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Original research article

Environmental Impact Assessment of LED Lamp Types for Industrial Lighting Purpose

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ABSTRACT

Thailand aims to cut final energy consumption to 30% of the 2010 level by 2037 via the National Energy Efficiency Plan (2018 - 2037). The plan focuses on promoting LED lighting and enhancing energy efficiency in the industrial sector. Thai authorities are working on long-term strategies for effective energy and environmental management. It’s important to avoid using residential LED lamps in industrial facilities to prevent energy wastage and environmental degradation. This study used Life Cycle Assessment (LCA) to evaluate the environmental impact of using the wrong LED lamp type in industrial lighting. It also examined how Thailand's current (2023), and future (2036) electricity mix affects environmental impact. The findings revealed that using residential LED lamps for industrial purposes results in a 25% higher environmental impact during the usage phase. The higher environmental impact during the usage phase is mainly caused by the lower efficiency of residential LED lamps. The sensitivity analysis found that the 2023 electricity mix has a more significant impact on 10 midpoint impact categories than the 2036 mix. Notably, ionizing radiation and water consumption were significantly affected by the 2036 electricity mix. However, at the endpoint level, the 2036 electricity mix had lower environmental impacts compared to the 2023 mix. Choosing the right LED lamp for industrial lighting is crucial to reduce energy waste and limit environmental harm. Furthermore, when planning for future clean energy generation, it's important to factor in the impact of the electricity mix.

Keywords: Environmental impact assessment; Energy-in-use; Industrial LED lamp type; Residential LED lamp type; Thai electricity mix

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1. Introduction

Following the COVID-19 pandemic, the ASEAN region is experiencing a substantial regrowth in its energy sector, bolstered by significant government support. This has resulted in a notable energy demand, amounting to 429.7 million tonnes of oil equivalent (Mtoe), with electricity playing a predominant role [1]. Additionally, global electricity consumption for lighting, currently at 20%, is projected to surge by 60% by 2030 [2, 3]. Thailand ranks 3rd in ASEAN for electricity consumption, driven by growing GDP, and this also poses environmental challenges [4, 5]. LED lighting is rapidly replacing incandescent bulbs and fluorescent tubes, and is expected to reach a 40% market share by 2020 [6]. Thailand prioritizes energy-efficient technologies and eco-friendly manufacturing, with the manufacturing sector dominating lighting consumption (58%) [7]. Initiatives from the Office of Energy Policy and Planning include mandatory and voluntary programs [8].

LED lighting technology has promptly advanced due to global energy-saving policies. More industrial consumers are opting for LED lamps, prioritizing efficient lighting for sustainable industrial facilities. Industrial LED lighting is built to withstand rigorous conditions, providing long life, workplace safety, and easy repairability. However, industrial LED types come with higher purchase and maintenance costs [9].

Product designers and consumers primarily focus on the energy efficiency of lighting devices. In contrast, consumer decisions in the lighting market are influenced by factors like price, installation cost, and maintenance. In developing countries, consumers often skip some decision-making steps and prioritize initial cost, leading to a preference for cheaper alternatives [10].

Given the higher electricity consumption for industrial lighting in Thailand, it’s vital to explore consumer choices for warehouse and factory lighting. Residential lighting, as a more affordable alternative, doesn’t require installation. This study focuses on determining the LED lamp types preferred by industrial consumers and their associated environmental impacts. Industrial consumers tend to buy residential lighting, leading to electricity wastage. Enhancing energy efficiency benefits the economy, environment, and human health.

Currently, Life Cycle Assessment (LCA) is the primary method for assessing a product’s environmental impacts throughout its life cycle. Comparative assessments aim to identify the best device for a given application with the same functional unit. A 2013 cradle-to-grave LCA found that eco-designed LED lamps had a 60% lower environmental impact compared to standard LEDs [11]. In 2019, Heather E. Dillon used LCA to gauge the energy and environmental improvements in LED types over time, favoring newer versions [12]. The US Department of Energy’s 2012-2017 LCA study focused on LED types and their impacts, highlighting energy use as the primary contributor to environmental effects [8]. This study primarily examines the environmental impacts during the LED lamp consumption phase.

