Life cycle assessment of lighting equipment: A comparison of fluorescent lamp and light emitting diode lamp in Thailand

Miss Waraporn Thavornvong

จุฬาลงกรณ์มหาวิทยาลัย
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บทคัดย่อและแฟ้มข้อมูลฉบับเต็มของวิทยานิพนธ์ตั้งแต่ปีการศึกษา 2554 ที่ให้บริการในคลังปัญญาจุฬาฯ (CUIR)
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การประเมินวัฏจักรชีวิตผลิตภัณฑ์ของอุปกรณ์ให้แสงสว่าง: เปรียบเทียบระหว่างหลอดฟลูออเรสเซนต์และหลอดแอลอีดีในประเทศไทย

นางสาววราภรณ์ ถาวรวงษ์

จุฬาลงกรณ์มหาวิทยาลัย
CHULALONGKORN UNIVERSITY

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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By	Miss Waraporn Thavornvong
Field of Study	Hazardous Substance and Environmental Management
Thesis Advisor	Sujitra Vassanadumrongdee, Ph.D.
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วราภรณ์ ถาวรวงษ์ : การประเมินวัฏจักรชีวิตผลิตภัณฑ์ของอุปกรณ์ให้แสงสว่าง: เปรียบเทียบระหว่างหลอดฟลูออเรสเซนต์และหลอดแอลอีดีในประเทศไทย (Life cycle assessment of lighting equipment: A comparison of fluorescent lamp and light emitting diode lamp in Thailand) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: อ. ดร.สุจิตรา วาสนาดำรงดี, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: อ. ดร.อัมพิรา เจริญแสง, 129 หน้า.

ซากหลอดไฟหรือหลอดไฟที่สิ้นสุดอายุการใช้งานจัดเป็นของเสียอันตรายชุมชน ส่วนใหญ่จะทิ้งลงถังขยะปะปนกับขยะมูลฝอยทั่วไป หากไม่ได้รับการจัดการอย่างถูกต้องอาจก่อให้เกิดผลกระทบต่อสุขภาพอนามัยและสิ่งแวดล้อมอย่างรุนแรง การศึกษานี้มีวัตถุประสงค์ คือ (1) เพื่อคาดการณ์ปริมาณซากหลอดไฟที่จะเกิดขึ้นในอนาคตของประเทศไทย (2) เพื่อศึกษาและเปรียบเทียบการประเมินผลกระทบต่อสิ่งแวดล้อม แนวทางการจัดการที่เหมาะสมของหลอดไฟที่สิ้นสุดอายุการใช้งาน 2 ชนิด ได้แก่ หลอดฟลูออเรสเซนต์และหลอดแอลอีดี โดยใช้หลักการการประเมินวัฏจักรชีวิต ครอบคลุมตั้งแต่ขั้นตอนกระบวนการผลิต การขนส่ง การใช้งาน และการกำจัด โดยใช้โปรแกรมสำเร็จรูป Simapro รุ่น 7.1.8 วิธี CML2001 สำหรับการประเมินผลกระทบสิ่งแวดล้อมขั้นกลาง และวิธี Eco-indicator 99 สำหรับการประเมินผลกระทบสิ่งแวดล้อมขั้นปลาย ทั้งนี้การวิจัยได้ประเมินและเปรียบเทียบผลกระทบต่อสิ่งแวดล้อมจาก 3 สถานการณ์ : 1) สถานการณ์ที่ 1: "หลุมฝังกลบ 100%", 2) สถานการณ์ที่ 2: "หลุมฝังกลบ 90% และ รีไซเคิล 10%" และ 3) สถานการณ์ที่ 3: " หลุมฝังกลบ 70% และรีไซเคิล 30% " ผลการศึกษาพบว่า (1) ในปี 2554 มีปริมาณซากหลอดฟลูออเรสเซนต์เกิดขึ้นจำนวน 60.15 ล้านหลอด และมีแนวโน้มลดลงอย่างต่อเนื่อง จนปี 2568 มีปริมาณซากหลอดฟลูออเรสเซนต์ จำนวน 27.23 ล้านหลอด ทั้งนี้ในทางกลับกันหลอดแอลอีดีมีแนวโน้มของปริมาณที่เพิ่มมากขึ้นอย่างมากในปี 2564 จำนวน 365.62 ล้านหลอด และลดลงในปี 2567 จากนั้นมีแนวโน้มเพิ่มขึ้นเล็กน้อยจนถึงปี 2573 เป็นจำนวน 250.1ล้านหลอด (2) ผลการประเมินผลกระทบสิ่งแวดล้อมหลอดแอลอีดีส่งผลกระทบโดยรวมน้อยกว่าหลอดฟลูออเรสเซนต์ ร้อยละ70 กระบวนการที่ส่งผลกระทบมากที่สุด ได้แก่กระบวนการใช้ 98.94% ในหลอดฟลูออเรสเซนต์ และ 96.46% ในหลอดแอลอีดี รองลงมาคือกระบวนการผลิต การขนส่งและกระบวนการกำจัด เมื่อพิจารณาขั้นตอนการกำจัด พบว่าการฝังกลบของหลอดฟลูออเรสเซนต์และหลอดแอลอีดีส่งผลกระทบมากที่สุด และจากการเปรียบเทียบวิธีการกำจัดพบว่าการรีไซเคิลของทั้งสองหลอดสามารถลดผลกระทบสิ่งแวดล้อมจากการฝังกลบได้มากถึง 90.44 เท่าในหลอดฟลูออเรสเซนต์ และ 296.36 เท่าในหลอดแอลอีดี จากการวิเคราะห์ผลกระทบเชิงเทคโนโลยี พบว่า หากกำจัดอะลูมิเนียมในหลอดฟลูออเรสเซนต์และบัลลาสต์แม่เหล็กสามารถลดผลกระทบจากการรีไซเคิลทั้งหมด 94.4% และในหลอดแอลอีดีควรมีการกำจัดอะลูมิเนียมจากแผ่นระบายความร้อนและโพลีคาร์บอเนตจากฝาครอบหลอด สำหรับข้อเสนอแนะการจัดการหลอดไฟที่สิ้นสุดอายุการใช้งานในประเทศไทย จากผลการทดสอบการชะสารปนเปื้อนในการศึกษาที่ผ่านมา พบว่าหลอดไฟแอลอีดีไม่ควรจัดให้เป็นของเสียอันตรายชุมชนและสามารถทิ้งรวมกับของเสียทั่วไปได้ ดังนั้น จึงควรมีการรีไซเคิลหลอดแอลอีดีและหลอดฟลูออเรสเซนต์อย่างมีประสิทธิภาพและกำหนดให้อุปกรณ์ให้แสงสว่างเป็นหนึ่งในผลิตภัณฑ์ในร่างพระราชบัญญัติการจัดการซากผลิตภัณฑ์เครื่องใช้ไฟฟ้าและอิเล็กทรอนิกส์เพื่อให้มีการกำหนดผู้รับผิดชอบร่วมกันระหว่างผู้ผลิตและภาครัฐที่เกี่ยวข้องต่อไป

สาขาวิชา การจัดการสารอันตรายและสิ่งแวดล้อม ลายมือชื่อนิสิต ....

ปีการศึกษา 2559 ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

ลายมือชื่อ อ.ที่ปรึกษาร่วม ....

5787539420 : MAJOR HAZARDOUS SUBSTANCE AND ENVIRONMENTAL MANAGEMENT
KEYWORDS: LCA / LIGHT EMITTING DIODE / FLUORESCENT LAMP

WARAPORN THAVORNVONG: Life cycle assessment of lighting equipment: A comparison of fluorescent lamp and light emitting diode lamp in Thailand. ADVISOR: SUJITRA VASSANADUMRONGDEE, Ph.D., CO-ADVISOR: AMPIRA CHAROENSAENG, Ph.D., 129 pp.

EOL lighting equipment has been regarded as hazardous household waste (HHW) which is often disposed together with general waste in Thailand. Such improper management of EOL has caused increasing risk of environmental and health impact to Thai society. This study has two main objectives: (1) To estimate an EOL inventory of FLs and LEDs in Thailand and (2) To evaluate and compare environment impacts of FLs and LEDs throughout their life cycle and identify the appropriate approach for handling discarded FLs and LEDs at the end of life stage in Thailand. The study presents life cycle assessment (LCA) of two lighting technologies, fluorescent lamp (FL) and light emitting diode (LED) that are used widely in Thailand. The gate to grave investigation for FL and LED includes manufacturing, distribution, use and end-of-life (EOL) scenarios. The analysis used the SimaPro 7.1.8 program under the CML2001 assessment method for the midpoint and the Eco-indicator 99 assessment method for the endpoint. Furthermore, this research evaluated the potential future impact from different management schemes including: (1) 100% landfilling, (2) 10% recycling and 90% landfilling, (3) 30% recycling and 70% landfilling. The results showed that (1) the quantity of EOL FL has been continuously decreased from 60.15 million units in 2011 to 27.23 million units in 2025. The EOL LED will be increased in 2021 (365.62 million units) and decreased in 2024. Then, the quantity of EOL LED will be still increased in 2030 (250.1 million units). The finding is based on the expectation that the government will continue promoting the fluorescent replacement with LEDs as one of energy saving measures of the country. (2) the environmental impact of LED has lower in major impact categories than that of FL about 70%. The use phase caused the majority of the environmental impacts: 98.94% in FL and 96.46% in LED, followed by the manufacturing and EOL stage. For the EOL stage, FL and LED landfilling could contribute highest negative burdens to the human health, ecosystem quality and resource depletion impact compared to recycling approach. The results found that the recycling would be better than landfilling about 90.44 fold in FL and 296.36 fold in LED, respectively. Additionally, it revealed that the most benefits come from aluminum scrap recycling which can reduce 94.4% in the FL and the magnetic ballast. On the other hand, the LED recycling also distributes the profits to resources sustainability by recycling the aluminum from the heatsink and polycarbonate from tube cover of LED lamp set. Based on this study finding and leaching test result from the literature, this study recommended that LED can be considered as a non-hazardous waste which can be disposed normally with other non-hazardous waste. Given the potential of recycling LED and the hazardous composition in FL, lighting equipment should be included as one of priority products in the draft Thai WEEE management law.

Field of Study:	Hazardous Substance and Environmental Management	Student's Signature	....
		Advisor's Signature	....
Academic Year:	2016	Co-Advisor's Signature	....

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ABBREVITIONS

DAILY	Disability adjusted life years
EOL	End-of-life
EPA	Environmental Protection Agency
E-Waste	Electronic Waste
FL	Fluorescent Lamps
ISO	International Standard Organization
kg	Kilogram
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LED	Light Emitting diode
NSO	National Statistical office
PWB	Printed Wired Board
PCD	Pollution Control Department
Pt.	point
RER	shortcut represents Europe in Ecoinvent
S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
WEE	Waste electrical and electronic equipment

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CHAPTER I

INTRODUCTION

1.1 Rationale for study

Development in technology and rapid economic growth results in increasing of production and consumption of electrical and electronic products. At the end of their life period, they become waste electrical and electronic equipment (WEEE) electronic–waste (e-waste). With growth of the production level of electronic devices amounts of WEEE also increase. As these have been shown to contain hazardous materials, they need to be either recycled or disposed of properly to avoid undesirable impact on human health and quality of the environment.

Most WEEE can be processed for recycling except for products that do not bring economic benefit such as light bulbs, and batteries, which are generally collected and disposed together with general waste. The Pollution Control Department (PCD), Thailand, concerned by the current situation and challenges of the WEEE management in the country, has draft a WEEE legislation introducing the extended producer responsibility (EPR) concept, mandating an effective take-back and proper disposal of such waste by the producers, in order to reduce environmental impact (PCD, 2015).

PCD (2012) has projected the amount of end-of-life (EOL) fluorescent lamps (FLs) generation in Thailand, using data on production volume from major producers and the import-export data from the Customs Department. PCD has estimated that about 273 million FLs lamp units were discarded in 2015 and 311 million units of EOL FLs could be generated in 2020. However, this estimation had not factored in the replacement rate of FLs with light emitting diode lamps (LEDs) which has been encouraged as a low energy device by the government and had gained popularity.

According to Caicedo et al. (2011), LEDs have better properties than FLs concerning product lifetime, energy efficiency, versatility, and color quality .The average lifetime of LEDs is 35,000-50,000 hours longer than that FLs which a reported lifetime ranging from 20,000-30,000 hours (DOE, 2011d).

Lighting accounts for approximately 15% of global electricity consumption. The Paris Agreement on climate change, signed by more than 190 countries to commit to further Green House Gas emission cuts of 20% by the year 2020 in order to combat global warming has apparently boosted the global interest in LED lighting with low levels of emission . Currently, LED products have a 31% of the world market share for lighting. According to Thailand Ministry of Energy (2015), the current 10-15% market share of LEDs in Thailand is expected to occupy the whole lighting market by 2036. In contrast, the lighting market share of FLs decreased from 45% in 2010 to 22% in 2015 in Thailand (Philips Electronics (Thailand) Ltd., 2014). With a long lifetime, and no mercury, LEDs have been promoted as energy efficient lighting and environmental friendly. Since 2011, as part of its energy conservation programs, the Electricity Generating Authority of Thailand (EGAT) has made campaigns and given subsidies to consumers to switch from FLs to LEDs which accelerated the increase in LEDs sale volumes replacing FLs. The replacement rate of LEDs to FLs, therefore, should be taken into account in the estimate of EOL lighting equipment in Thailand.

Although LEDs have gained popularity over FLs, scientific researchers have indicated that LEDs still contain some hazardous substances. Lim et al. (2010) obtained that the low-intensity red LEDs had the highest content of lead (Pb) and the high-intensity yellow LEDs had high contents of arsenic and copper which have Eco toxicity potential. Overall, white LEDs display relatively low toxicity potentials due to they consist of less copper and do not consist of arsenic or lead (Pb). The Department for Environment, Food and Rural Affairs (DEFRA) of UK, had analyzed the

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environmental impact of LED throughout the product life cycle. LEDs have an aluminum heat sink which can cause several environmental impacts from manufacturing and also in end-of- life waste with human toxicity potential (DEFRA, 2009). The United Stated Department of Energy (2013) emphasized that the heat sink in LEDs exceeds FLs in hazardous waste toxicity. This may need special provisions for their disposal such as landfill at the end-of-life. Therefore, it is necessary to investigate and compare environmental impacts of LEDs and FLs throughout its lifecycle.

The life cycle assessment (LCA) is an internationally standardized methodology, to assess environmental impacts correlated with the life cycle of goods and services and is determined one of the most efficient management tools (Durlinger et al., 2012; Saner et al., 2012). It has been used to the management of electrical electronic and electromechanical (EEE) waste (known as e-waste), by evaluating the potential environmental impacts of PC products, cathode ray tube (CRT) monitors etc. The broad aspects of LCA generate it probable to study different types of EEE and consider their environmental benefits for both particular stages and throughout their life cycles.

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Several LCA studies implemented on the luminaries sector have correlated the life cycle accomplishment of various lighting technologies of Incandescent lamps (ILs), halogen lamps, FLs including linear and compact FLs, and LED lamps (Welz et al.,2011; Tahkamo et al., 2013; Principi and Fioretti,2014). However, relatively few studies have been conducted in Thailand to forecast end-of-life (EOL) amount of FLs and LEDs despite their abundant use.

This study compares the life-cycle assessment of LEDs to those of FLs based on the replacement lamps and develops an inventory of EOL FLs and LEDs for evaluating their environmental performances.

1.2 Research Objectives

This study has three objectives:

1. To compare the environment impacts of FLs and LEDs throughout their lifecycle.
2. To develop an EOL inventory of FLs and LEDs in Thailand.
3. To identify the appropriate approach for handling end-of-life stage of FLs and LEDs in Thailand.

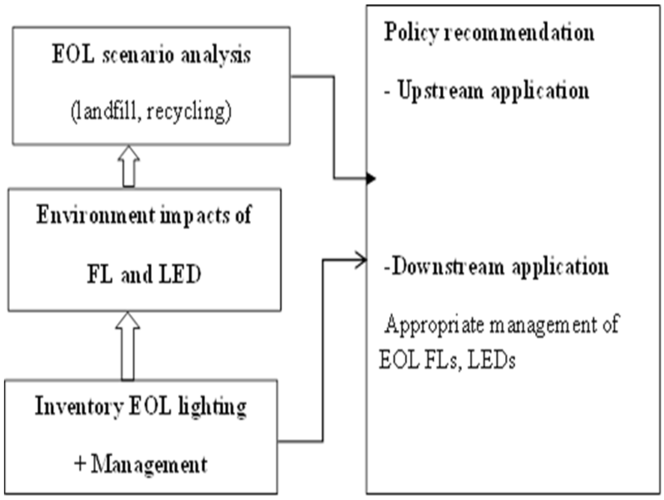
1.3 Hypotheses

This study is based on the following hypotheses

1. The environmental impact of LED is less than that of FL throughout their life cycles.
2. The disposal of lighting into landfill can contribute higher degrees of environmental impacts as compared to the proper recycling approach.

1.4 Scope of the study

The scope of this study is to evaluate environmental impacts of lighting equipment using LCA approach and to develop an inventory of EOL lighting equipment. Its scope extends to identification of appropriate approach(s) of EOL management in Thailand. It will explore possible ways of reducing the environmental impacts through lighting equipment with low electricity consumption and intends to recommend the most environmentally friendly EOL disposal scenario.



1.5 Expected outcomes

The study expects the following outcomes on its completion in compliance with its objectives

1. An appropriate scenario verified for end-of-life management of lighting equipment in Thailand
2. Comparative assessment of environmental impacts FLs and LED lamp units throughout their life cycles
3. Formulate recommendation to support policy making for up streaming and down streaming of the recommended end-of-life management of FLs and LEDs

CHAPTER II

LITERATURE REVIEW

2.1 Life cycle assessment

Life cycle assessment is one of the tools that are commonly used to aim environmentally friendly electronic devices and to decrease e-waste problems. Since the 1990s many research related to waste management has been managed the LCA of electronic devices in terms of eco-design, product improvement and environmental impacts (Kiddee et al., 2013).

