	367	36.7
Fluorescent (FL)	20	265	832	41.6
Light-emitting diode (LED)	10	580	1,821	182.1
Light-emitting diode (LED)	20	1,420	4,459	222.9

When comparing the specific measurements, the 10 W LED lamp produced approximately 1,821 lumens, compared to only 367 lumens produced by the 10 W FL lamp, while consuming the same amount of electrical power. Similarly, at the 20 W rating, the LED lamp produced 4,459 lumens, substantially higher than the 832 lumens from the FL lamp. This performance highlights not only the superior energy efficiency of LEDs but also their ability to deliver much higher illumination levels without additional power consumption.

The results confirm that replacing FL lamps with LED alternatives can lead to significant gains in lighting efficiency and output intensity. These improvements form the basis for further energy-saving potential when applied to the shipboard lighting systems evaluated in subsequent sections.

Current lighting system audit: power consumption and light output

An audit of the existing lighting system onboard the Sultan Hasanuddin training ship was conducted to document the number of light points, the types of lamps installed, the total power consumption, and the cumulative light output produced across different deck levels. The lighting system currently in use primarily relies on fluorescent (FL) lamps with power ratings of either 10 watts or 20 watts, depending on the specific location and lighting requirements.

The audit revealed that the ship's accommodation and operational spaces, including the Bridge Deck, Crew Deck, Main Deck, and Bottom Plan, were equipped with a total of 165 fluorescent lamp points. The cumulative power consumption for these FL lamps was calculated to be 4,860 watts. A breakdown of the lighting data across different deck levels is presented in Table 3.

The audit findings indicate that although the number of FL lamps installed is substantial, the luminous output achieved is relatively moderate compared to the total power consumed. For instance, the Main Deck, which has the highest lighting demand, utilized 55 FL lamps drawing 1,820 watts to produce approximately 141,960 lumens. Similarly, the Bottom Plan required 1,840 watts to generate 143,520 lumens.

The overall lighting efficacy across the ship's accommodation and operational areas under the FL system thus remained relatively low, consistent with the previously measured luminous efficacy values during lamp testing. These findings highlight a significant opportunity to enhance lighting performance and energy efficiency through the adoption of higher-efficacy lighting solutions, such as LEDs, which are further explored in the following section through a simulated replacement scenario.

Simulation of LED lighting replacement

Following the audit of the existing fluorescent (FL) lighting system, a simulation was conducted to estimate the potential improvements achievable by replacing the FL lamps with light-emitting diode (LED) lamps onboard the Sultan Hasanuddin training ship. The simulation aimed to determine the number of LED lamps required to achieve at least equivalent, if not superior, illumination levels across all deck areas while significantly reducing power consumption.

Based on the measured luminous efficacy of the LED lamps, which averaged 202.4 lumens per watt, it was found that fewer LED units were needed to produce the same or greater total light output compared to the FL lamps. Consequently, the number of light points could be reduced from 165 to 120 without compromising the lighting quality or safety requirements onboard. The calculated power consumption and lumen output for the LED system are summarized in Table 4.

Compared to the original FL system, the simulated LED system achieved substantial improvements. The total power consumption was reduced from 4,860 watts to 1,482 watts, representing a 69.5% reduction in accommodation lighting energy requirements. Simultaneously, the total luminous output increased from 375,963 lumens under the FL system to 535,190 lumens with the LED system, resulting in a 29.7% increase in lighting output quality.

These results underscore the significant advantages of LED technology not only in terms of energy savings but also in enhancing illumination levels across key operational and accommodation areas. In addition, the reduction in the number of lighting fixtures required implies potential savings in future maintenance, replacement costs, and installation complexity.

The simulated replacement scenario demonstrates that transitioning to an LED lighting system offers a highly effective strategy for improving energy management onboard maritime training ships without compromising operational safety or comfort.

Energy consumption comparison over seven months

An energy consumption analysis was conducted over a seven-month operational period from June to December 2024 to quantify the practical energy savings achievable through the transition from fluorescent (FL) to light-emitting diode (LED) lighting. The analysis was based on the assumption that the ship's lighting systems operated for approximately 12 hours each day, reflecting typical conditions for accommodation and navigation lighting on a training vessel.

Table 3. Distribution of fluorescent lighting across ship decks, including the number of fixtures, total power consumption, and lumen output.