Previous studies have employed impact assessment methods such as ECO-I-99, ReCiPe, and ILCD (European) and used scenario analysis in LED research for sustainable policy and product development. Researchers have primarily focused on energy-related factors during the consumption phase, creating scenarios involving various lifetimes and electricity mixes [13-15]. For instance, Takhamo et al. [16] considered two lifetimes (15,000 and 36,000 hours) and different electricity mixes (French and European) in their study.

Expected economic growth, rising energy demand, and the adoption of alternative energy technologies are shaping Thailand's energy development plan. The government aims to increase the share of renewable energy and decrease energy dependency. Key environmental objectives include minimizing environmental and social impacts and reducing CO_2 emissions per energy unit. A proposed \$200/tCO_2 carbon tax targets emissions from Thailand's electricity sector [17]. The main difference between current and future power generation is the addition of 5% nuclear power to the grid in 2036 [18].

The objective of this study is to conduct a comparative environmental impact assessment between residential and industrial LED lamp types during the use phase. The assessment was conducted based on 2 scenarios, considering Thailand's current and future electricity generation mix. The authors also focused on identifying the sensitivity of environmental impact categories to electricity mixes.

2. Materials and Methods

2.1 Selecting LED lamp types

A survey was conducted to identify the most consumed LED types in 35 small factories in the electronics and electrical equipment industry in 9 industrial areas of Thailand (industrial estates include Lad Krabang, Pathumthani, Samut Prakarn, industrial parks include Saraburi, Rayong, Ayuthaya, and industrial zones include Prachinburi and Navanakorn) [19]. Stratified random sampling was used to select the small-scale factories for the study. The Thai and English surveys targeting industrial lighting consumers are attached in the supplemental information. Survey responses indicate that 68% of consumers use T8 LED lamps as their lighting source, which is classified as a residential lighting type, while 32% use high bay/low bay lamps (industrial LED lamp type) LED. This raised the question of the energy efficiency of industrial lighting. Therefore, the T8 tube and high bay lamp LED types were selected to represent the residential and industrial sectors. Both lamps are produced by the same manufacturer. Table 1 explains the luminous performances of selected lighting types.

Table 1. Luminous Performances of Selected LED Types.

Parameter	Residential LED lamp type	Industrial LED lamp type
Light quality		
• Correlated Color Temperature (CCT) (K)	4,000	4,000
• Color Rendering Index (CRI)	73	80-90
Power consumption (W)	8	85
Light quantity (lm)	800	10,000
Durability (hr.)	15,000	50,000
No. of lamps per Functional Unit	42	1

2.2 Life Cycle Assessment (LCA)

LCA quantifies the environmental impact of a product or process by assessing inputs and emissions throughout its life cycle. It involves four key steps: goal and scope definition, inventory analysis, impact assessment, and interpretation.

In this study, the environmental impacts of two different usage patterns of industrial LED lighting are analyzed and compared to assess the significant differences or similarities between the usage patterns. The usage patterns considered in this study are,

1. Use of residential LED lamp types (T8 and E27) for warehouse lighting.
2. Use of industrial LED lamp types (High Bay/Low Bay) for warehouse lighting.

The LCA was carried out in accordance with the standard guidelines ISO 14040 and ISO 14044 (ISO, 2006a, ISO, 2006b). This study is aimed at lighting manufacturers and consumers, policymakers, and researchers.

2.2.1 Goal and scope definition

This study evaluates the environmental impact of using residential lamps in industrial settings instead of industrial lamps. It compares two LED types: residential T8 tubes and industrial high bays, focusing only on their consumption phase. The study provides insights for enhancing warehouse energy efficiency, excluding LED lamp maintenance during the use phase.