According to ISO 14040 and 14044 standards (Finkbeiner et al., 2006), a LCA can be achieved in four different phases as shown in Figure 1, including definition of goal and scope, inventory analysis, impact assessment and interpretation of results.

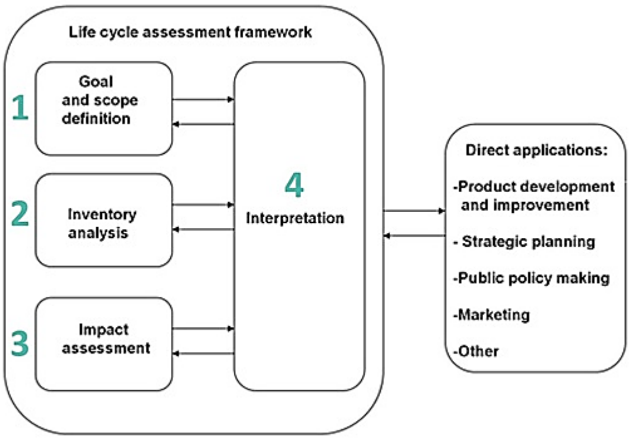


Figure 1 Life cycle assessment According to ISO Standards

(Finkbeiner et al., 2006)

ISO 14044 created the guidelines for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

2.1.1 Goal and scope definitions

This part is the primary ways in order to define the objective and method of total LCA process.

2.1.2 Life cycle inventory analysis

A life cycle inventory phase (LCI phase) is the second phase of LCA. It is an inventory of input or output data with regard to the system being studied. It involves the data collection which is needed to reach the targets of the defined study. A life cycle inventory is a phase of estimating the amount of energy and raw materials input or output data for the whole life cycle of a product, process or activity. These data may also focus the use of reserved supply and releases to the atmosphere, water resources and land associated with the system. In the life cycle inventory phase, designing the diagrams that represented the unit processes and collecting the data for each processes was also need to be done.

LCI can help an organization in comparison between products or processes and by focusing on environmental consideration in substance selection. In addition, the inventory analysis can be used in policy making process by assisting the development of regulations associating with resources and environmental impacts (Guinée, 2004, SAIC, 2006).

2.1.3 Life cycle impact assessment

The third phase of the LCA is Life cycle impact Assessment (LCIA). The aim of LCIA is to establish additional data to evaluate a product system's LCI results so concerning understand more about their environmental significance and to evaluate the performance of environmental impacts and human health along the LCI process. It also showed resource depletion (Guinée, 2004). LCIA are involving of the below mandatory components:

a) Selection and Definition of Impact Categories – To identify the huge environmental impact categories (e.g., global warming, acidification, terrestrial toxicity).
b) Classification – To assign LCI results to the impact categories (e.g., classifying carbon dioxide emissions to global warming).
c) Characterization – To create the model of LCI impacts within impact categories via science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).
d) Normalization – To express potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options).
e) Grouping – To source or rank the indicators (e.g. sorting the indicators by location: local, regional, and global).
f) Weighting – To emphasize the most important potential impacts.
g) Evaluating and Reporting LCIA Results – To obtain an understanding of the reliability of the LCIA results. (SAIC, 2006).

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2.1.4 Life Cycle Interpretation

Life cycle interpretation is the final phase of the LCA process, in which the results of an LCI or an LCIA or both, are sum up and discusses as a guideline for conclusions, recommendations and decision making associated with the goal and scope definition.

It analyzes and concludes the results, reveal limitations, and establish recommendations using the findings of the preceding phases of the LCA as a baseline, and to present the results of the life cycle interpretation in a transparent manner. The process establishes a readily understandable, complete, and consistent presentation of the results of an LCA study, in which associated with the goal and scope of the study (SAIC, 2006).

2.2 Lighting equipment

2.2.1 Current situation of the lighting equipment

Different type of the lighting equipment has differing properties. These differences such as luminous flux, energy efficacy, lifetime etc. are made use of to make choices between different types. Navigant (2012b) reported the linear fluorescent lighting technologies weighting 80% of the installed equipment and 72% of total annual energy consumption for commercial lighting.

It had been more than a decade that manufacturers have incorporated incremental improvements to linear fluorescent efficiency. Reduction of wattage T8 offers a higher energy savings compare to conventional T8, but may not a suitable choice for replacement in all applications. Lighting output from reduced wattage T8 is roughly 10% lower than standard T8 technology, and these lamps may work improperly and facing the problems in cold conditions. A number of manufacturers provided tube-shaped LED replacements that can be fitted into existing fixtures, generally bypassing the ballast (ACEEE, 2012). Furthermore, McKinsey (2012) also predicted the development of the total global lighting market and lamp type shares. By 2019, LED will be the highest amount of lighting as shown in Figure 2.

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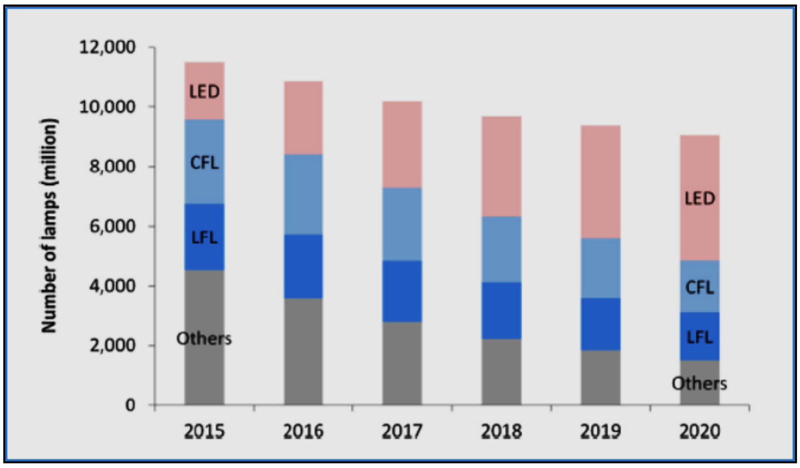

Figure 2 Forecasted development of the total global lighting market and lamp type shares

(Adapted from McKinsey, 2012)

For Thailand, the use of FLs was initially promoted around the year of 1996 by a campaign to replace incandescent lamps with compact FLs to save energy in Thailand. This increased the market share for FLs to around 30% while the market share of incandescent lamps gradually decreased to around 30-40% (Manager online, 2008). Subsequently, the forecasting of lighting equipment market share by Philip, it was seen that FLs decreased from 45% in 2010 to 22% in 2015 while LEDs increased from 5% in 2010 to 22% in 2015 (Philips Electronics (Thailand) Ltd., 2014) as illustrated Figure 3.

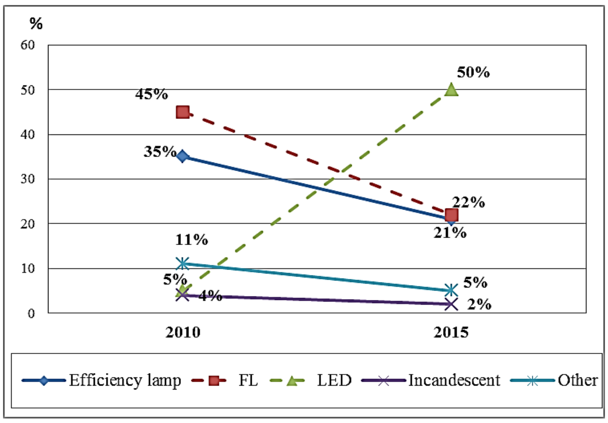

Figure 3 Lighting equipment forecasting year 2010-2015

(Philips Electronics (Thailand) Ltd., 2014)

Currently, Thailand Energy Efficiency Development Plan 2015-2036 (EEDP) is formulated with a target to reduce energy intensity by 30% in 2036, compared with that in 2010, or equivalent to reduction of final energy consumption about 51,700 thousand tons of crude oil equivalent (ktoe). The assessment of energy conservation potential of the small commercial building and residential group, which based on the forecast utilization of higher energy-efficient equipment/appliances, is derived from the use of fluorescent tubes, electronic ballasts, air-conditioners and water heaters.

An important energy reduction measure undertaken by EGAT is promoting greater use of LED using price mechanism and supporting 36-watt FL replacement with LED. By fully implementing this measure, it is expected that Thailand can save energy by 30% (EGAT, 2015). Additionally, Provincial Electricity Authority (PEA) conducted the pilot project in government buildings by replacing 200,000 tubes of 36 watts (T8) FLs with 23-watt LEDs in 2014-2015. With the current energy reduction policy, the LEDs market share in Thailand has increased rapidly as can be seen in Figure 4 and is expected to totally replace FLs in 2036 (Thailand Ministry of Energy, 2015).

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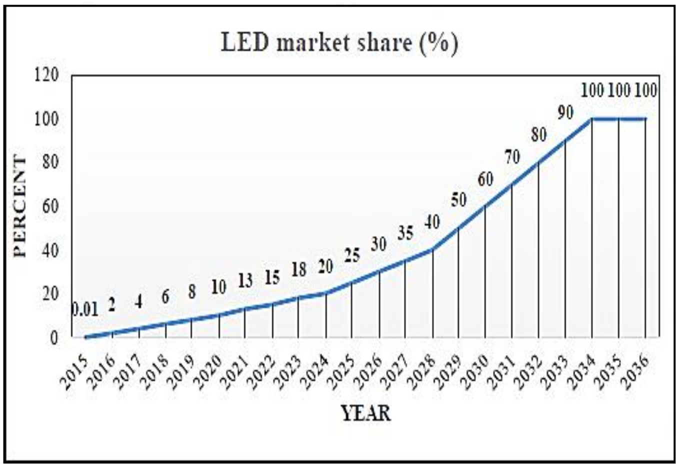

Figure 4 Increasing of LED market share in Thailand

(Thailand Ministry of Energy, 2015)

2.2.2 Standard for lighting equipment

In general, minimum energy performance standard (MEPS) and mandatory labeling are used to increase the efficiency of technologies. Labeling stimulates technological innovation and introduction of new more efficient product. Together, MEPS and labeling facilitate market growth and reduce financing risk by helping to ensure that new EE technologies have a rapid market impact (UNEP, 2008b).

For Thailand, the performance and energy efficiency requirements of all lighting equipment was proposed by Thai Industrial Standards Institute (TISI). They set Thai mandatory standards that follow the full national standard of the International Electro technical Commission (IEC) since 1991. IEC standard was used by policies and programs to promote efficient lighting products and the key lighting terms, including luminous flux, lumens maintenance, Efficacy, color rendering, color temperature and lamp lifespans.

Another regulatory for controlling substances in electronics for whole products sold in the European Community (EC, 2006), it is the Restriction on Hazardous Substances directive (RoHS). There has been in force since 2003, controlling the usage of hazardous substances in electrical and electronic equipment. RoHS indicates maximum levels for the subsequent six restricted materials: Lead (Pb), Mercury (Hg), Cadmium (Cd), Hexavalent Chromium (CrVI), Polybrominated Biphenyls (PBB) and Polybrominated Diphenyl Ethers (PBDE). It also provides thresholds for measurement of concentrations level to safeguard human health and proper recovery and disposal of e-waste. These standards as illustrated in Table 1.

Table 1 The standards for FL and LED were used for Thailand

Standard	FL	LED
Performance and energy efficiency requirements		
International Standard	IEC 81 for single-capped FL IEC 901 for bi-capped FL	IES LM-79,IES LM-80
Thai industrial standard	TIS.236-2533 for single-capped FL TIS.1713-2548 for bi-capped FL	TIS.1955-2551 for self-ballasted LED-lamps
Safety specifications		
International Standard	IEC/EN 61347-1	IEC62560
Thai industrial standard	TIS.956-2533 for single-capped FL TIS.956-2548 for bi-capped FL	-
Other device		
International Standard	Ballast-IEC 82-1973	Driver-IEC 61347–2–13
Thai industrial standard	Ballast-TIS.1506-2541	-
Restriction of Hazardous Substances (RoHs)		
International Standard	IEC 62321	IEC 62321
Thai industrial standard	TIS. 2368	-

Source: Adapted from EEI (2014) and PEA (2014)

In the market, the light sources have several types with various characteristics for the various lighting applications. When choosing the lamp, consideration should be comparing the standard of the various types by Energy Efficiency Index (EEI) (European Federation, 2013).

According to CALIPER (2013) and Temkasemsuk (2012), fluorescent lamps can be substituted by LEDs in the same range efficacy. Simulation results show that 20W of LED can replace 36W of fluorescent lamp with the accepted luminance standard of IEC.

In this study, the 36WT8 FL and 18WT8 LED were chosen for study. The luminous flux of the T8 FL of the grade one is 2,690 lm and LED 18 W and luminous flux of 1,800 lm. For comparing two lamps by Energy Efficiency Index (EEI), the EEI of FL and LED are 75 and 100, respectively. Therefore, LED is substituted for FL and followed the lighting equipment standard for using in Thailand as illustrated in Table 2.

Table 2 The compare of standard for 36WFL and 18WLED

Indicator	Description	FL	LED
Power (Watt)	The whole quantity of electricity consumed by the lamp, in watts	36	17-23
Efficacy (lumen/W)	An indicator for the efficiency in which the power consumed is transformed to light; proportion of light output to power consumption, in lumens/watt	>65	> 70
CRI (Color Rendering Index)	A decimal amount of the ability of a light source to show the colors of different objects reliably in	63-72	>80*

Indicator	Description	FL	LED
	comparison with a standard or natural light source		
Lifetime (hours)	Average life time at which 50% of the groups of samples are busted, in hours	10,000-15,000	20,000-30,000

Source: Adapted from TIEA (2014) and *EGAT (2013)

2.2.3 The performance characteristics of the FL and LED

The function of the system describes the performance characteristics of the FL and LED family in Thailand. The general function of the lamps being studied is to provide lighting for different applications for commercial and industrial applications, The lamp types and technology are summarized in Table 3.

Table 3 Summary of FL and LED types

Lamp family	Lamp type	Figure	Main uses
Fluorescent (FL)	Linear fluorescent lamp (LFL)		Commercial and industrial
	Compact fluorescent lamp (CFL)		Commercial and residential
	Circular fluorescent lamp		Commercial and residential
Light emitting	Directional lamp (MR16, PAR30)		Industrial

Lamp family	Lamp type	Figure	Main uses
diode (LED)	Non-directional lamp (A lamp)		Residential
	Tubular LED		Commercial and industrial

Source: EEI (2014)

(1) The component of FL and LED

The study examines two types of lighting, linear fluorescent lamps (36WT8FL) and LED replacements (18WT8LED) using LCA approach. Their components are explained in detail below.

a) Linear FL component

There are two major parts in FL: the gas-filled tube that contain a small amount of mercury, a combination of argon and are coated on the inside with phosphors and another part; the magnetic or electronic ballast. An electrical current in the gas urges mercury vapor, causing it to produce ultraviolet light. The phosphor coating absorbs the ultraviolet light and re-radiates it. The components of the tube are shown in Figure 5 and Table 4.

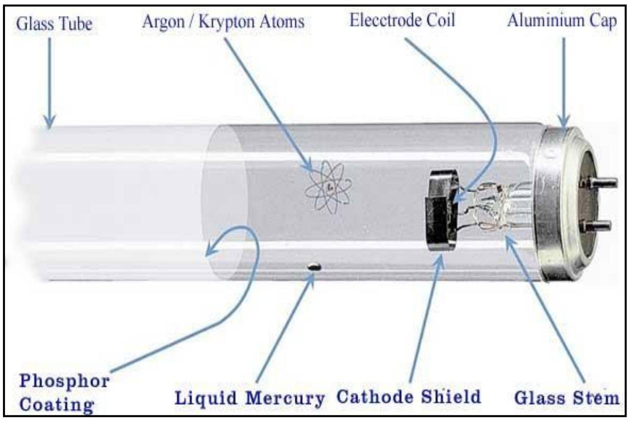

Figure 5 The linear fluorescent lamp component

(Available from: http://www.electrical4u.com/fluorescent-lamp-its-working-principle.jpg, 2016)

Table 4 FL components

Components	The Details of each components
Glass tube	The part contains working element of the lamp.
Cathode	It emits particles, call electron.
Fill gas	It creates flow of energy between cathodes.
Mercury vapor	It gives off UV rays when excited by the electron.
Phosphor coating	The part converts UV light into visible light

The previous research by Navigant Consulting Europe (2009) allocated the FL with ballast inventory data giving in Table 5. Glass content at about 93% is the highest weight fraction in FL lamp with about 3% for aluminum, 2-3% for rare earth powder and mercury.

Table 5 The inventory of a set of FL

Component	SimaPro material	Weight (kg)	% (w/w)
Light source	Glass tube	0.38858	92.96%
	Aluminum	0.0126	3.01%
	Mercury, liquid	0.00002	0.01%
	Krypton, gaseous	0.0042	1.005%
	Argon, liquid	0.0042	1.005%
	Tri-phosphor	0.0084	2.01%
	Total	0.418	
Ballast	Steel (Housing)	0.19375	57.32%
	Aluminum (Coil, Metal Film)	0.1023	30.28%
	Polyethylene terephthalate (PET film ,Luster Terminal)	0.01085	3.25%
	Solder Paste	0.031	9.15%
	Total	0.3379	

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Sources: Navigant Consulting Europe (2009)

b) Linear LED components

LED or sometimes called solid-state lighting (SSL) is one of the most energy-efficient and rapidly growing lighting technologies. They can provide efficient, high-quality alternatives to traditional sources in many applications. Its components are shown in Figure 6. Moreover, LED lamp contains amounts of aluminum accounting for 69.87% which the source of them are founded in LED array, heat sink and LED cover as shown in the Table 6. The driver comprised of about 59.72% for plastics, 22.05% for a transformer, and 8.27% for a capacitor (Tahkamo et al., 2013 and Hendrickson, 2010).