Deck Location	Number of Light Points (FL)	Total Power Consumption (W)	Total Lumen Output (lm)
Bridge deck	11	370	28,860
Crew deck	39	830	61,623
Main deck	55	1,820	141,960
Bottom plan	60	1,840	143,520
Total	**165**	**4,860**	**375,963**

Table 4. Simulated LED lighting distribution across ship decks, including the number of fixtures, total power consumption, and lumen output.

Deck Location	Number of Light Points (FL)	Total Power Consumption (W)	Total Lumen Output (lm)
Bridge deck	8	89	32,273
Crew deck	37	367	132,487
Main deck	39	574	207,258
Bottom plan	36	452	163,172
Total	**120**	**1,482**	**535,190**

Monthly energy consumption values for both the existing FL system and the simulated LED system were calculated by multiplying the total installed lighting power by operational hours and days within each month. The results are summarized in Table 5.

The analysis revealed that the fluorescent lighting system consumed a total of 27,253,061 watt-hours (Wh) over the seven months, while the simulated LED system would have consumed only 5,264,796 Wh. This translates to an approximate 80.7% reduction in energy consumption attributable solely to the change in lighting technology.

On a monthly basis, the energy savings were consistently substantial, with LED lighting consuming only around 18 to 20 percent of the energy required by the FL system. For instance, in August, the ship would have consumed approximately 4,142,443 Wh using FL lamps, compared to only 800,245 Wh under the LED system, resulting in a monthly energy saving of 3,342,198 Wh.

The significant reduction in energy consumption has important implications not only for operational cost savings but also for environmental sustainability. Lower energy demand directly reduces the load on shipboard generators, leading to decreased fuel consumption and associated emissions, thereby supporting the broader goals of energy efficiency and greenhouse gas emission reductions as advocated by the International Maritime Organization (IMO).

These findings reinforce the practical benefits of LED adoption, suggesting that maritime training vessels could achieve meaningful reductions in operating expenses and environmental impacts through relatively simple technological upgrades.

Performance stability observation

In addition to measuring energy consumption and luminous efficacy, the study also monitored the performance stability of both fluorescent (FL) and light-emitting diode (LED) lighting systems over the seven-month operational period. Performance stability was assessed primarily by observing changes in brightness levels, operational consistency, and maintenance requirements during routine ship operations (Figure 4).

The observations indicated that fluorescent lamps were directly monitored onboard for seven months and showed a gradual brightness decline, while LED lamps were evaluated through controlled laboratory testing and seven-month performance simulations. In these controlled tests, LED lamps consistently maintained their initial illumination levels without noticeable degradation, and no premature failures were recorded. The simulated shipboard replacement scenario, therefore, assumes that LED systems would maintain stable illumination quality throughout extended operations. No significant reductions in brightness or color quality were detected, and the LED fixtures showed no incidents of premature failure or noticeable degradation. This stability is consistent with the characteristics of LED technology, which is known for its slow lumen depreciation rates and robust operational performance under varying environmental conditions.

In contrast, the fluorescent lamps exhibited a gradual decline in brightness over time. By the fourth month of observation, a noticeable reduction in light output was recorded in several areas, particularly in fixtures exposed to higher ambient temperatures or continuous usage. Furthermore, several fluorescent lamps required replacement due to flickering or complete failure, leading to increased maintenance activities. This pattern aligns with previous findings that highlight the relatively short lifespan and higher sensitivity of fluorescent lamps to operational stresses compared to LEDs (Allwyn *et al.* 2021).

The superior performance stability of LEDs not only ensures consistent lighting quality, which is critical for safety and operational efficiency on a training ship, but also reduces maintenance frequency and associated costs. This advantage is particularly significant in maritime environments where maintenance tasks can be complex, costly, and disruptive to normal operations.

These findings further reinforce the case for adopting LED lighting on maritime training ships, as the long-term operational reliability of LEDs translates into tangible benefits in terms of reduced maintenance burden, enhanced safety, and uninterrupted service performance.

Implications and practical recommendations

The findings of this study have broader implications for energy management and operational efficiency in maritime training ships and potentially in other sectors of the maritime industry. The results demonstrate that transitioning from fluorescent (FL) to light-emitting diode (LED) lighting systems can achieve significant reductions in energy consumption, operational costs, and maintenance needs without compromising illumination quality or safety standards.