2.2.2 Functional unit

Both LED lamp types aim to produce a specific amount of light. Parameters considered include light quality (determined by correlated color temperature and color rendering index) and light quantity (measured in luminous flux, (lm)). Electricity usage during the use phase correlates with light production [20]. Given small variations in light quality (CRI), their impact on electricity consumption was expected to be minimal. Lamp lifetimes were sourced from product data sheets, with the functional unit being the production of 10,000 lm of light over 50,000 hours (500,000,000 lm.hr). For this study, 42 T8 lamps were considered equivalent to a high bay lamp in terms of luminous output.

2.2.3 Life cycle inventory

To determine the amount of electricity consumed by the LED types, the technical datasheet and environmental product declaration were utilized to obtain information on the electricity consumption per lamp (in W) and the lamp's lifetime (in hours). Input data for electricity generation were obtained from the Ecoinvent version 3 databases [21]. These data were adjusted to reflect the conditions in Thailand, including the use of national electricity mix data and fuel type [22].

2.2.4 Life cycle impact assessment and scenario analysis

We used the Recipe V1.12 method to assess the environmental impacts of the selected LED types. This method yields results in 18 midpoint impact categories, covering areas like climate change, human toxicity, and resource depletion [23]. These average impacts were categorized into three endpoint impacts: human health, ecosystem quality, and resource depletion. To align with policy principles on timeframes, we used the Hierarchist (H) version for both midpoint and endpoint approaches, excluding long-term emissions from the analysis.

2.2.5 Interpretation

Interpreting LCA results offers various approaches, with ISO 10440 outlining key methods: uncertainty analysis, sensitivity analysis, contribution analysis, and inventory analysis. This study employs scenario analysis, a form of sensitivity analysis, to illustrate findings. It explores how different input data impact the output results within the system boundary.

Environmental impacts of electronic devices are primarily tied to the use phase, influenced by factors like energy mix and lifespan. As a result, the study presents findings through multiple scenarios using distinct input data.

To determine the sensitivity of results, two scenarios were employed for the impact assessment. The baseline scenario, which is the most common practice, was chosen. It assumes that both LED lamp types reach their ideal lifespan and consume electricity generated according to the 2023 energy mix. Data on fuel sources and percentages for 2023 energy generation were sourced from EGAT, while figures for the 2036 energy mix were obtained from the Thai Energy Development Plan 2015-2036. Table 2 presents the two energy mixes that influenced the scenario's generation.

Table 2. Thailand's Electricity Mix by Fuel.

	Natural gas	Imported Hydropower	Lignite	Renewable	Nuclear
% of the energy generated in 2023	57	22	18	3	0
% of the energy generated in 2036	40	20	20	15	5

The study considered two scenarios as follows:

1. Replacing the industrial LED lamp types with residential LED lamp types for warehouse lighting using the 2020 electricity mix.
2. Replacing the industrial LED lamp types with residential LED lamp types for warehouse lighting using the 2036 electricity mix.

2.2.6 Assumptions and limitations

The authors assume stable future electricity consumption for LED lamp types. They justify this by noting that while residential and industrial LEDs have varying consumption, the relative efficiency ratio between them will persist, with the industrial type being more energy efficient. Background data on Thailand's electricity generation was utilized, including default values for nuclear power (which Thailand does not currently use). The study also considered imported hydropower from Laos, though data on electricity transformation between the two countries is lacking. Additionally, country-specific data on natural gas, lignite, and renewable energy combustion were considered.

3. Results and Discussion

3.1 Base case scenario

Fig. 1 displays the environmental impact comparison of the two selected LED lamp types across 18 midpoint categories in the baseline scenario. The residential LED type used for industrial lighting had a 25% higher impact on all environmental impact indicators than the industrial LED type.

Furthermore, during the use phase, the residential LED lamp emitted 32.71% more CO_2 compared to the industrial LED lamp. Using the industrial LED type in warehouses instead of the residential one could reduce approximately 974 kg of CO_2 emissions annually. This indicates that the excess CO_2 emissions into the atmosphere are due to the higher electricity consumption of the residential lighting type.