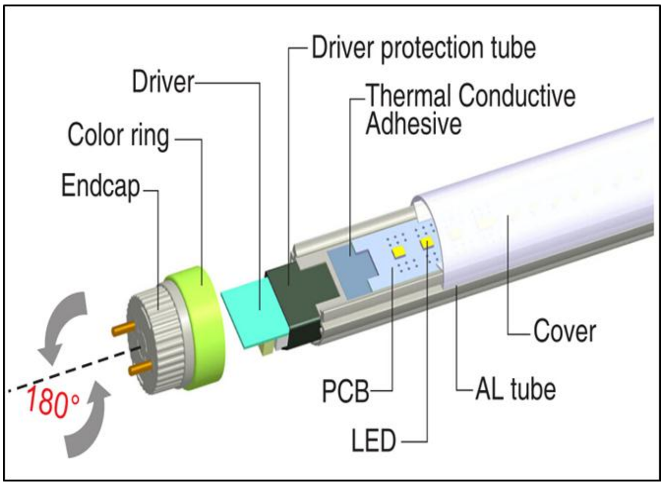

Figure 6 The linear LED lamp component

(Available from: http://www.huge-led.com ,2016)

Table 6 LED components

Components	The Details of each components
LED Arrays/LED module	The electronic device which comprise of printed circuit board and LED chip to deliver high lumen output and efficacy in system.
Heat sink	It incorporates either a fan or a device to keep a hot component such as a cooling of the tube.
LED enclosure	There are LED cover and end cap
Driver	It changes electricity into the tube. Linear Technology LED driver include integrated diodes, accurate LED current matching and multiple output capability.

Source: Thai manufacture (2016)

Table 7 The inventory of a set of LED

Component	SimaPro material	Weight (kg)	% (w/w)
Light source	LED array		
	- Light-emitting diodes	0.028	15.06%
	- Silicone product	0.004	2.15%
	- aluminum	0.023	12.37%
	Heat sink		
	- Acrylic, polycarbonate	0.011	5.92%
	- Aluminum	0.0369	19.85%
	LED cover		
	- Aluminum	0.070	37.65%
	- coating	0.001	0.54%
	Edison base (Steel)	0.012	6.46%
	Total	0.1859	
Driver	Printed circuit board (PCB)	0.009	4.13%
	Capacitors	0.018	8.27%
	Transformers	0.048	22.05%
	Diodes	0.0006	0.275%
	Resistors	0.0003	0.137%
	Integrated circuits	0.004	1.84%
	Steel	0.005	2.29%
	Plastic part	0.130	59.72%
	Total	0.2177	

Sources: Adapted from Tahkamo et al. (2013) and Hendrickson (2010)

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(2) The toxicity of material and precious metal inside the E-waste components

Over 1,000 substances of chemical elements were found in E-waste. Some of them were considered as harmful pollutants (Grossman, 2006). The lists of toxic items in Table 8 partially showed some of harmful substances that may cause chronic impact in living thing. There were effects that could indicate the human exposure due to improper management practices such as open-dumping or basic recycling activities that result in leach out causing contamination of soil, water and air (Pirzada, 2006).

Table 8 Toxic substances composition in E-waste

Substances	Toxicity
Arsenic	skin diseases, lung cancer, decreased nerve conduction velocity
Barium	brain swelling, muscle weakness, damage to heart, liver
Beryllium	lung cancer , skin disease
BFRs	severe hormonal disorders
CFCs	skin cancer, deleterious to ozone layer
Chromium	irritating to eyes, skin and mucous membranes, DNA damage
Dioxins	impairment of the immune system
Lead	vomiting, diarrhea, convulsions, coma, even death
Mercury	brain and liver damage if ingested or inhaled
PVC	respiratory problems
Selenium	hair loss, nail brittleness, and neurological abnormalities

Source: Pirzada (2006)

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a) The toxic material and precious metal inside the FL components

A brief of significant environmental and human health aspects for the raw materials of the FL lamp is presented in Table 9.

Table 9 Summary of environmental and health aspects for FL

Component	Material	Environmental aspects	Health aspects
FL Lamp	Mercury	The terrestrial and marine environments.	Mercuric chloride and Methyl mercury are probable human carcinogens (IRIS)
	Chromium	Biological effects on the organisms living there	chromium (VI) is classified as a known human carcinogen by the inhalation route of exposure (EPA)
	Copper	Toxic to aquatic and terrestrial organisms.	Gastrointestinal distress, including nausea, vomiting, and/or abdominal pain. Irritating to the respiratory tract. Liver damage (EPA)
	Tin	The terrestrial and marine environments.	No serious health
	Lead	Biodiversity, changes in community composition	Lead is possible human carcinogen based on adequate evidence of carcinogenicity in animals

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Component	Material	Environmental aspects	Health aspects
			(IRIS).
	Manganese	Aquatic organisms	Parkinson's Disease Manganese poisoning (EPA)
	Barium	The terrestrial and marine environments and air impact	muscle weakness, damage to heart, liver
Magnetic Ballast	Polyvinyl Chloride	Most of the environmental impacts are correlated with generating PVC and the management of waste PVC.	No serious health
	Steel	Particulate emissions	Emissions can cause health concerns.
	Copper	Toxic to aquatic and terrestrial organisms.	Gastrointestinal distress, including nausea, vomiting, and/or abdominal pain. Irritating to the respiratory tract. Liver damage (EPA)

Source: US.EPA (2010)

b) The toxic material and precious metal inside the LED components

A brief of significant environmental and human health aspect for the raw materials of the LED is presented in Table 10.

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Table 10 Summary of environmental and health aspect for LED

Component	Material	Environmental aspects	Health aspects
LED Lamp	Ammonia	Highly toxic to aquatic animals	The nose, throat and respiratory tract.
	Copper	Toxic to aquatic and terrestrial organisms.	Gastrointestinal distress, including nausea, vomiting, and/or abdominal pain. Irritating to the respiratory tract. Liver damage (EPA)
Driver	Printed Circuit Boards (PCBs)	The heavy metals found in landfills.	-
	Copper	Toxic to aquatic and terrestrial organisms.	Gastrointestinal distress, including nausea, vomiting, and/or abdominal pain. Irritating to the respiratory tract. Liver damage (EPA)
	Steel	Particulate emissions	Emissions can cause health concerns.
	Solder (Tin-Silver-Copper)	Water quality and habitat loss for both land and aquatic animals	Silver and Tin are not toxic

Source: US.EPA (2010)

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Manufacturing process of lighting equipment

Both of FL and LED factory manufacture in Thailand undergo and industrial assembly process. FL and LED components are received from many suppliers both in Thailand (e.g. glass tube, exhaust tube, stem tube, mercury, etc.) and from some foreign countries (e.g. Aluminum cap, lead in wire, coil, argon gas, etc.). LED focus on the assembly of lamp and some components imported from foreign countries (especially heat sink and LED arrays).

Fluorescent lamp manufacture is a complex process as shown in Figure 7 and explained in Table 11.

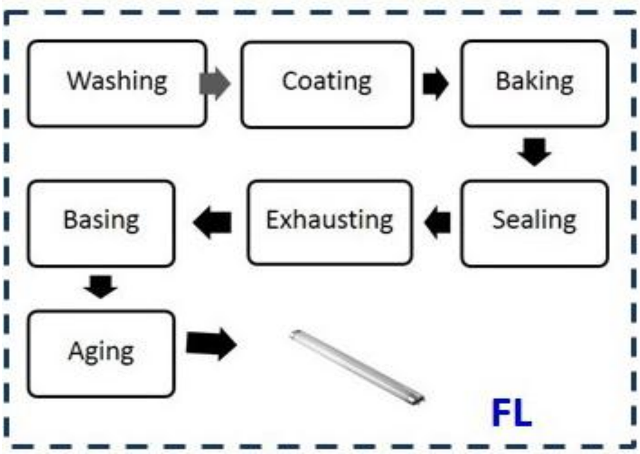

Figure 7 Process diagram of fluorescent lamp manufacture

(Thai manufacture, 2016)

Table 11 The overview of the main manufacturing processes of FL

Process	The Details of each components
Washing	A glass bulb by hot water and drying a wet glass bulb by hot air
Coating	The dry glass bulb by phosphor solution and drying the coated glass bulb by hot air

Process	The Details of each components
Marking	the coated glass bulb at 650 °C for remove some residue and made the phosphor adhere to the inside of glass bulb
Sealing	Both side of glass bulb by stem that is the stem tube contains with lead in wire, exhaust tube and filament coil. The aim of usage the stem is completely close glass bulb. One of side will have a hole for make to vacuum bulb.
Exhausting	the step that making the glass bulb to the vacuum bulb and then filling argon gases and mercury into the glass bulb
Basing	entering the aluminum cab that fill the capping cement on both sides of the glass bulb and baking the caps adhere to the glass bulb and pin staking: clinching the copper wire of the pin leg adhere to the brass wire of aluminum cap
Aging	The lamp for checking efficiency of the fluorescent lamp and activating the lamp for easier to use of consumer.

Source: Thai manufacture (2016)

LED lamp manufacture is not complex process. It only focuses on the assembly of imported appliance. The overview of the main manufacturing processes of LED as shown in Figure 8 and is explained as in Table 12.

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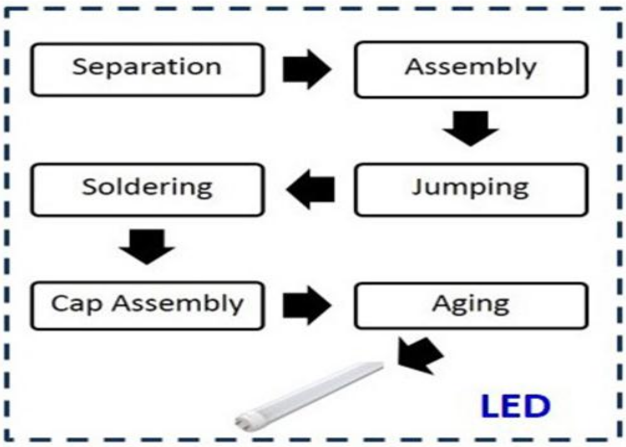

Figure 8 Process diagram of LED lamp manufacture

(Thai manufacture, 2016)

Table 12 The overview of the main manufacturing processes of LED

Process	The Details of each components
Separating	PCB LED board was separated into small pieces
Assembly& Jumping	The small PCB LED pieces were linked together with aluminum heat sink and Then, it was connected with a tube cover
Soldering	A process in which two metal items are joined together by melting that used to form a permanent connection between electronic components.
Cap Assembly	The cover is installed onto the connector with the pins by the machine.
Aging	The lamp for checking efficiency of the LED lamp and activating the lamp for easier to use of consumer.

Source: Thai manufacture (2016)

2.3 Increasing of EOL lighting equipment problems in the former times

For Thailand, the Pollution Control Department (PCD) classified EOL FLs and LEDs as household hazardous waste (HHW) and represented that the quantity of HHW discarded in Thailand is about 0.59 million tons per year. Only small amount of HHW have been separated and disposed properly with 250 tons (4%) being collected and merely 3% having proper disposal. Data from PCD show that approximately 101 million FLs were discarded in 2007 and still increase continuously 123 million units in 2010 (PCD, 2012) Meanwhile, the study of PCD (2012) also forecasted the number of EOL FLs during 2015-2020. It was reported that EOL FLs in Thailand still reach to 311 million units in 2020 as can be seen in Figure 9.

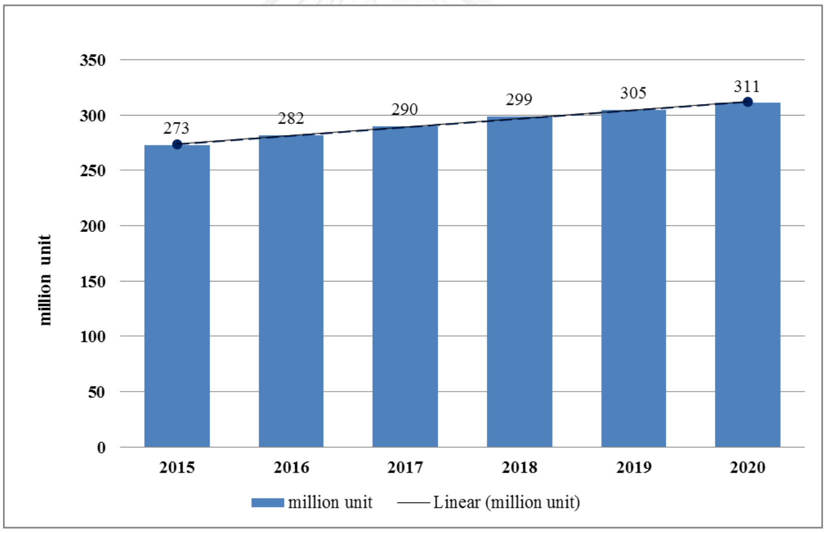

Figure 9 EOL FLs forecasting year 2015-2020

(PCD, 2012)

Typically, a number of methods for quantifying WEEE inventory are discussed in the current WEEE research and literature. Generally, these methods can be classified into four groups: disposal related analysis, time series analysis (projections), factor analysis (using determinant factors for correlation) and Input-Output analysis (IOA) (Walk, 2004; Beigl et al., 2008; Chung, 2011).

1) Disposal related analysis uses WEEE figures obtained from collection channels, treatment facilities and disposal sites. It usually requires empirical data from parallel disposal streams to estimate the overall generation.

2) Time series analysis forecast the trend of WEEE generation by extrapolating historical data into the future.

3) Factor analysis is based on hypothesized causal relationships between exogenous factors, like population size and income level, versus WEEE inventory.

4) Input-Output analysis (IOA) quantitatively maps the sources, pathways and final sinks of material flows, and so far it is the most frequently used method.

Globally five methods for selection of the methodology for WEEE inventory were recommended by UNEP (UNEP, 2007). Details are provided in Table 13.

Table 13 The guideline for selection of the methodology for WEEE inventory

Method	Description	Mathematically
The Time Step Method	The calculation of WEEE is made up of the base of private and industrial stock and sales data. It can be calculated the WEEE potential during collection phase at time t by differing the stock levels of private and industrial equipment during consumption phase in the period between two points in time t, plus sales in that period minus the annual	WEEE inventory (t) = [Stock (t1) – Stock (t)] private + [Stock (t1) - Stock (t)] industry + Sales (n) - WEEE (n)

Method	Description	Mathematically
	waste generated in that a period of time up to time t-1.	
The Market Supply Method	The calculation of WEEE is made up of sales data, along with ordinary lifespan. The waste prospective during collection phase at time t is calculated from sales figures and information about consumption patterns. Disposal is seen as the opposite of the acquirement of appliances, but with an exact time postpone in the following process.	WEEE inventory (t) = sales (t - dN) + reuse (t - dS) Where, dN - Average lifetime of new items dS - Average lifetime of second-hand items
The Carnegie Mellon Method	This method is a variety of "market supply method", where the calculation of WEEE is made up of sales data, and assumptions about specific lifetimes, recycling and storage. The model focuses on consumer behavior when disposing of end-of-life electrical and electronic equipment. This method identifies the pathways of electrical and electronic equipment from obtain to end-of-life.	a variety of "market supply method" There are four options available to the owner as described below : reuse,storage,recycle, landfill
Approximation 1	The calculation of WEEE is evaluated on the base of stock and average	WEEE inventory (t) =

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Method	Description	Mathematically
	lifetime data. This method has also been claimed to as the 'Consumption and Use' method. This method was used to calculate WEEE/ E-waste in the Netherlands. Mathematically, the method is expressed by the subsequent equation.	[Stock private (t) + Stock industry (t)] / average lifetime
Approximation 2	Sales statistics is used to calculate WEEE inventory in a specific year assuming a saturated market. This method is based on the assumption, that with the sale of a new appliance, an old appliance has to be disposed.	WEEE inventory (t) = sales (t)

Source: UNEP (2007)

Stock private = Number of households x saturation level of the households / 100

Stock industry = number of work places x saturation level in the industry / 100

For Thailand, the study of Apisitpuvakul.et al. (2008); CoCusi Coque (Thailand) Co., Ltd. (2004) suggested that the EOL FLs has been estimating due to the consumption of FLs and the lifetime. The FLs consumed in Thailand have normally been supplied by Thai manufacturers. Imports have been collected from the Thai Customs Department. As a result, the amount of FLs nationwide was estimated by the following relationship equation (1):

Number of lighting equipment consumed nationwide ----- (1)

= Number of FLs supplied from Thai manufactures

+ Number of FLs imported from foreign countries

Apisitpuvakul.et al. (2008) also used the proportion of the GDP of each province to the total GDP coupled with the total number of FLs consumed in Thailand to approximate the number of used FLs generated in each province and used these numbers to estimate a 20-year projection of used FLs available in each province using a regression analysis with a 2007-base year. The results of the projection provided information on the EOL FLs loads and growth rates of each province. The projection equations predicting the SFL loads over the planning horizon were obtained. The information was and input policy on EOL FL management over the planning horizon.

2.4 End-of-life of lighting equipment and other E-waste management

2.4.1 The landfill approach

The California regulation classified all fluorescent lamps and tubes as hazardous waste when they are discarded because they contain mercury. (Title 22, division 4.5, chapter 11, section 66261.50). When the mercury-containing lamps or tubes are placed in the trash and collected for disposal, the mercury may be released to the environment from broken fluorescent lamps.

Studies have indicated that the TCLP (Toxicity Characteristic Leaching Procedure) limits are higher than standard. According to the study of Lim et al. (2010) studied metallic resources, toxicity, and hazardous waste classification of LED products by the leaching tests. They concluded that the low-intensity red LEDs were displayed the highest content of lead (Pb). The high-intensity yellow LEDs were demonstrated the high content of arsenic and copper which have relatively ecotoxicity potentials. Overall, white LEDs display relatively low toxicity potentials because they contain less copper and do not contain arsenic or lead (Pb). TCLP tests have shown that the metal screw bases, ballasts in CFL exceed the California regulations for hazardous waste (US.DOE, 2013).