For maritime training ships like the Sultan Hasanuddin, where lighting operates for extended periods to support accommodation, navigation, and educational activities, the benefits of adopting LED technology are particularly pronounced. The substantial reduction of approximately 80 percent in lighting-related energy consumption directly translates into lower fuel usage by onboard generators, contributing not only to financial savings but also to environmental sustainability by reducing greenhouse gas emissions. These outcomes align with the strategic objectives outlined by the International Maritime Organization (IMO) for greener maritime operations (Serra and Fancello 2020).

Table 5. Monthly and total energy consumption of fluorescent and simulated LED lighting systems over seven months (June–December 2024).

Month	Energy Consumption with FL (Wh)	Energy Consumption with LED (Wh)
June	3,926,160	758,463
July	3,971,621	767,245
August	4,142,443	800,245
September	3,595,536	694,592
October	3,800,798	734,245
November	3,802,176	734,511
December	4,014,326	775,495
Total	**27,253,061**	**5,264,796**

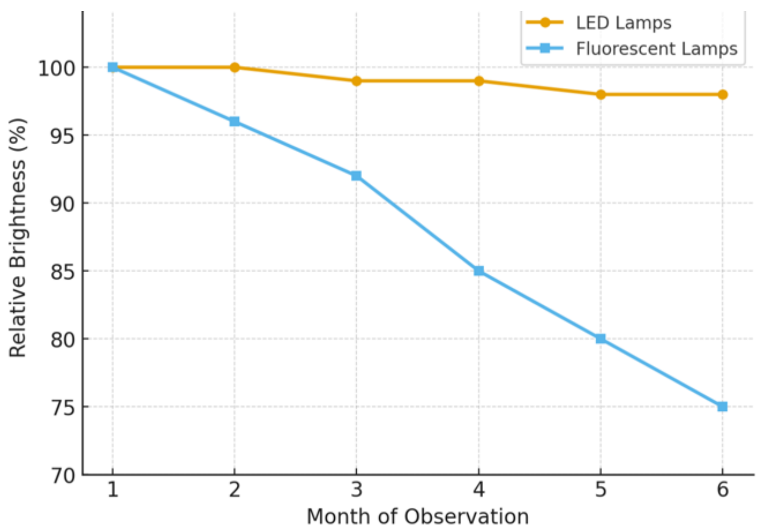

Figure 4. Comparison of the relative brightness stability of LED and fluorescent lamps over seven months of observation.

Moreover, the increased lighting stability and reduced maintenance requirements associated with LED systems offer operational advantages in maritime settings. Frequent maintenance tasks, such as lamp replacements, can be challenging and costly aboard ships due to limited accessibility, safety risks, and disruptions to regular activities. By minimizing the need for maintenance interventions, LED systems can improve overall vessel reliability and operational continuity.

Based on these findings, it is recommended that maritime training institutions, as well as commercial and passenger vessel operators, consider the phased or full replacement of outdated fluorescent lighting systems with high-efficiency LED alternatives. Although the initial investment costs for LED installations may be slightly higher than for traditional lighting, the long-term savings in energy and maintenance expenses, coupled with improvements in safety and environmental performance, clearly outweigh the initial financial outlay.

Additionally, broader adoption of LED lighting technologies across the maritime sector could contribute to cumulative industry-wide impacts, helping to meet international emissions targets and supporting the transition toward more sustainable shipping practices. Future studies could expand on this research by incorporating life-cycle cost analyses, exploring different LED product variants optimized for maritime environments, and assessing long-term durability in harsher offshore conditions.

Overall, the adoption of LED lighting technology represents a straightforward yet highly impactful strategy for promoting energy efficiency, sustainability, and operational excellence in the maritime industry.

CONCLUSION

This study examined the energy efficiency, luminous efficacy, and performance stability of light-emitting diode (LED) and fluorescent (FL) lighting systems aboard the Sultan Hasanuddin maritime training ship. Based on experimental testing, lighting audits, and simulation-based analysis, the findings indicate that LED technology has strong potential to improve lighting efficiency in maritime environments. LED lamps achieved a substantially higher average luminous efficacy (202.4 lm/W) compared to FL lamps (39.1 lm/W). The simulated replacement scenario suggests that transitioning to LED systems could reduce total lighting power consumption from 4,860 W to 1,482 W while increasing overall luminous output by 29.7%. Over seven months, projected energy consumption decreased by approximately 80.7%, indicating considerable potential for operational cost savings and reduced emissions. In terms of performance, fluorescent lamps exhibited gradual brightness degradation and higher maintenance requirements during onboard observation. In contrast, LED lamps demonstrated stable illumination under controlled testing conditions. However, it is important to note that the LED performance results are partly based on simulation rather than long-term onboard implementation. Therefore, the findings should be interpreted with appropriate caution. Future research should conduct full-scale onboard deployment of LED systems over extended periods to validate their long-term performance, durability, and impact on crew comfort and operational safety. Overall, this study provides empirical and simulation-based evidence supporting the potential benefits of LED adoption as part of energy efficiency strategies in maritime training vessels.