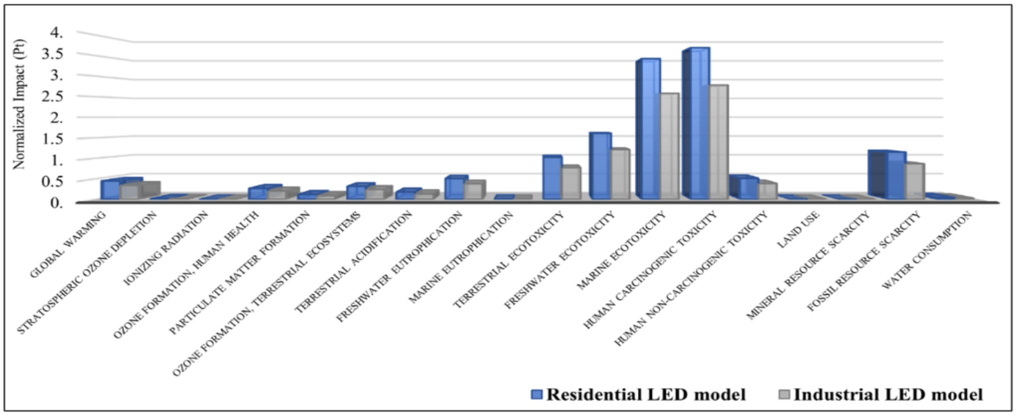

Fig. 1. Base Case Scenario – Midpoint Environmental Impact of Residential and Industrial LED Types.

The higher impact of the residential LED type on each endpoint environmental indicator is also displayed in Fig. 2. Human health was identified as the category with the highest environmental impact for both LED types. Luminous efficacy, which determines electricity consumption, was found to be critical. The industrial LED lamp, which produces more brightness per unit of electricity (118 lm/W), had a higher luminous efficacy.

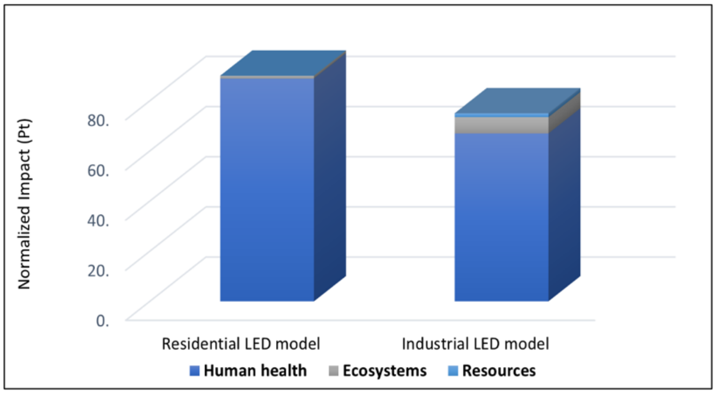

Fig. 2. Base Case Scenario – Impacts on the Environment (Endpoint Indicators) by Impact Category of Residential and Industrial LED Types.

3.2 Sensitivity analysis

The study focused on three dominant factors affecting consumption-related environmental impact: useful lifespan, brightness, and energy mix. Fig. 3 and SI Table 1 present the percentage differences in midpoint environmental impacts caused by the 2020 and 2036 electricity mixes in Thailand for Scenarios 1 and 2 of both types. Scenario 2 showed greater impacts on categories such as ionizing radiation, freshwater eutrophication, human carcinogenic toxicity, and water consumption due to the energy mix in 2036. The 5% nuclear energy in the 2036 mix resulted in increased ionizing radiation due to radionuclide emissions. Additionally, the 2% increase in lignite-based electricity generation led to greater carcinogenic toxicity and freshwater eutrophication due to emissions of toxic chemicals (such as selenium, molybdenum, beryllium, and phosphates). Finally, domestic hydropower generation, which constitutes 15% of renewables in the energy mix, accounted for most of the impact on water consumption.