Hazardous wastes must be deposited in so-called secure landfills. Typically, a secure landfill is a hole in the ground, but may also be built above ground. If the depression is in the ground, it must provide a 3 meter (10 foot) separation between the bottom of the landfill and the underlying bedrock or groundwater Table. The purpose of a secure landfill is to prevent any waterborne connection between the waste products and the surrounding natural environment. It is imperative that groundwater does not cause run off onto the surrounding landscape. All fluorescent lamps and tubes are examined hazardous waste in California that is disposed in secure landfills as shown in Figure 10 (Pollution Control Research Institute, 2010).

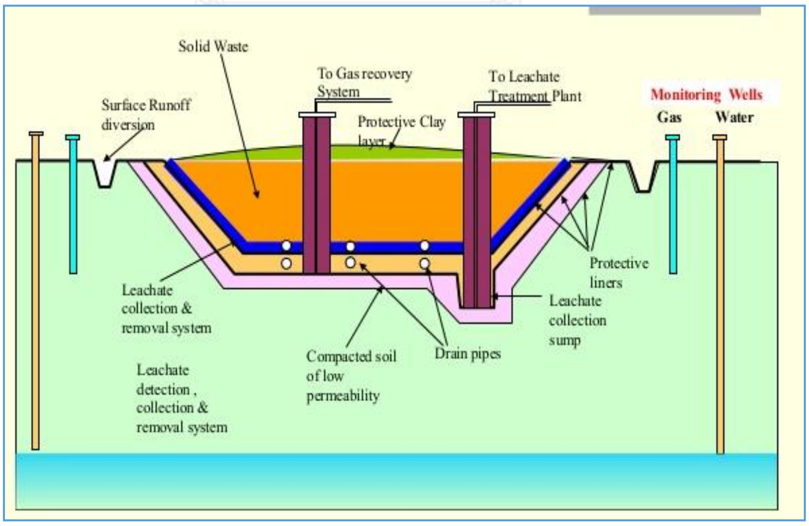

Figure 10 The secure landfills.

(Pollution Control Research Institute, 2010)

2.4.2 The Recycling approach

The e-waste recycling process composes of three major following steps: collection, preprocessing and end-processing as illustrated in Figure 11. The first, all of end-of-life item will be collected. This step is necessary step for recycling and may be various depending on places and device properties (StEP, 2009).

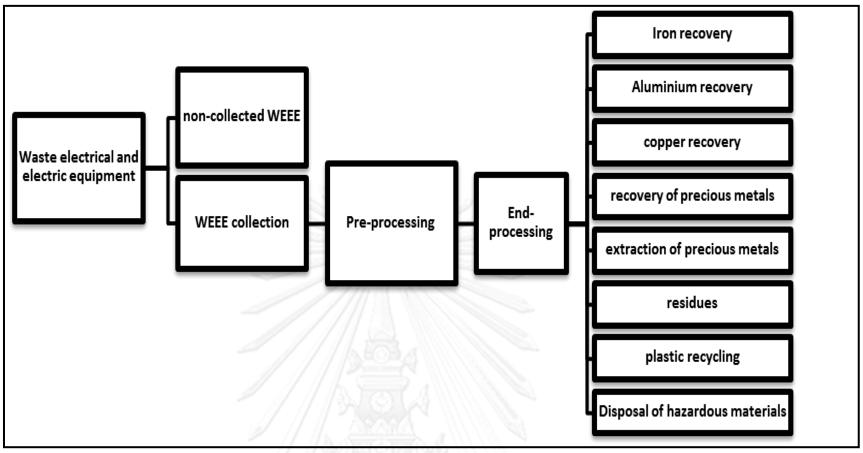

Figure 11 The recycling process for e-waste

(StEP, 2009).

The pre-processing of recycling lighting equipment

The preprocessing is applying the physical techniques to release and enhance desirable substances into relatively homogeneous streams which are going to input in the end-processing. Ordinarily, there were three major processes: (1) sorting, (2) selective disassembly or removal of hazardous and (3) upgrading, using mechanical/physical processing and/or metallurgical processing to develop the substances for the final refining process (Cui and Forssberg, 2003).

The study by Hendrickson et al (2010), states that disassembly or removing out is suitable for recycling LED lamp. Possible ways of decreasing the environmental impact could be achieved by eliminating aluminum from the heatsink and develop the lighting equipment with electricity consumption efficiency.

The end processing of recycling lighting equipment

The end processing is the last recovery treatment from output components after preprocessing takes place at three main destinations. For example, ferrous fractions will be sent to steel as well as aluminum fraction send to smelters. Meanwhile, copper/lead fractions, circuit boards and other precious metals containing fractions are targeted for integrated metal smelters, which recover , copper and other non-ferrous metals (StEP, 2009).

This state-of-the art in recovery process of precious metals from electronic waste are including: (1) *Pyro-metallurgy approach* that use the high degree of heat to chemically transformed the feed materials and separate metals and impurities into different phases so valuable metals can be recovered, (2) *Hydrometallurgy* is to eliminate the impurities through the strong acidic or caustic watery solutions which pure fraction would dissolve and precipitate at the end and (3) *Electro-metallurgy* consume electrical current to recover metals (Cui & Forssberg, 2003).

The recycling approach depicted in Figure 12, it is the integrating two processes which comprise of the pre-processing and the end processing together. The process start cutting away both metals ends with a cutter and crushing the glass section. Fine crushing and washing are conducted, and substances are separated into glass cullet and sludge. The water used in washing is recycled. After disposal, the glass cullet is once more used in glass manufacture, and generated residues are sent to the secure landfill.

The recycling of fluorescent lamps in the industry for making new raw material. It was explained the details of them as below.

a) Aluminum is smelted and recycle back to produce new fluorescent lamp or used in the aluminum industry as raw material.

b) Mercury brought back to the production of new fluorescent lamp.

c) Phosphor powder, such as tri-phosphor would be recycled to produce new fluorescent lamp or halo phosphor used as raw materials in the cement industry.

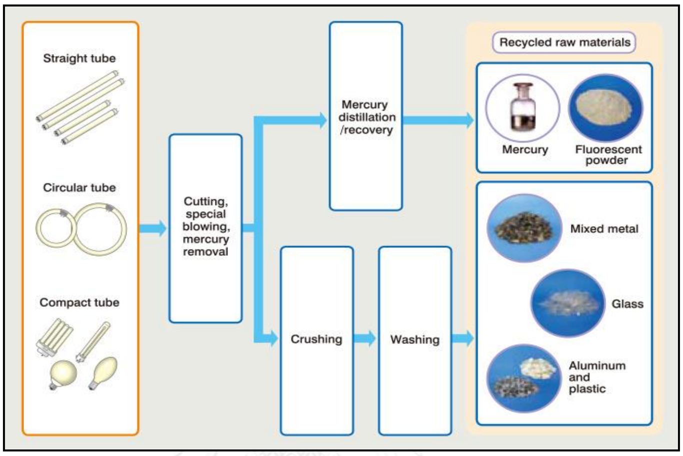

Figure 12 The process of recycling of fluorescent lamps

(Available from: https://www.jfe-kankyo.co.jp , 2016)

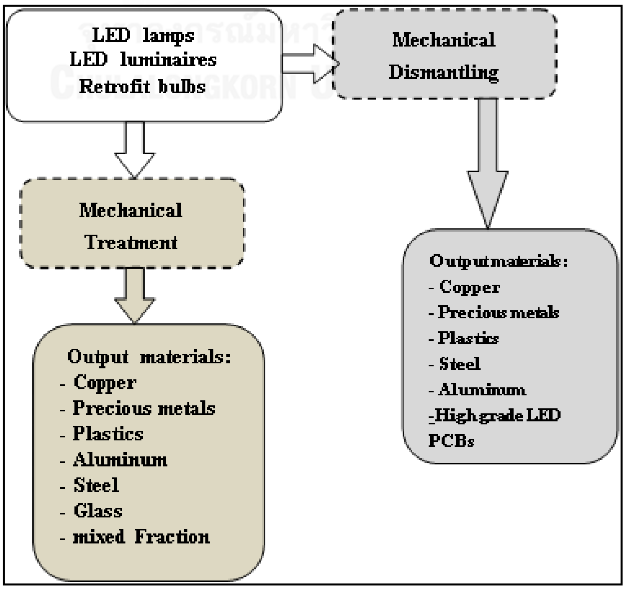

Figure 13 The process of recycling of LED lamps

(Available from: http://www.cyc-led.eu.com,2016)

Research by Nordic Recycling (2014) allocated the FL composition as depicted in Table 14. Glass content composition is the highest weight fraction at 45 – 80%. Aluminum and other metals comprise about 18 – 30%. , A mix of plastic, 2-3% rare earth powder, also containing mercury.

Table 14 Fractions and end uses from waste gas discharge lamps

Fractions	Approximate part	End use / disposal
Aluminum / other metals	18-30%	Reuse or recycle
Mix of plastic and metal	20%	Recycler; energy recovery; landfill
Glass	45%-80%	Reuse for fluorescent tubes; lamp
Rare earth powder, also containing mercury	2-3%	Separate and reuse as mercury or phosphorus in new lamps, separate and recycle after rare earth processing; powder and Hg landfilled as hazardous waste

Sources: Nordic Recycling (2014)

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For Thailand, as is shown in Figure 14, 65% of Hazardous household wastes (0.58 million tons) that are WEEE (0.38 million tons) and 35% are the other (0.20 million tons). The other comprise of spray, lamp and batteries are 64%, 27% and 9%, respectively. Only small amount of HHW have been separated and disposed properly with 250 tons (4%) being collected and merely 3% having proper disposal. The proper disposal of the lighting equipment undergo final disposal in secure landfills and incineration. (PCD, 2014; BMA, 2013)

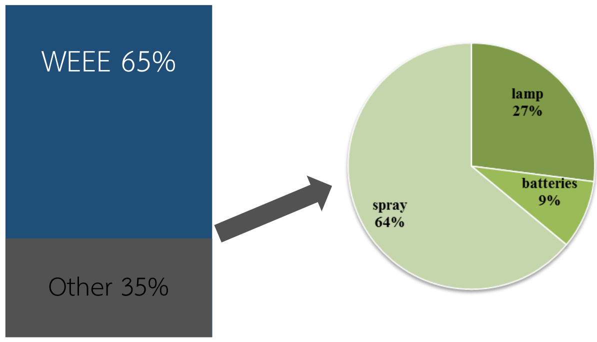

Figure 14 The generation of hazardous household wastes in Thailand

(PCD, 2014; BMA, 2013)

Thailand had the FL recycling facilities by Thai Toshiba Lighting Co. Ltd since 2006 which conducts the collection and recycling of fluorescent lamps targeting government offices and private sector companies (office buildings and factories). Currently, the technology for recycling FLs waste is limited and the recycling of Thai Toshiba Lighting Co. Ltd has closed down since October 2016.

2.5 Various policies for end-of-life management: international regulation scheme

According to StEP (2014), the definition of electrical and electronic equipment (EEE) includes both household and business equipment. Some e-waste legislation uses the different meaning of household and business as they have different route and different function in production process. The European Union's WEEE Directive classifies all electrical and electronic items.

In the United States, there is no federal electronic waste law. Therefore, the definition of e-waste varies in each state. E-waste in the United States commonly refers to mobile phones, IT equipment and televisions, while other electrical and electronic appliances are usually placed in municipal solid wastes. However, according to the Organization for Economic Co-operation and Development (OECD), e-waste is "any appliance using an electric power supply that has approached its end-of-life" as shown in Table 15.

Table 15 The definition of Waste electrical and electronic equipment (WEEE) in various sources

Reference	Definition
EU WEEE Directive	The Directive on waste electrical and electronic equipment including all components, sub-assemblies and consumables, which are part of the product at the time of discarding Directive 75/442/EEC, Article1(a) defines waste as any substance which the holder disposes of or is required to dispose of in according with the provisions of national law in force.
Basel Action Network (BAN)	E-waste enclosed a broad and growing range of electronic devices ranging from large household devices such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users.
OECD	Any appliance using an electric power supply that has extended its end-of-life.

Source: StEP (2014)

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The Waste Electronic and Electrical Equipment (WEEE) Directive is the well-known regulation to mandates electronics take back or recycling systems in 27 countries of European Union. WEEE includes all 10 categories as specified in the EU WEEE directive as seen in Table 16.

Table 16 The 10 categories as specified in the EU WEEE directive

No.	Category	Label
1	Large household appliances	Large HH
2	Small household appliances	Small HH
3	IT and telecommunications equipment	ICT
4	Consumer equipment	CE
5	Lighting equipment	Lighting
6	Electrical and electronic tools (with the exception of large-scale stationary industrial tools)	E & E tools
7	Toys, leisure and sports equipment	Toys
8	Medical devices (with the exception of all implanted and infected products)	Medical equipment
9	Monitoring and control instruments	M & C
10	Automatic dispensers	Dispensers

Source: Widmer et al. (2005)

2.6 The policy of end-of-life management in Thailand

The main regulation in Thailand related to waste disposal is the Master Plan on Solid Waste Management (2016-2021) and the operational progress is in accordance with the roadmap on solid and hazardous waste management, Ministry of Interior was assigned to overseas the preparation of Solid Waste Management Plan of Provincial and Local Administration Offices to be in accordance with the Master Plan on Solid Waste Management (2016-2021) as well as to prepare operational plan and request for budget on environmental quality management at the provincial level.

The progressive operation based on the Roadmap on solid and hazardous waste management is as follows:

1) Undertaking the management of remaining waste in landfill

2) Development of appropriate standards on solid and hazardous waste management

3) Implementation of measures on solid and hazardous waste management

4) Promotion of self-discipline on waste management

The Master Plan on Solid Waste Management (2016-2021) consists of;

1. Framework: reducing the amount of solid and hazardous waste produced from its point of origin, encouraging integrated solid and hazardous waste management, as well as creating awareness on responsibility and participation of all agencies;
2. Goals of Master Plan on Solid Waste Management (2016-2021);
3. Solid and hazardous waste management measures: reducing the amount of solid and hazardous waste produced from its point of origin, enhancing the capacity on solid and hazardous waste management, and promoting solid and hazardous waste management;
4. Prioritizing areas for actions: Model L, Model M, Model S, Transfer Station and Stand Alone;

These regulations and the Public Health Act, B.E. 2550 (A.D. 2007) facilitates local governments to set the local regulations, levy service collection and disposal of municipal solid waste. Moreover, the Factory Act, B.E. 2535 (A.D. 1992) also provided guidance to waste disposal.

For economic inducement, the regulation related to waste management under the implementation models of EPR and classified into two broad groups which are producer compliance schemes and governmental funds. The advantages and disadvantages of each model can be analyzed and a synthesis proposed for Thailand in the form of a stepwise hybrid model, considering local conditions. The compliance plans have to outline how they intend to support the free take-back obligations stipulated in the draft law. Collection targets can be added to improve system performance in the later years. Unlike a typical producer-led system, the government retains the power to levy product fees into the National Environmental Fund. So, the research ensures the leverage in the case that the producer's plans fail to function in a developing country context. Moreover, the revenues would then be earmarked to support investments and campaigns to achieve the objectives of this law (Manomaivibool et.al, 2016)

Moreover, the legislation concerning hazardous waste management comprises the Hazardous Substances Act and the Factories Act as divided into: Hazardous Substances Act prescribed the Hazardous Substances list including e-waste. While the e-waste generated in manufacturing plants during manufacturing include hazardous substances, they are prescribed as hazardous wastes, and discharging parties are responsible for disposing them. Facilities that conduct the recycling of E-wastes are subject to the Factories Act.

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2.7 Evaluation of the environmental impact throughout the cycle of lighting equipment

The LCAs found in the literature compare incandescent lamps, halogen lamps, CFLs, HPS luminaires, induction luminaires, FL luminaires, and CMH luminaires, LED lamps, and LED luminaires. The methods of the LCAs vary. The differences were in the stages of life cycle included, how the life cycle stages were divided and modeled. The conclusions of the LCAs were similar. Improper landfill or incineration appears to be the most substantial factor leading to human toxicity.

The previous LCA studies (US.DOE (2013); Welz et al. (2011); Navigant Consulting Europe (2009) and Principi and Fioretti (2014)) compared the environmental impact categories of the different lighting equipment. According to these, the use of the product causes the greatest environmental impacts over the life cycle due to the emissions from the energy production. The dominance of the use stage is clearest in incandescent lamp (90 % or greater) due to its low luminous efficacy.

Navigant Consulting Europe (2009) and Hendrickson (2010) investigated in-depth analysis the manufacturing processes and founded that the manufacturing of an incandescent lamp caused approximately 1-7 %, a CFL 1-30 % and an LED lamp 2-20 % of the total life cycle impacts on average. Generally, the environmental impacts in CFL manufacturing are due mainly to the ballast (printed circuit board and components), while the LED lamp manufacturing caused environmental impacts primarily due to the aluminum heat sink.

Moreover, the results from various sources of end-of-life assessment have modeled appropriate EOL scenario using SimaPro 7.1 with the Eco-indicator 99 method (Bunprom et al., 2009; Abdul Hadi et al., 2013; Tahkamo et al., 2015).

Comparison between disposal options has been done by Principi and Fioretti (2014). The result has shown that recycling can reduce the adverse effects to the environment as shown in Table 17.

Table 17 LCA results comparing EOL CFL and LED with recycling and no recycling

Impact categories	Units	No recycling		recycling	
		CFL	LED	CFL	LED
Global warming potential (GWP)	kg CO_{2eq}	7.59E–03	2.38E-02	5.52E-04	1.69E-02
Acidification (AP)	MolcH+$_{eq}$	3.97E-06	1.87E-05	3.38E-07	1.01E-05
Freshwater ecotoxicity(FETP)	CTUe	3.30E-02	1.54E-01	2.82E-03	9.07E-02

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CHAPTER III

METHODOLOGY

This chapter explains methodologies in conducting this research. The study looked at the entire products composed of the manufacturing, consumption, waste generation and focused on EOL lighting equipment in Thailand. Both primary and secondary data were collected. The methodologies are divided into three main sections including (I) EOL lighting equipment estimation in Thailand, (II) life cycle analysis approach, (III) EOL lighting equipment management Scheme. Details of each section are as following.