REFERENCES

Allwyn RG, Al Abri R, Malik A, Al-Hinai A. 2021. Economic Analysis of Replacing HPS Lamp with LED Lamp and Cost Estimation to Set Up PV/Battery System for Street Lighting in Oman. *Energies*. 14(22): 7697. DOI: https://doi.org/10.3390/en14227697.

Kazemi R, Choobineh A, Taheri S, Rastipishe P. 2018. Comparing Task Performance, Visual Comfort and Alertness Under Different Lighting Sources: An Experimental Study. *EXCLI Journal*. 17: 1018–1029. DOI: https://doi.org/10.17179/excli2018-1676.

Kim J, Choi A. 2023. Reduction of Lighting Power Consumption through Lighting Control Using The KNX/Digital Addressable Lighting Interface Protocol in Liquefied Natural Gas Carrier Accommodation Mock-Up. *Renewable and Sustainable Energy Reviews*. 182: 113374. DOI: https://doi.org/10.1016/j.rser.2023.113374.

Pattison PM, Hansen M, Tsao JY. 2018. LED Lighting Efficacy: Status and Directions. *Comptes Rendus, Physique*. 19(3): 134–145. DOI: https://doi.org/10.1016/j.crhy.2017.10.013.

Qian XY, Tang YY, Zhou W, Shen Y, Guo ML, Li YQ, Tang JX. 2021. Strategies to Improve Luminescence Efficiency and Stability of Blue Perovskite Light-Emitting Devices. *Small Science*. 1(8): 1–15. DOI: https://doi.org/10.1002/smsc.202000048.

Qin Y, Lin D, Hui SY. 2009. A Simple Method for Comparative Study on the Thermal Performance of LEDs and Fluorescent Lamps. *IEEE Transactions on Power Electronics*. 24(7): 1811–1818. DOI: https://doi.org/10.1109/TPEL.2009.2017021.

Serra P, Fancello G. 2020. Towards the IMO's GHG Goals: A Critical Overview of the Perspectives and Challenges of the Main Options for Decarbonizing International Shipping. *Sustainability*. 12(8): 3220. DOI: https://doi.org/10.3390/su12083220.

Sulkhani E, Purbayanto A, Wisodo SH, Mawardi W. 2014. Lampu LED Bawah Air sebagai Alat Bantu Pemikat Ikan pada Bagan Apung. *Jurnal Teknologi Perikanan dan Kelautan*. 5(1): 83–93. DOI: https://doi.org/10.24319/jtpk.5.83-93.

Uyan E, Atlar M, Ölçer AI. 2023. Improving the Energy Efficiency of Lighting Systems for a Marine Equipment Manufacturing Plant through Retrofitting, Daylighting, and Behaviour Change. *Journal of Cleaner Production*. 413: 137216. DOI: https://doi.org/10.1016/j.jclepro.2023.137216.

Van Der Zee B, Li Y, Wetzelaer GAH, Blom PWM. 2022. Efficiency of Polymer Light-Emitting Diodes: A Perspective. *Advanced Materials*. 34(13): 1–14. DOI: https://doi.org/10.1002/adma.202108887.

Yang D, Zhao B, Yang T, Lai R, Lan D, Friend RH, Di D. 2022. Toward Stable and Efficient Perovskite Light-Emitting Diodes. *Advanced Functional Materials*. 32(9): 1–24. DOI: https://doi.org/10.1002/adfm.202109495.

Yeremenko K. 2022. International Maritime Organization and Decarbonization of Maritime Industry: Mandate and Instruments. *Lex Portus*. 8(3): 30–57. DOI: https://doi.org/10.26886/2524-101X.8.3.2022.2.

Zhang Q, Zhou J, Liu J, Zhang Y. 2023. Design of a Ship Light Environment Control System. *The 3rd International Conference on Artificial Intelligence, Automation, and High-Performance Computing (AIAHPC 2023), 22–23 April 2023, Wuhan, China*. SPIE Proceedings 12717. DOI: https://doi.org/10.1117/12.2684693.