Scenario 1 is associated with higher impacts on the global warming category because of the predominance of natural gas combustion in the 2020 electricity mix. Although GHG emissions from natural gas-fired power plants are lower than those from coal and fossil fuel combustion, there is still an additive effect from natural gas emissions of CO_2, CH_4, and N_2O [24].

The steam reforming process of natural gas-fired power plants negatively affects terrestrial ecotoxicity [25].

Fossil fuels such as natural gas, oil, and coal are the primary types of fuel [26]. As natural gas comprises a larger proportion than other fossil fuels in the 2020 electricity mix, the fossil resource scarcity category has a more significant impact in 2020 [27]. The incomplete combustion of natural gas can produce by-products that can lead to non-carcinogenic diseases in the population, with a high probability of emitting toxic air pollutants [28]. The negative impacts on these categories primarily arise from the 2020 electricity mix.

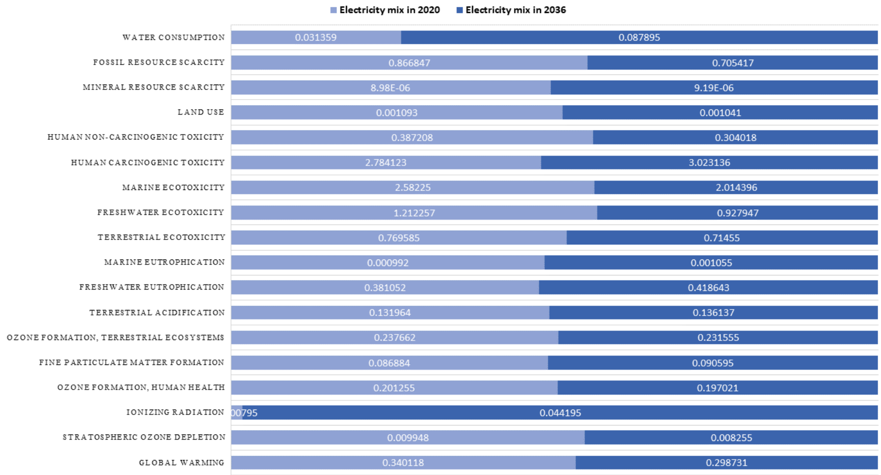

Fig. 3. Estimated Contribution of Current and Future Electricity Mixes to Midpoint Environmental Impact Categories.

Scenario 1 yielded the highest endpoint environmental impacts for both LED types, with human health impacts being the predominant driver of the endpoint indicators for each scenario, as illustrated in Fig. 4. The combined effects of human carcinogenic toxicity, human non-carcinogenic toxicity, global warming, ozone formation, particulate matter formation, and water consumption resulted in a higher value in the human health category.

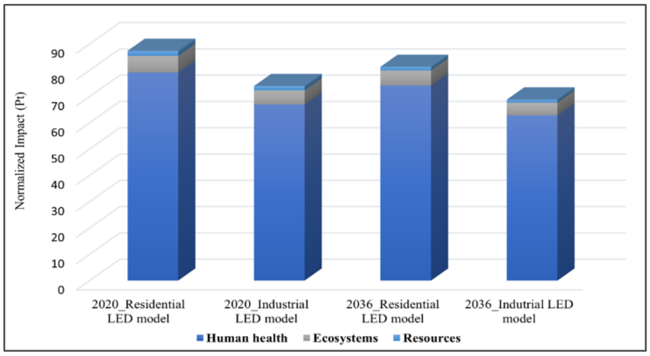

Fig. 4. Sensitivity Analysis – Impacts on the Environment (Endpoint Indicators) by Impact Category of Residential and Industrial LED Types.

4. Conclusion

Thailand has taken measures to address climate change and its effects on the environment, with the National Climate Change Master Plan 2015-2050 outlining the reduction of energy production's environmental impact as one of its key objectives. Enhancing energy efficiency is a critical component in achieving energy security, which means using less energy to achieve the same output and minimizing energy wastage. While energy-efficient appliances are recommended as best practices for improving energy efficiency, careful consideration is required in selecting electronic and electrical equipment to maximize the benefits.