3.1 EOL lighting equipment estimation in Thailand

Light emitting diode lamps (LEDs) are widely used in both homes and commercial as well as governmental, because of their energy-saving features and long lifespan compared with traditional fluorescent lamps (FLs). Indeed, replacement of FLs with LEDs has been heavily promoted in recent years, as well as LEDs market share is expected to occupy the whole lighting market by 2036 in Thailand (Thailand Ministry of Energy, 2015). Additionally, the rapid introduction of new technologies to satisfy consumer demand, LED is replaced within a few years. The product lifecycle for lighting equipment become shorter. After a certain time period of first usage, lighting equipment become the waste and goes to the landfill. The environmental impact of EOL lighting equipment is an increasingly serious problem in Thailand. Understanding the status and trends in the generation of EOL lighting equipment is important for formulating social responses. The most recent work is a benchmark study by the U.S. Environmental Protection Agency, which includes estimates of generation of e-waste in the near future based on historical sales data (US.EPA, 2007) When estimating the generation of EOL electronic appliances, first a constant growth rate on historical sales data is assumed to extend the model to the future and forecast future generation. Therefore, this study applies the market supply method to predict the EOL lighting equipment.

3.1.1 Review and collection data

Primary data was collected from interviews as well as questionnaires to assess the production volume of LEDs. The secondary data was collected from government organizations and private sectors organizations involved in the lighting sector. The details of needed information and source of lighting equipment in this study is presented in Table 18.

Table 18 Details of Information and Source of in Thailand

No	Description	Source of information
1	Amount of raw material/energy/fuel which is used to produce lighting equipment and transport	Thai manufacture LCI database Literature review
2	Amount of electricity consumption in use phase	The Electricity Generating Authority of Thailand
3	Amount of imported lighting equipment	The Custom Department
4	Amount of exported lighting equipment	The Custom Department
5	Amount of production of lighting	-The Office of Industrial

No	Description	Source of information
	equipment	Economics -Questionnaire
6	Amount of Domestic sale	-The Office of Industrial Economics -Questionnaire
7	Amount of EOL lighting equipment generation	The Pollution Control Department
8	The performance characteristics of the FL and LED	The Thai Electrical and Electronic Institute
9	The international and Thai standard for the FL and LED	-The Illuminating Engineering Association of Thailand -The Electricity Generating Authority of Thailand
10	The company of lighting equipment	The Thai Electrical and Electronic Institute

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3.1.2 Method used for EOL lighting equipment estimation

To determine the sources of waste generation, two phases were included, namely sales and reuse (UNEP, 2007). For lighting equipment, no reuse or refurbishment values exist. When they come to their end-of-life, they flow directly into the waste stream. Consequently, a Market Supply Method that does not investigate reuse (or refurbishment) was adopted in this study.

3.2 Life cycle analysis approach

In this methodology section, environmental assessment followed the international standards of the ISO 14040 series (ISO 14044, 2006).

3.2.1 SIMAPRO Program

In this study, the System for combined environmental assessment of products program SimaPro versions 7.1.8 was used to develop LCA.

3.2.2 Purpose of the LCA study

The major objective was to evaluate environmental impact of T8FL and T8LED. The sub-objectives were to suggest the improvement scenario for disposing EOL lighting equipment and to compare environmental impact between FL and LED.

3.2.3 Functional units

The functional unit identifies the base for the assessment of products and particularly for comparisons between products. The functional unit in this case of study is the FL with the magnetic ballast together with the LED with the driver. It is based on the operating time of lamps in the use phase in hours; therefore, the FL with the magnetic ballast is 2 units, and the LED with the driver is 1 unit.

This study followed the methodology used by Abdul Hadi et. Al., (2013), which normalized the operating time required for predicting the future. As presented on Figure 15 and Table 19, two units of FL with the magnetic ballast is equivalent to one unit of LED with the driver.

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Table 19 Lighting equipment functional unit

Performance	FL and magnetic ballast	LED and driver
Brightness per lamp (lumen)	2,690	1,800
Efficiency(lumen/watt)	75	100
Lifetime (hour)	20,000 hours	40,000 hours

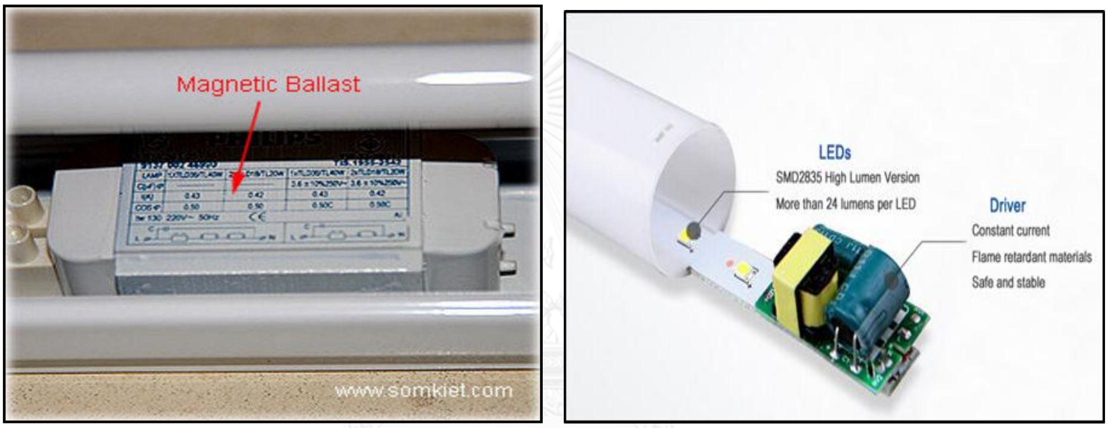

Figure 15 The lighting equipment in this study

(Left: FL with the magnetic ballast, Right: LED with the driver)

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3.2.4 Scope and System boundaries

The system boundary of FL with the magnetic ballast and LED with the driver, included manufacturing, distribution, consumer use and end-of-life.

In this study, the T8 FL was selected for the representative linear FL, because it accounts for the largest proportion of linear FL production. (EGAT, 2014) The minimum rated power of T8 FL is set to 36 W in the state standard for the energy efficiency values and grades of double-capped fluorescent lamps (AQSIQ and SAC 2013).

The T8 FL standard, which has a rated power of 36 Wand luminous flux of 2,690 lm, and the T8 LED, with the rated power of 18 Wand luminous flux of 1,800 lm, were chosen for the assessment of environmental impact. To ensure comparability of the FL and LED, the lifetime 40,000 hours was taken as a reference parameter; FL with the magnetic ballast was taken as 2 units and the LED with the driver as 1 unit.

4 samples of each model were collected. Rated performance claims are presented, where they were available. The model used in this study represents the performance of the other brand as well because they are having the same trend as shown in Table 20.

Table 20 The performance of the lamp in the study compare with the other brand

Model ID	Company	Power (watt)	CCT (K)	Lifetime (hours)	Flux (lm)	Efficacy (lm/W)
FL						
FL1	A	36	6,500	15,000	3,070	85.0
FL2	B	36	6,500	22,000	2,600	72
FL3	C	36	6,500	15,000	2,500	69.4
In study	D	36	6,500	20,000	2,690	75.0
LED						
LED1	A	16	6,500	30,000	1,600	86.8
LED2	B	20	6500	30,000	1,700	85.0
LED3	C	18	6,500	30,000	1,700	94.0
In study	D	18	6,500	40,000	1,800	100.0

Source: (website: Phillip, Osram, Lekise, Toshiba and Panasonic, 2016)

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3.2.5 Building a process map

The process map diagram given below is separated into two types; FL and magnetic ballast, LED lamp. Life cycle covers starting from the extraction and processing of raw materials to disposal of the product as illustrated in Figures 16 to 17, respectively.

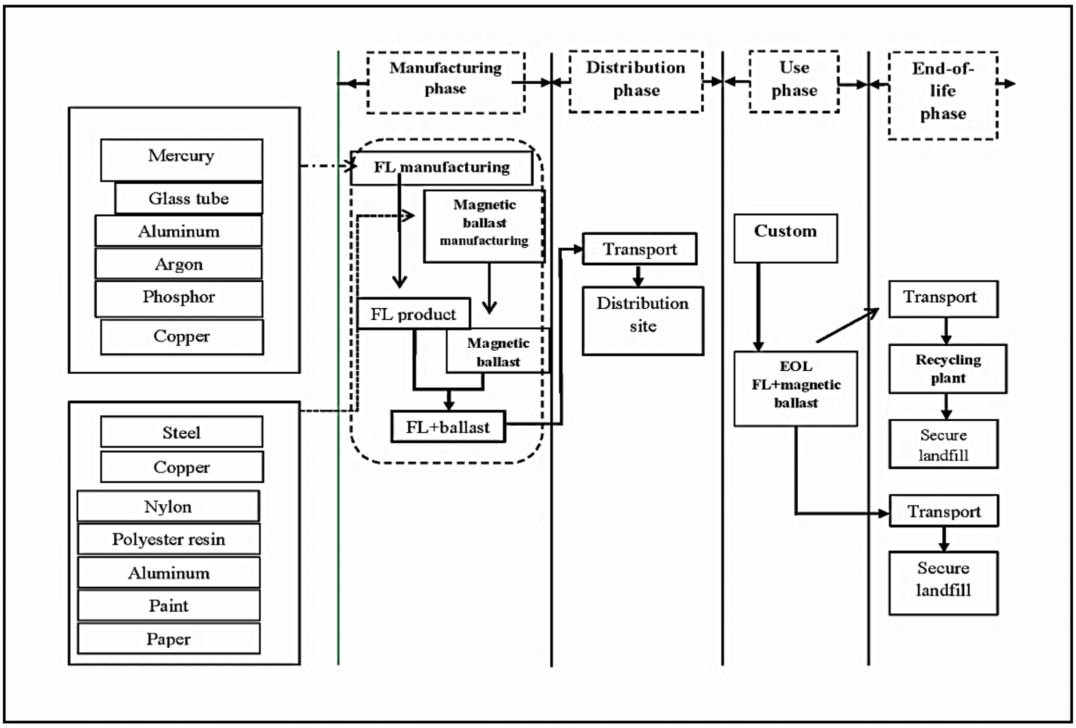

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Figure 16 Life cycle assessment of FL and ballast (a set of FL)

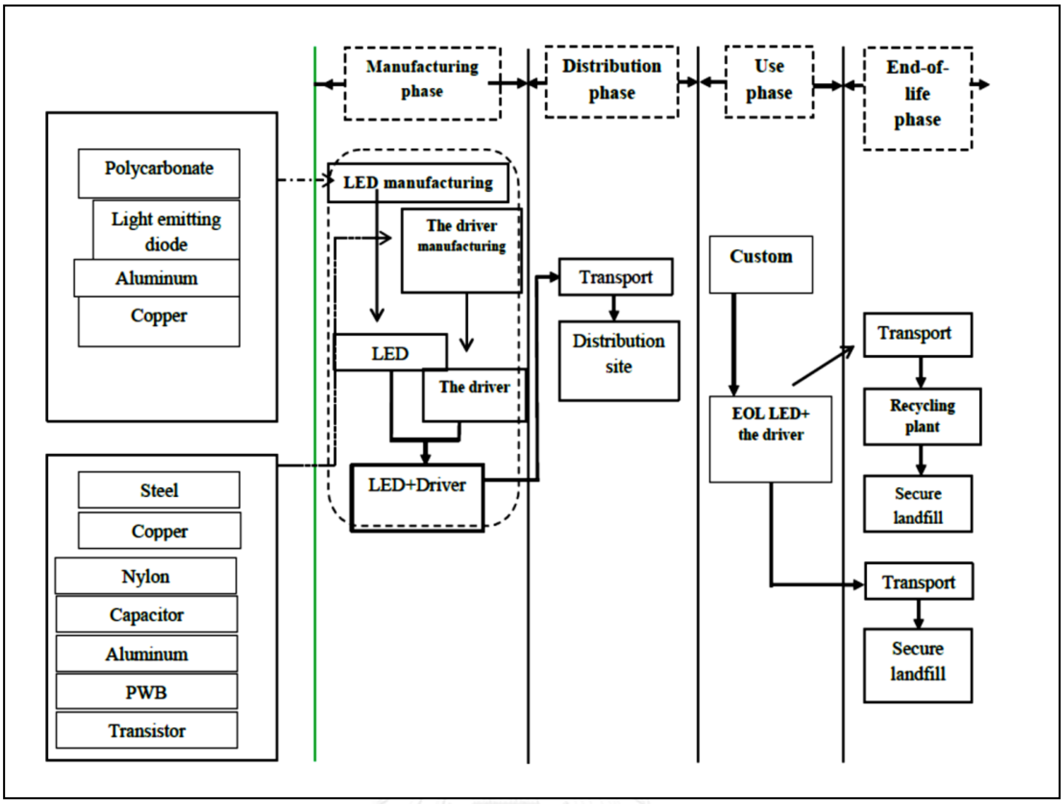

Figure 17 Life cycle assessment of LED and driver (a set of LED)

(1) Manufacturing process: Environmental impact from the manufacturing process was obtained from the amount of energy and other utilities used in the manufacturing process of FL lamp. In the case of the LED lamp, the driver and the magnetic ballast manufacturing is the only assembly process that uses the electricity in production.

(2) Distribution: FL and LED transportation between manufacturers with the main distributors were considered. There were eight FL distributors and nineteen LED distributors around the center region of Thailand (Boundary does not include the transport of consumer). The vehicle types used are 6-wheel trucks with a carrying capacity of 13 tons. The average distance is estimated from the distance between the distributors and the producer, where the weight of product transported equals to the number of lamps multiplied by the weight per each product. The minimum distance between the distributors to the final disposal or waste management was estimated from a previous study (TGO, 2012).

(3) Use: The average life time of FL and LED were 20,000 hours and 40,000 hours respectively. They were obtained from the life time test of the selected lamp manufacturer. The driver lifetime depend on LED. The magnetic ballast has no specific lifetime and is long-lasting. Therefore, the average life time of the magnetic ballast employed 20,000 hour (depended on FL).

(4) End-of-life: Two lighting equipment were modeled for three end-of-life scenarios.

In this study, scenario 1 was estimating the environmental impact if the secure landfilling scheme was applied in Thailand. The result was considered as the baseline scenario for the comparison between this scenario and the others two recycling approaches. Scenario 2 was performed to verify the environmental performance after recycling collection rate reached 10%. The rate was represented the national plan of household hazardous waste (HHW) collection strategy goal in the Master Plan on Solid Waste Management (2016-2021). Scenario 3 was focus on the environmental performance according to the goal in 2021, which was expected to increase the HHW recycling rate (30% recycling collection rate) as shown in Table 21.

Environmental impact categories were done by the Eco-indicator 99 method. The impact categories studied were human health, ecosystem quality and resources depletion.

Table 21 The scenario analysis in this study

Scenario	Recycling Collection rate	Landfill dumping rate	Scenario descriptions
1	-	100%	All waste disposal 2017-2027 should be performed in a secure landfill, without recycling process
2	10 %	90%	10% collection rate under the Thailand master plan on solid waste management, year 2016-2021 (PCD,2016) have been applied
3	30%	70%	30% collection rate under the hazardous household recycling rate in 2021 of the Thailand master solid waste plan (PCD,2016) have been applied

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CHAPTER IV

RESULT AND DISCUSSION

This chapter presents the current situation of lighting equipment in Thailand. A modified market supply method was used as a tool to quantify the generation of EOL lighting equipment in Thailand. This study analyzes the environmental burden of FL with the magnetic ballast and LED with the driver, using the life cycle assessment by the CML2001 and the Eco-indicator 99 methodology. This chapter attempts to recommend prospective management to tackle EOL lighting equipment in future.

4.1 EOL lighting equipment estimation in Thailand

4.1.1 Current Situation of lighting equipment in Thailand

(1) Lighting equipment producers and dealers in Thailand

The Lighting equipment companies in Thailand comprise of 79 facilities throughout the country. The majority are small and medium facilities, while less than 14% of these factories are operated by major enterprises. The lighting equipment data of producers and dealers displayed in the Figure18 are obtained from Thai Electrical and electronic institute.

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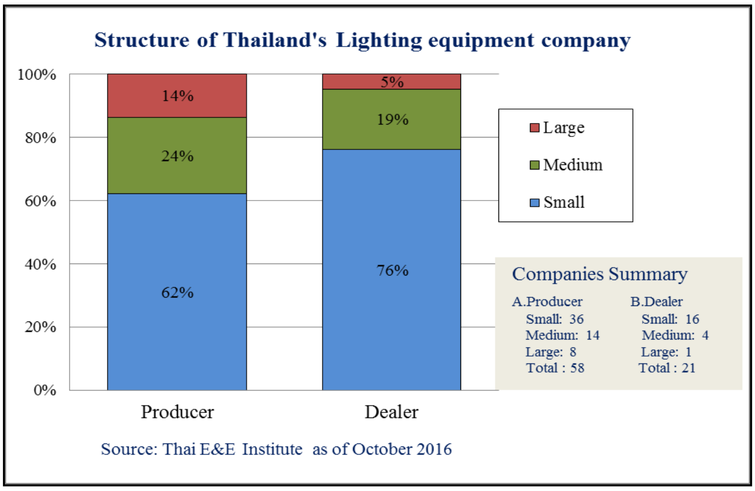

Figure 18 Current Situation of the Lighting Equipment Company in Thailand

(EEI, 2016)

There are two groups in the lighting market in Thailand, as follows: local manufacturer and foreign manufacturer.

(2) Lighting equipment production in Thailand

The lighting equipment considered FLs and LED. The production data of FL was collected from the Office of Industrial Economics (OIE) and the domestic sale of FL was calculated by the production minus the export of FL. While the domestic sale of LED 2013-2014 was retrieved from the Department of Alternative Energy Development and Efficiency (DEDE). Markups are used for wholesale from the data of the questionnaires survey since 2011-2012, 2015.

The production of FL had decreased from 2011 to 2015, while LED production had increased. Domestic sale of FL had decreased since 2012 but LED had shown fluctuations during 2011-2015 as shown in Table 22.

Table 22 Production and Domestic consumption of FLs and LED from 2011 to 2015 (million units)

Year	Production		Domestic sale	
	FL*	LED**	FL*	LED**
2011	82.89	46.57	36.00	3.06
2012	82.45	51.99	21.24	3.35
2013	76.25	36.38	23.64	4.50***
2014	64.67	19.17	22.17	11.50***
2015	62.02	44.18	17.83	33.33

* Source: OIE (2015) **Source: Questionnaires survey (2016)

*** Source: Department of Alternative Energy Development and Efficiency (2014) (DEDE)

(3) Export and import quantities

The import and export volumes of FL and LED in Thailand, for the year 2011 through 2015, are given in Table 23. The imported quantity of LED in 2015 was approximately 170 million units, while the quantity of exports was approximately 11 million units. Additionally, the FL export volume accounted for more than 40 million units, while the imported FL was approximately 16 million units in 2015.

Table 23 Import and export of FLs and LED from 2011 to 2015 (million units)

Year	Import		Export	
	FL	LED	FL	LED
2011	24.16	286.72	46.89	43.51
2012	31.93	362.27	61.21	48.64

Year	Import		Export	
	FL	LED	FL	LED
2013	20.59	282.04	53.28	31.88
2014	16.25	223.82	42.52	7.67
2015	15.72	170.01	44.19	10.85

Source: Custom Department (2015)

4.1.2 EOL lighting equipment estimation in Thailand

For Thailand, the use of FLs was initially promoted around the year of 1996 by a campaign to replace incandescent lamps with compact FLs to save energy. Ten years after this campaign, the government decided on a policy to ban all incandescent lamps in Thailand (Electricity Generating Authority of Thailand, 2014). This increased the market share for FLs to around 30% while the market share of incandescent lamps gradually decreased to around 30-40%. In 2012, the Pollution Control Department (PCD) reported that the use of FLs in Thailand increased from 101 million lamps in 2007 to 123 million lamps in 2010 (Pollution Control Department, 2012). Along with the increased use of FL, the FL waste stream of the country has surged.

Currently, light emitting diode lamps (LEDs) are widely used in all sectors including households and office buildings due to their energy-saving characteristics and long lifespan compared with former fluorescent lamps (FLs). Indeed, replacement of FLs with LEDs has been massively promoted in recent years as a potential energy saving measure. It is expected that LEDs market share will occupy the whole lighting market by 2036 in Thailand (Thailand Ministry of Energy, 2015). The product lifecycle for lighting equipment become shorter. At end of use, lighting equipment will be sent for disposal, mostly in landfill. The environmental impact of EOL lighting equipment is an increasingly becoming a serious problem in Thailand. Understanding the status and trends in the generation of EOL lighting equipment is significant for formulating social responses. The most recent work is a benchmark study by the U.S. Environmental Protection Agency, which includes evaluates of generation of e-waste in the near future based on historical sales data (US.EPA, 2007). When estimating the generation of EOL electronic appliances, first a constant growth rate on historical sales data is assumed to enhance the model to the future and predict generation. Therefore, this study applies the market supply method to predict the EOL lighting equipment.

a) Lighting equipment sales in Thailand

The data of domestic sales, imports, exports and the production were collected from the Office of Industrial Economics, the Custom Department of Thailand and the questionnaire survey with lighting producers. The total sales were calculated by equation (1)

Total sale (domestic sale) = (Production- export) + import------ (1)

The total sale of FL between 2011 and 2015 were calculated from the production of FL in Table22 and the export of in Table23. These values for estimating EOL FL generation as shown in Table 24 and Table 25.

Table 24 Quantity of production, exports and domestic sales of FL (million units)

Year	Production	Export	Domestic sales	Import	Total sale
2011	82.89	46.89	36.00	24.16	60.15
2012	82.45	61.21	21.24	31.93	53.18
2013	76.25	53.28	23.64	20.59	44.23
2014	64.67	42.52	22.17	16.25	38.42
2015	62.02	44.19	17.83	15.72	33.55

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While, the domestic sales of LED between 2013 and 2014 were from the Department of Alternative Energy Development and Efficiency and the remaining years were calculated from the proportion of the total sales of the questionnaire survey.

Table 25 Quantity of total sales, imports and domestic sales of LED (million units)

Year	Domestic sales	Import	Total sales
2011	3.06	286.72	289.78
2012	3.35	362.27	365.62
2013	4.50*	282.04	286.54
2014	11.50*	223.82	235.32
2015	33.33	170.01	203.34

*Source: Department of Alternative Energy Development and Efficiency (2014)

http://www.engineeringtoday.net/news/newsview.asp?id=7298

From the questionnaire survey using 11 companies, it was revealed that most lamps have a longer lifetime than that stated in Thai industrial standards. This is one of the crucial factors for marketing. The average lifetimes of a straight fluorescent, circular fluorescent and compact fluorescent account for 15,545 hours, 8,833 hours and 10,800 hours, respectively. In addition, lifetimes of LED are much longer that FLs by two to four times. The average lifetimes of LED tube and LED bulb are 30,188 hours and 22,397 hours, respectively.

According to market survey, lifetimes of FLs and LEDs are as following:

- Straight fluorescent: 13,0000-20,000 hours
- Circular fluorescent: 8,000-15,000 hours

- Compact fluorescent: 6,000-15,000 hours
- LED tube: 17,250- 40,000 hours
- LED bulb: 8,750-35,000 hours

b) The market supply method

In this study, the EOL lighting equipment generation was assumed equal to the total sales (100% of the bought product became waste at the same time with no additional lighting equipment buying) following the market supply method. The disposal years were calculated from a sum of the sales year and the average of surveyed lifetime from all types of equipment. This study assumed that Thai people switch on the lighting equipment 8 hours per day and 365 days per year. The average lifetime per year is shown in Table 26.

Table 26 Average weight and lifespan of lighting equipment

Type of lighting equipment	Average weight (kg)	Average lifespan (years)
FL	0.216	4
LED	0.192	9

According to Table 26, LEDs tend to have a longer lifespan (9 years) compared to FLs (4 years). Therefore, our study could predict the waste volume of FL since 2015 to 2019 and since 2020 to 2024 for LEDs.

The first year of recorded FL sales was 2011 with 60.15 domestic sales. Total FL sales continuously decreased from 53.18 million units in 2012 to 33.55 million units in 2015.

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Table 27 Estimated EOL FLs and LEDs for the year 2015 – 2019 and 2020 – 2024 respectively

Lamp type	Year Sale	Total sale (million units)	Estimate lifetime (year)	Year Dispose	Waste disposal (million units)
FL	2011	60.15	4	2015	60.15
	2012	53.18	4	2016	53.18
	2013	44.23	4	2017	44.23
	2014	38.42	4	2018	38.42
	2015	33.55	4	2019	33.55
LED	2011	289.78	9	2020	289.78
	2012	365.62	9	2021	365.62
	2013	286.54	9	2022	286.54
	2014	235.32	9	2023	235.32
	2015	203.34	9	2024	203.34

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c) The past and the expected growth rate

For LED, the past growth rates (2012-2015) were calculated year by year. Year 2016 onwards the rate was assumed by following the Economic Intelligence Center of Thailand (EIC). The EIC data predicted the market share of LED will be 33% in 2016 with a growth rate of 5.3% from 2015. They also assumed that the LED market share will reach the saturation point in 2021. Therefore, we assumed that the growth rate will be gradually increased up to 40% in 2017 because the government has continuously promoted the fluorescent replacement with LEDs. The growth rate is expected to increase to 46% in 2018. The growth rate will become steady in 2019 (48%), 2020 (49%) and reach the saturation point in 2021 (50%). The growth rate after this may decrease due to the launch of OLED (organic light emitting diode), which is the latest technology of light emitting diode believed to be a replacement to the LEDs in the future. Therefore, the market share might change due to the consumer behavior. Table 28 shows the expected growth rate of FL and LED sales in Thailand in future (2016-2021).

For FL, the past growth rates (2012-2015) were calculated year by year. Year 2016 onwards the rate was assumed based on the data from the questionnaire survey. Survey data from 11 companies, the average market share of FL will be 5% in 2016. The growth rate of FL has decreased due to the increasing replacement with LED.

Table 28 The raw data of past growth rate and expected growth rate of FL and LED in Thailand

Year	Growth rate of FL	Growth rate of LED
2012	11.58	26.66
2013	-16.83	-21.62
2014	-13.13	-17.88
2015	-12.67	-13.59
2016	5.00	33.00
2017	3.00	40.00
2018	3.00	46.00
2019	-2.00	48.00
2020	-4.00	49.00

Year	Growth rate of FL	Growth rate of LED
2021	-4.00	50.00

Approximate amount of total sales from 2016 and 2021 is given in Table 29.

Table 29 The approximation of total sales in 2016-2021 for FLs and LEDs (million units)

Year	FLs	LEDs
2016	35.23	214.12
2017	34.52	224.82
2018	32.80	233.82
2019	30.83	243.17
2020	29.60	248.03
2021	27.23	250.51

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This Table shows that the sales of LEDs are much higher than that of FLs. The number of LEDs sales is about 6 times higher than FLs sales in 2016 and higher than FLs 90 times in 2021,

Extending Table 29, we could predict the EOL FLs and LEDs during 2020 to 2025, 2025 to 2030 in Table 30.

Table 30 The approximation of domestic sale of the lighting equipment from 2016-2021 and the estimate disposal year

Type lamp	Year Sale (Month)	Total sale (million units)	Estimate lifetime (year)	Year Dispose (Month)	EOL Lighting (million units)
FL	2016	35.23	4	2020	35.23
	2017	34.52	4	2021	34.52
	2018	32.80	4	2022	32.80
	2019	30.83	4	2023	30.83
	2020	29.60	4	2024	29.60
	2021	27.23	4	2025	27.23
LED	2016	214.12	9	2025	214.12
	2017	224.82	9	2026	224.82
	2018	233.82	9	2027	233.82
	2019	243.17	9	2028	243.17
	2020	248.03	9	2029	248.03
	2021	250.51	9	2030	250.51

According to Table 30, this study could predict the EOL volume from fluorescent since 2015 to 2021 and since 2020 to 2030 for LEDs as shown in the Figure 19.

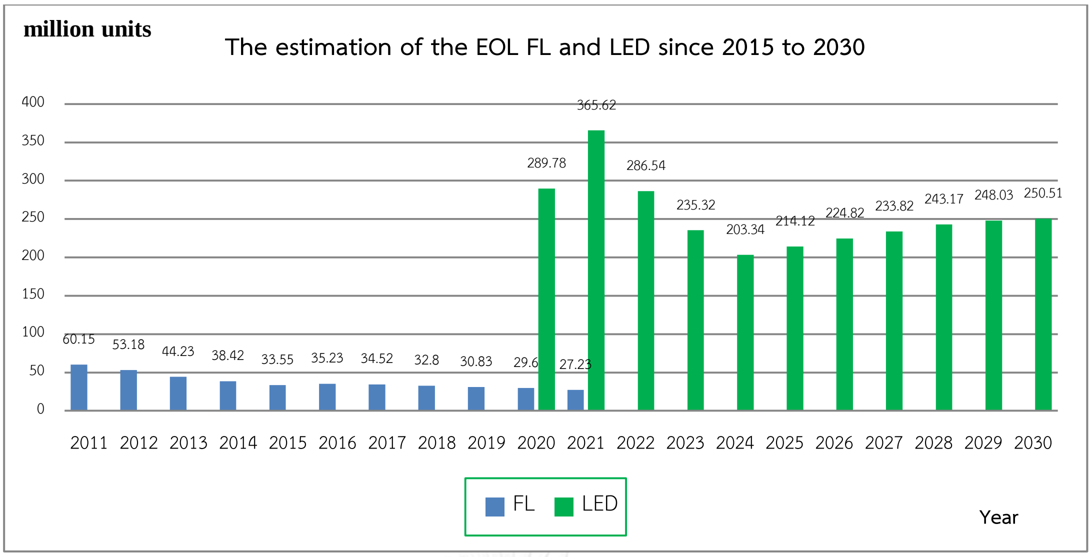

Figure 19 The estimation of the EOL FL and LED since 2015 to 2030

The predicted total EOL FL continuously decreased from 60.15 million units in in 2011 to approximately 27.23 million units in 2025.

The EOL LED will still sharply increase in 2021 (365.62 million units) and decrease in 2024. Then, the quantity of EOL LED will slightly increase in 2025 (214.12 million units), 2027 (233.82 million units) and still increase in 2030 (250.1 million units). The finding is based on the expectation that the government will promote the fluorescent replacement with LEDs as one of energy saving measures of the country.

According to the prediction from this study, the increasing market share of LEDs will also end up with high waste generation. LED should not be classified as hazardous waste and could be disposed with other non-hazardous waste. This waste should be end up at the landfill. However, some component of the LEDs such as plastic could by recycled. So the recycling of these components should be considered for decreasing the environmental impact. The result also similar to the study by Lim et al. (2010), the white LEDs exhibit relatively low toxicity potentials because they contain less copper and do not contain arsenic or lead. These hazardous substances can indicate by the TCLP (Toxicity Characteristic Leaching

Procedure). However, most materials used in LED lighting products can be recycled or recovered at the end-of-life such as plastic. So the recycle of these components should be considered for decreasing the environmental impact.

4.2 Life cycle inventory of lighting equipment

The lighting equipment was considered by directly analyzing the manufacturing processes through to the final disposal. This collection of data inputs (Material and energy) and outputs (products, pollutants released into the air, water and soil) were obtained from the manufacturers. Some of the raw materials and the emissions that relates to the production process were from secondary sources except for the material and weight of LED which were collected by weighting.

4.2.1 The manufacturing stage

The raw materials and manufacturing process of the FL and LED are described below. FL manufacturing consumes electricity energy for the mechanical operation and lighting systems, water for cleaning and mixing chemicals, and LPG for baking and exhausting process. LED production consumes electricity for assembling of raw materials (Energy Works). Figures 20 and 21 and Tables 31 and 32 present the components in inventory data that were used as the input and output in SimaPro software in order to produce one unit of 36WT8 FL and 18WT8LED, respectively.

According to available published research studies, the glass tube contributes approximately 98.20% of total weight in FL lamp. Apart from this, phosphor composition consists of 1.62% and 0.19% in lead in wire. Moreover, the magnetic ballast contains steel about 86% following by copper wire and nylon bobbin (plastic) 10% and 2%, respectively.

The main components of the LED lamp are 83% polycarbonate in the tube cover and 4% polyvinylchloride (plastic) respectively. The driver contains PCB and nylon bobbin (plastic) accounting for 97.2% and 1.3%, respectively.

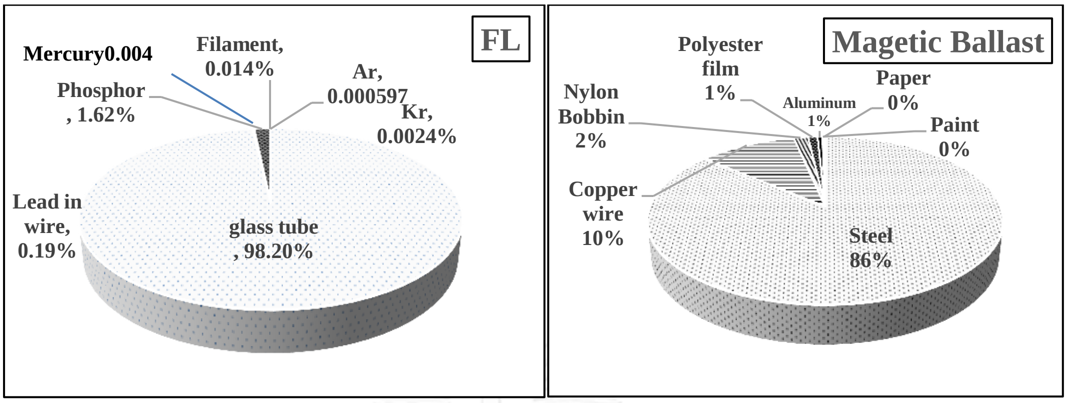

Figure 20 The component of FL and the magnetic ballast

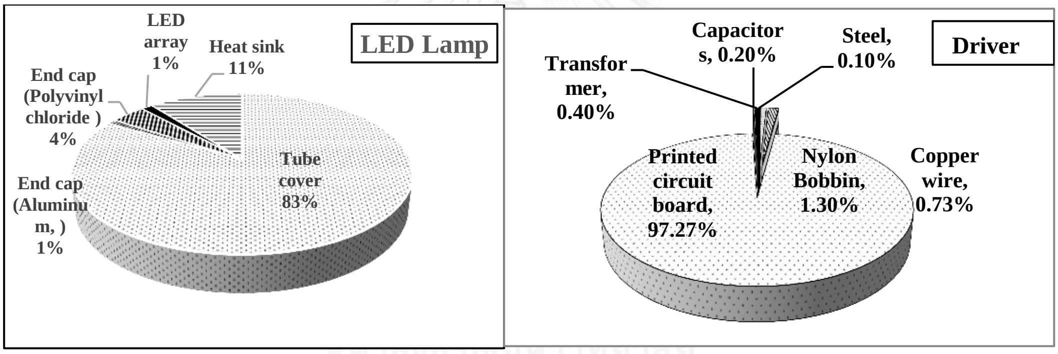

Figure 21 The component of LED and the driver

Table 31 The inventory of FL and the ballast based on 1 set of lamp

Component	Items	Ecoinvent database	Weight	Unit	Source	%
FL	Tube cover	Glass tube, borosilicate, at plant	1.94E-01	kg	Manufacture Navigant (2009)	98.17
	Lead in wire	Copper, at regional storage	3.80E-04	kg	Manufacture	0.19