The Minimum Energy Efficiency Standards, which mandate that products meet specific energy efficiency criteria, are a common feature in many developed countries' energy policies, particularly for lighting systems. Thailand may propose a maximum allowable energy consumption for a given level of brightness in industrial lighting applications [29]. This study's findings suggest that using industrial lighting types in warehouse lighting is the most environmentally friendly approach. However, it is crucial to consider other factors such as cost and workplace safety when selecting lighting systems. Industrial lighting types are more expensive than residential lighting types but offer a longer lifespan and better workplace efficiency in harsh factory environments [30].

The study also demonstrates that different electricity mixes result in varying midpoint impact categories, with the electricity mix that has the least endpoint impacts being the most suited for clean energy generation [31]. Future research could examine the environmental impact of industrial LED types from a cradle-to-grave perspective, considering the entire product lifecycle, from raw material extraction to disposal.

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Appendix

Survey for LED consumers and included it into online link stated below,
https://sites.google.com/view/appendixforenvironmentalimpact/home

Table SI 1. Midpoint environmental impact of current and future electricity mixes in Thailand (Normalized results (Pt)).

Impact category label	Environmental impact values		
	Electricity mix in 2020	Electricity mix in 2036	% of difference
Global warming	0.340118	0.298731	12.16833
Stratospheric ozone depletion	0.009948	0.008255	17.01807
Ionizing radiation	0.000795	0.044195	-5457.53
Ozone formation, Human health	0.201255	0.197021	2.103594
Fine particulate matter formation	0.086884	0.090595	-4.27052
Ozone formation, Terrestrial ecosystems	0.237662	0.231555	2.569603
Terrestrial acidification	0.131964	0.136137	-3.16269
Freshwater eutrophication	0.381052	0.418643	-9.86514
Marine eutrophication	0.000992	0.001055	-6.34999
Terrestrial ecotoxicity	0.769585	0.71455	7.151262
Freshwater ecotoxicity	1.212257	0.927947	23.45293
Marine ecotoxicity	2.58225	2.014396	21.99068
Human carcinogenic toxicity	2.784123	3.023136	-8.58488
Human non-carcinogenic toxicity	0.387208	0.304018	21.48453
Land use	0.001093	0.001041	4.775774
Mineral resource scarcity	8.98E-06	9.19E-06	-2.37677
Fossil resource scarcity	0.866847	0.705417	18.62259
Water consumption	0.031359	0.087895	-180.285

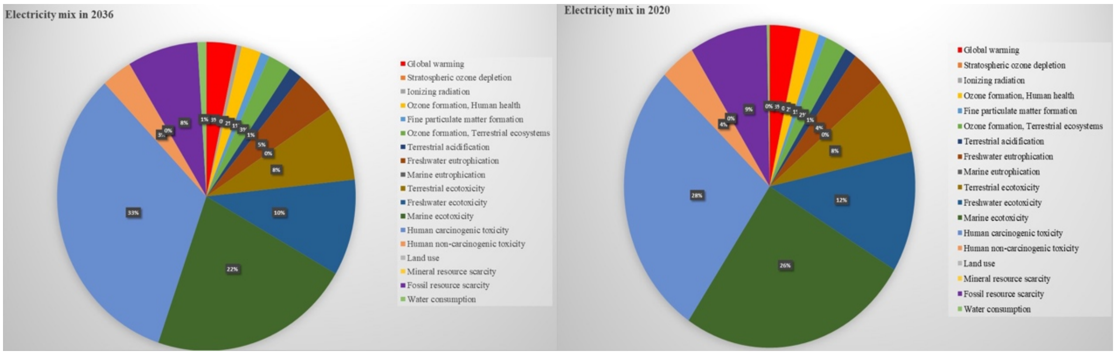

Fig. SI 1. Midpoint environmental impact category contribution of current and future electricity mixes.