Component	Items	Ecoinvent database	Weight	Unit	Source	%
	Phosphor	Rare earth concentrate,70% REO, from bastnasite, at beneficiation	3.20E-03	kg	(2016)	1.62
	Mercury	Mercury, liquid, at plant	8.50E-06	kg		0.004
	Filament	Electrode, negative, Ni, at plant	2.80E-05	kg		0.010
	Ar-Kr (20:80%)	Argon, liquid, at plant Krypton, gaseous ,at plant	1.18E-06 4.72E-06	kg kg		0.0006 0.0024
Energy		LPG	4.38E-02	kg		
		Diesel, at refinery/RER	2.00E-04	kg		
Water		Water, decarbonized at plant	3.99E-01	kg		
Electricity for FL manufacturing		Electricity, production mix RER	1.05E-01	kWh		
Magnetic Ballast	Steel	Steel, low alloyed, at plant	8.50E-01	kg	Suesareetham (2010).	86.2
	Copper wire	Copper, at regional storage	1.03E-01	kg		10.4
	Nylon Bobbin	Nylon6, at plant	1.50E-02	kg		1.52
	Polyester film	Polyester resin, unsaturated, at plant	1.00E-02	kg		1.01
	Aluminum	Aluminum,	5.00E-03	kg		0.507

Component	Items	Ecoinvent database	Weight	Unit	Source	%
		production mix, cast alloy, at plant				
	Paint	Paint, ETH U	2.00E-03	kg		0.203
	Paper	Paper, wood free, coated, at regional storage	1.00E-03	kg		0.101
Electricity for ballast manufacturing		Electricity, production mix RER	3.00E-02	kWh	Suesareetham (2010).	
Transportation to distribution		Transport, lorry 75-16t EURO4/RER	8.32E-02	tkm	Manufacture (2016)	
Output						
Waste					Manufacture (2016)	
EOL FL		-	2.16E-01	kg		
Phosphor sludge		-	5.00E-03	kg		
Weld Cu		-	1.00E-03	kg		
Emissions to water						
Waste water		-	3.99E-01	kg		
Emission to air					Manufacture (2016)	
Ar		-	3.18E-05	kg		
N_2		-	3.00E-04	kg		
CO_2		-	1.23E-10	kg		
Particulate		-	7.00E-04	kg		
Mercury		-	4.20E-10	kg		

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Table 32 The inventory of LED and the driver based on 1 set of lamp

Component	Items	Ecoinvent database	Weight	Unit	Source	%
LED Lamp	Tube cover	Polycarbonate, at plant	1.35E-01	kg	By weighting	83.3
	End cap	Aluminum, production mix, cast alloy, at plant	1.58E-03	kg		0.975
		Polyvinylchloride at regional storage	6.32E-03	kg		3.90
	LED array	Light emitting diode, at plant	2.10E-03	kg		1.30
	Heat sink	Aluminum, production mix, cast alloy, at plant	1.70E-02	kg	Tahkamo et al. (2013,2015) Hendrickson (2010)	10.5
Electricity for LED assembly			2.90E-02	kWh	manufacture	
Driver	Steel	Steel, low alloyed, at plant	1.09E-05	kg	By weighting	0.0056
	Copper wire	Copper, at regional storage	8.01E-05	kg	Tahkamo et al. (2013,2015) Hendrickson (2010)	0.0411
	Nylon Bobbin	Nylon6, at plant	1.43E-04	kg		0.0733
	Printed circuit	Printed wiring board, surface	1.07E-02	kg		5.49

Component	Items	Ecoinvent database	Weight	Unit	Source	%
	board	mounting, lead-free surface, at plant				
	Capacitors	Capacitor, unspecified, at plant	2.20E-05	kg		0.0113
	Transformer	Transformer, low voltage use, at plant	4.40E-05	kg		0.0226
		Injection molding	1.84E-01	kg		94.40
Transportation to distribution		Transport, lorry 75-16t EURO4/RER	8.32E-02	tkm	Manufacture (2016)	-
Output						
EOL LED		-	1.92E-02	kg	Navigant (2009)	
Emissions to air						
SO_2		-	5.00E-04	kg		
No_2		-	2.51E-04	kg		
CO_2		-	6.52E-02	kg		
N_2		-	3.00E-08	kg		

4.2.2 Use stage

The amounts of electricity consumed by 36WT8FL, 18WT8LED and magnetic ballast through the period of their use are presented in Table 33. The driver is the one component of LED that consumes electricity with LED.

Table 33 Electricity consumption

Type	Power per lamp (kWh)	Average life Time (hours)	Electricity consumption (kWh)	Source
36WT8 FL	0.036	20,000	720	Manufacture (2016)
18WT8LED	0.018	40,000	540	
Magnetic ballast	0.010	20,000	200	Suesareetham (2010)

4.2.3 End-of-life stage

In baseline scenario, the lamps disposed to secure landfill were assumed to be disposed without waste segregation. Therefore, the data set of the disposal, hazardous waste, 0% water to underground deposit/DE U in Ecoinvent database was selected as the input for SimaPro.

In addition to the landfilling method, FL and LED recycling mass inputs in this study was considered the transfer coefficient in the mechanical treatment of WEEE obtained from Ecoinvent 2.0 report No. 13. Basically, FL and LED mass had defined and separated flow direction and then transferred into sequential treatment level 2. This study, the treatment levels 1 of FL and LED mass flow was represented in sections below.

According to the treatment level 1 dataset, the dismantled FL and LED were disassembly and sorted in this step. The manual clean up step and mechanical sorting transfer coefficient were retrieved. To calculate the distribution fraction of waste which results differently in each specific device as shown in Tables 34 and 35?

Table 34 shows the component of WEEE device in which separating into four fractions. One of those fractions is sent to the proper operation of incinerator following working instruction. With respect to this approach, the FL components was entered to sequential treatment level2 including; 94.99% to shredding process (2.05E-01 kg), 5.12% to metal scrap recycling (1.05E-02 kg) and 0.03% to incineration (3.16E-04 kg). While, the magnetic ballast components were entered to 2nd treatment including; 56.44% to shredding process (5.57E-01kg), 43.36% to metal scrap recycling (4.28E-01kg) and 0.26% to incineration (2.00E-03 kg), respectively.

Table 34 Treatment level 1 the recycling of FL lamp and the magnetic ballast

Material		Component in Ecoinvent	Weight (kg)	Shredder process (kg)	Metal Scrap for 2nd Recycling (kg)	Incineration (kg)
1	**FL lamp**		**2.16E-01**	**2.05E-01**	**1.05E-02**	**3.16E-04**
1.1	Glass	glass	1.94E-01	1.94E-01	-	-
1.2	Aluminum	metal, outside	2.10E-02	1.05E-02	1.05E-02	-
1.3	Copper	metal, inside	2.80E-04	2.80E-04	-	-
1.4	Phosphor	mineral	3.20E-04	3.20E-04	-	-
1.5	Filament	electronic	2.80E-05	2.80E-05	-	-
1.6	Cement	construction	3.10E-04	-	-	3.10E-04
1.7	Zinc	metal, inside	4.25E-06	4.25E-06	-	-
1.8	Mercury	metal, inside	4.25E-06	4.25E-06	-	-
1.9	Argon	chemical	1.18E-06	-	-	1.18E-06
1.10	Krypton	chemical	4.72E-06	-	-	4.72E-06
2	**Ballast**		**9.86E-01**	**5.57E-01**	**4.28E-01**	**2.00E-03**
2.1	Steel	metal, outside	8.50E-01	4.25E-01	4.25E-01	-
2.2	Aluminum	metal, outside	5.00E-03	2.50E-03	2.50E-03	-
2.3	Copper	metal, inside	1.03E-01	1.03E-01	-	-

Material		Component in Ecoinvent	Weight (kg)	Shredder process (kg)	Metal Scrap for 2nd Recycling (kg)	Incineration (kg)
2.4	Nylon	plastic, inside	1.50E-02	1.50E-02	-	-
2.5	Polyester	plastic, inside	1.00E-02	1.00E-02	-	-
2.6	Paint	construction	2.00E-03	-	-	2.00E-03
2.7	paper	paper	1.00E-03	1.00E-03	-	-

The LED components were set to be disposed by 2nd treatment (Table 35 including: 50.68% to shredding process (9.16E-02 kg), 9.83% to metal scrap recycling (1.78E-02 kg) and 39.06% to incineration (7.07E-02 kg). While, the driver components were also entered to 2nd treatment including: 51.01% to shredding process (5.61E-03 kg), 48.94% % to PCB for further treatment (5.38E-03 kg), respectively.

Table 35 Treatment level 1 the recycling of LED lamp and the driver

Material		Component in Ecoinvent	Weight (kg)	Shredder process (kg)	Metal Scrap for 2nd Recycling (kg)	PCB further Treatment (kg)	Incineration (kg)
1	**LED lamp**		**1.81E-01**	**9.16E-02**	**1.78E-02**	**-**	**7.07E-02**
1.1	Polycarbonate	plastic, outside	1.35E-01	6.75E-02	-	-	6.75E-02
1.2	Aluminum	metal, outside	3.56E-02	1.78-02	1.78E-02	-	-
1.3	Polyvinyl Chloride	plastic, outside	6.32E-03	3.16E-03	-	-	3.16E-03
1.4	Light emitting diode	electronic	4.10E-03	4.10E-03	-	-	-
2	**Driver**		**1.10E-02**	**5.61E-03**		**5.38E-03**	**-**

Material		Component in Ecoinvent	Weight (kg)	Shredder process (kg)	Metal Scrap for 2nd Recycling (kg)	PCB further Treatment (kg)	Incineration (kg)
2.1	Steel	metal, outside	1.09E-05	5.45E-06	-	-	-
2.2	Copper	metal, inside	8.01E-05	8.01E-05	-	-	-
2.3	Nylon	plastic, inside	1.43E-04	1.43E-04	-	-	-
2.4	PCB	electronic	1.07E-02	5.35E-03	-	5.35E-03	-
2.5	Capacitors	electronic	2.20E-05	1.10E-05	-	1.10E-05	-
2.6	Transformer	electronic	4.40E-05	2.20E-05	-	2.20E-05	-

4.3 Life cycle analysis approach

In this study the environmental burdens of FL with the magnetic ballast and LED with the driver were evaluated and compared, following the life cycle assessment concept of ISO 14040 (2006). The LCA assessment includes four stages of the life cycle of lighting equipment based on "gate-to-grave" approach or so called business-to-consumer (B2C) assessment. In addition, the stages of Business-to-Consumer include the manufacturing process, transportation and distribution, consumer use and final disposal. The 36WT8 FL and 18WT8 LED was chosen as the lighting system representative. The luminous flux of the T8 FL is 2,690 lm, while LED 18 W has luminous flux of 1,800 lm. The functional unit was set based on its lifetime. The system boundaries of the lighting systems are as the following;

(1) Manufacturing process: the environment impacts from the manufacturing process of FL lamp emit primarily from energy and other utilities used. While, the LED set, the assembly process of the driver is the only process that uses the electricity.

(2) Distribution: FL and LED transportation among manufacturers were accounted for eight distributors around the center region of Thailand. In this study, the transportation to consumers was not included. The vehicle types used were 6-wheel trucks with a carrying capacity of 13 tons. The average distance was estimated from the distance between the distributors and the producer, where the weight of product transported equals to the number of lamps multiplied by the weight per each product. While, the minimum distance between the distributors to the final disposal or waste management facilities was averaged to be 40 km. (TGO, 2012). Overall of the study the transportation was set to be one way.

(3) Use: Consideration of the environmental impacts from the uses of electrical energy was counted throughout the entire life of the lamp. The power's reference list used to produce electricity was obtained from the EGAT.

(4) End-of-life: Two lighting equipment. FL and LED were modeled by means of the three end-of-life scenarios.

In this study, scenario 1 determines the environmental impacts when applying the secure landfilling scheme in Thailand. Apart from a baseline scenario for comparing with the others two recycling approaches. Scenario 2 is established in order to represent the environmental impacts related to difference percentage of recycling collection rate. This rated number was retrieved from the Master Plan on Solid Waste Management (Year 2016-2021) for national strategy goal plan of household hazardous waste (HHW) collection. Scenario 3 aims to represent the environmental performance based on the waste management goal in 2021 which targets the high rate of HHW recycling to be 30% of recycling rate.

4.3.1 A comparison of environmental impacts between FL and LED

All impact categories was assessed by the Eco-indicator 99 method, the result indicates that the LED has lower environmental impacts compared with FL. The LED has significantly lower environmental impact by 70% of the overall impact when compared to FL as shown in Figure 22.

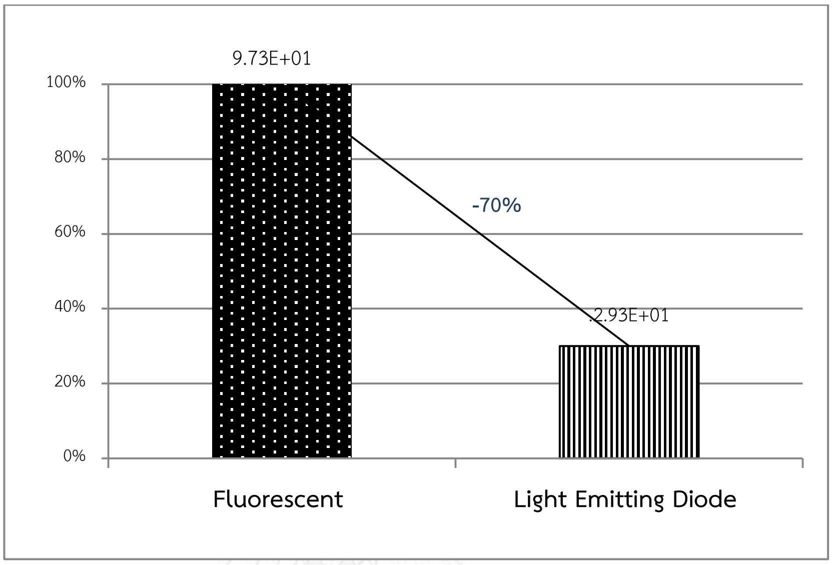

Figure 22 A comparison of environmental impacts between FL and LED

Environmental impacts caused by the use phase amounted to 98.94% in FL and 96.46% in LED. These results are in accordance with the assessments by Sangwan (2014) and Navigant Consulting Europe (2009) representing that the use phase accounted more than 90% of the total impact. The second most significant phase in the assessment is the manufacturing, which contributes about 0.99% in FL and 3.53% in LED. While the end-of-life accounts for 0.04% and 0.01% in FL and LED, respectively. The remaining is the distribution as illustrated in Figure 23.

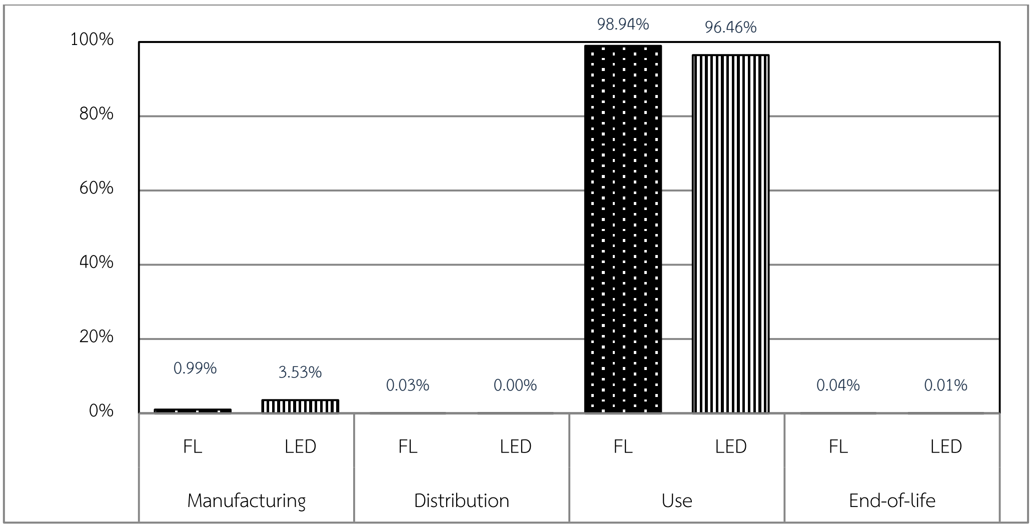

Figure 23 The environmental impacts between FL and LED using the Eco-Indicator 99 Method

For the manufacturing stage, the main components including the magnetic ballast (or driver) of FL and LED were analyzed. The result shows that the magnetic ballast of FLs and aluminum base for end cap in LEDs cause significant environmental impacts. These were 50.29% for FLs and 45.60% for LEDs, . Magnetic ballast has high potential impacts in terms of respiratory inorganic, fossil fuel and minerals accounting for 55.37%, 12.91% and 12.41%, respectively. The majority of the magnetic ballast manufacturing is mainly due to the steel production that contributed to 90.55 % of the total environmental categories. For in-depth analysis, the steel production has the largest impacts on the respiratory inorganics, minerals and ecotoxicity accounting for 57.78%, 12.58% and 10.33%, respectively as shown in the appendix C.

Meanwhile, the driver and LED array are the components that contribute the highest impact in LED, about 53.65% and 39.98%, respectively. The driver is the main component that has the considerable impacts on the respiratory inorganic, fossil fuels and carcinogen contribute 63.57%, 11.62% and 7.55%, respectively. The components driver was analyzed; it was found that the printed circuit board (PCB) has the most environmental impacts in the driver accounting for 99.12%. In addition, of all impacts, the PCB has high potential impacts in terms of the respiratory inorganics, carcinogen and climate change accounting for 63.20%, 7.70% and 5.58%, respectively as shown in Figure 24.

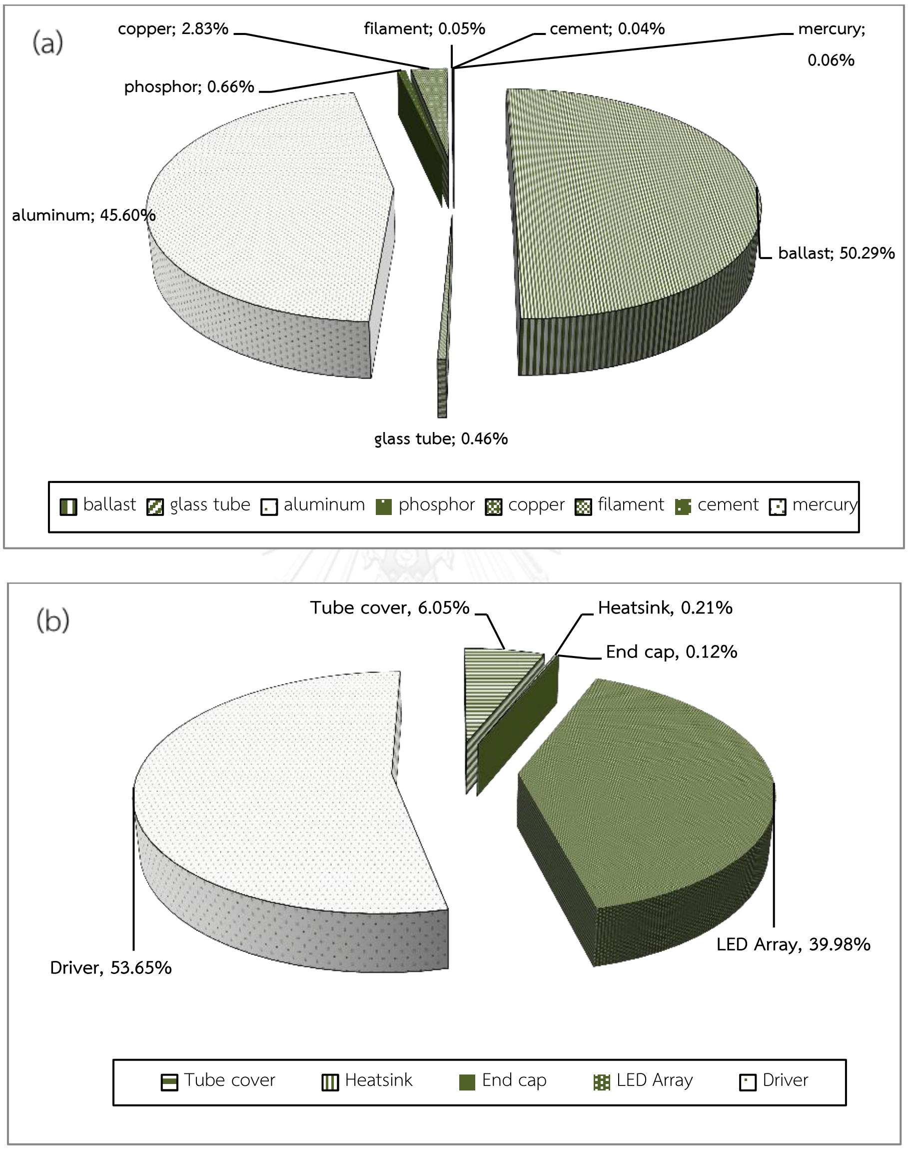

Figure 24 Environmental impacts of the main component (a) FL (b) LED

Similar results have been recorded in other studies (OSRAM (2009) and Navigant Consulting (2009)). Their results represented that the top rank of the components that caused significant environmental impacts, was the ballast in CFL. In addition, the result investigated by Chan, Ho-kan (2012) is similar to the result of LED in this study. His study analyzed the dominating component of LED road lighting. The result showed that PCB contributed the highest impact.

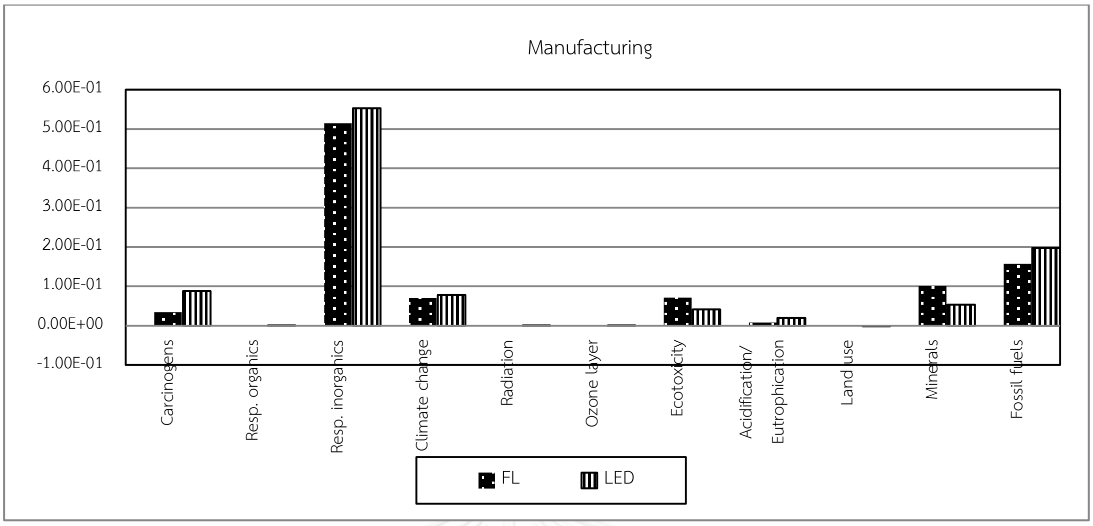

Figure 25 The environmental impact in the manufacturing process of FL and LED

The result of the single score contribution is shown in Figure 25. The FL manufacturing process had high potential impacts in terms of respiratory inorganic, fossil fuel and minerals accounting for 53.52%, 16.14% and 10.50%, respectively.

The LED manufacturing process also contributed to the respiratory inorganic, fossil fuels and carcinogen about 53.57%, 19.15% and 8.54%, respectively. The particular categories are described below,

The respiratory inorganic displayed as the highest impact of all environmental categories. It can be seen that this category generated emissions from 16.58% glass production in FL process and 49.02% Light emitting diode production in LED process. Specifically, the substances causing the respiratory inorganic impact in the all FL process was from the fine particles with a diameter of 2.5 µm or less (48.86% of impact), nitrogen oxide (22.47%) and sulfur dioxide (18.51%), respectively. In particular, the glass production in FL process contributed about 21.27% for sulfate, 20.47% for ammonia and 19.68% for the coarse particle with a diameter between 2.5 and 102.5 μm, respectively as illustrated in Figure 26.

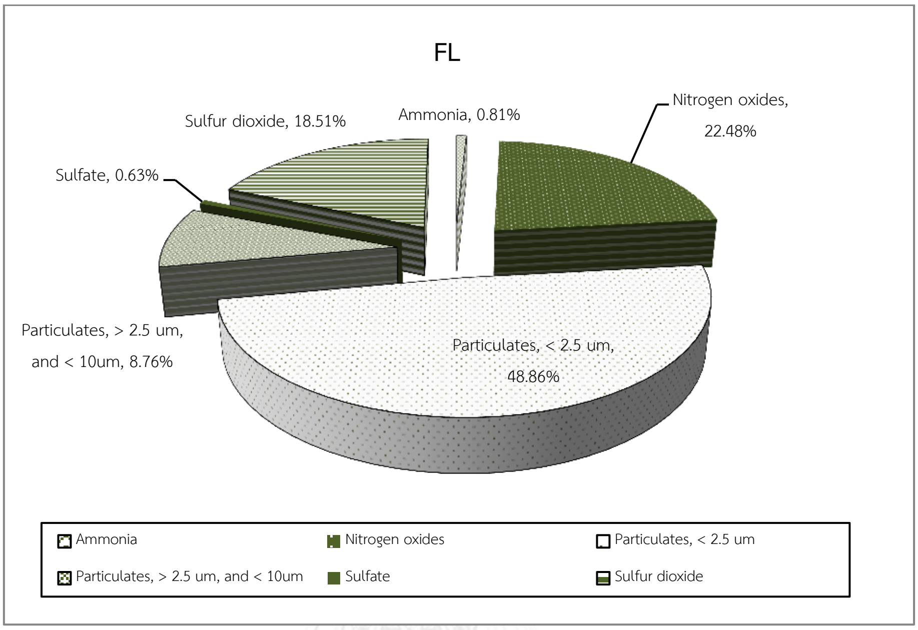

Figure 26 The substance causing the respiratory inorganic impact in FL process

As shown in Figure 26, the environmental impacts for LED process had 38.27% form the fine particles with a diameter of 2.5 μm or less, 22.46% for nitrogen oxide and 22.37% for sulfur dioxide, respectively. For the Light emitting diode production in LED process, it contributed 44.84% form the fine particles with a diameter of 2.5 μm or less, 25.59% for sulfur dioxide and 22.47% for nitrogen oxide, respectively as illustrated in Figure 27.

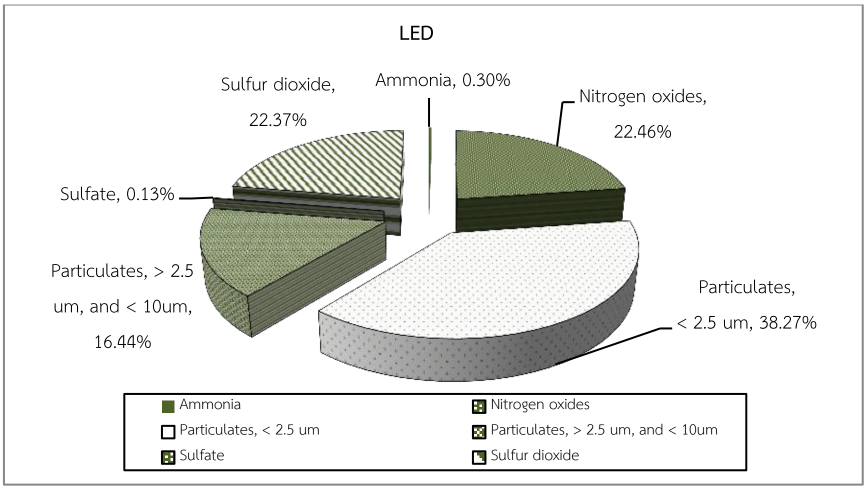

Figure 27 The substance causing the respiratory inorganic impact in LED process

The fossil fuel impact is the second highest category of the total impacts in the manufacturing process. The main substances causing the fossil fuels impact in the both FL and LED process were caused by the gas, natural 79.44% for FL process and 71.56% for LED process, oil crude 17.85% for FL process and 26.03% for LED process and coal hard 1.89% for FL process and 1.96% for LED process, respectively as shown in Figure 28.

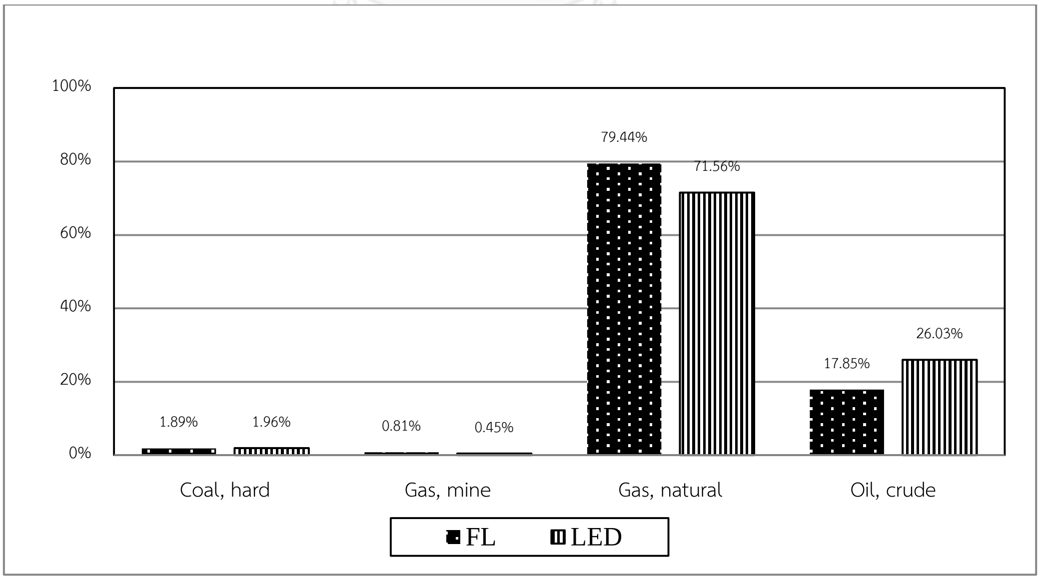

Figure 28 The substance causing the fossil fuel impact in FL and LED process

The glass production has the highest fossil impact for FL process. The main substances causing the fossil fuels impact in this process were from 93.88% by natural gas, and 5.51%, by oil crude, respectively. While, the polycarbonate production is the largest fossil category of LED process in which the main substances are natural gas (72.94%) and oil crude (26.45%).

For the distribution stage, the FLs and LEDs were transported from manufacturers to the distributors by 13 tons truck using diesel as a fuel. The transportation from the distributor to the final disposal was assumed according to previous study (TGO, 2012). All transportation was considered to be one way.

The single score contribution is shown in Figure 29. The FL and LED distribution has high amount of fossil fuel, respiratory inorganic and climate change accounting for 53.52%, 16.14% and 10.50%, respectively.

The main substances causing the fossil fuels impact in the distribution stage are oil in diesel using for the truck.

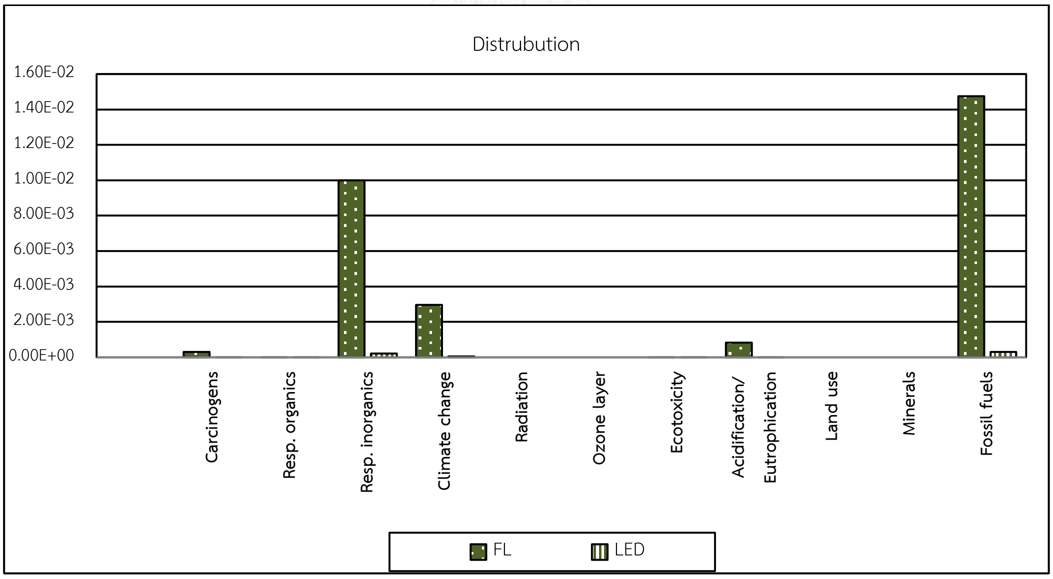

Figure 29 The environmental impact in the distribution stage of FL and LED

The use phase mainly consumes the electric energy where the source of the dataset was selected from EGAT (EGAT, 2015). As shown in Figure 30, the use of FL and LED contributes to fossil fuel, respiratory inorganic and climate change accounting for 60.70%, 24.51% and 13.60%, respectively.

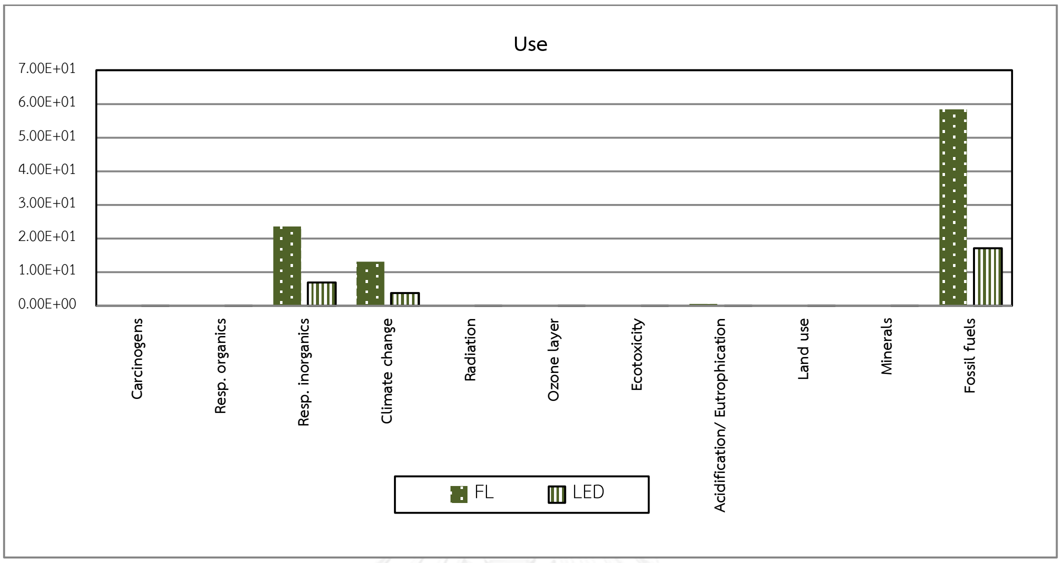

Figure 30 The environmental impact in the use stage of FL and LED

Regarding to EOL treatment technology, environmental benefits were gained from the recycling of aluminum, steel, and cullet. The recycling approach can reduce environmental impacts to be 3.39E+00 pt. While polycarbonate, steel and aluminum in LED can be recycled. This creates more benefit for environment about 8.92E-01 pt.

The multi impacts associated with the 11 categories of the FL life cycle presented in Figures 30 and 31. The largest proportion is fossil fuel, which is at 60.24 % of the total impact for the entire life cycle of FL, run after by respiratory inorganic, climate change and acidification/ eutrophication with proportions of about 24.81%, 13.54% and 0.58%, respectively. These are similar to the LED study; the proportions for the three categories are 59.23%, 25.54%, 13.38% where 0.63% is the carcinogen impact.

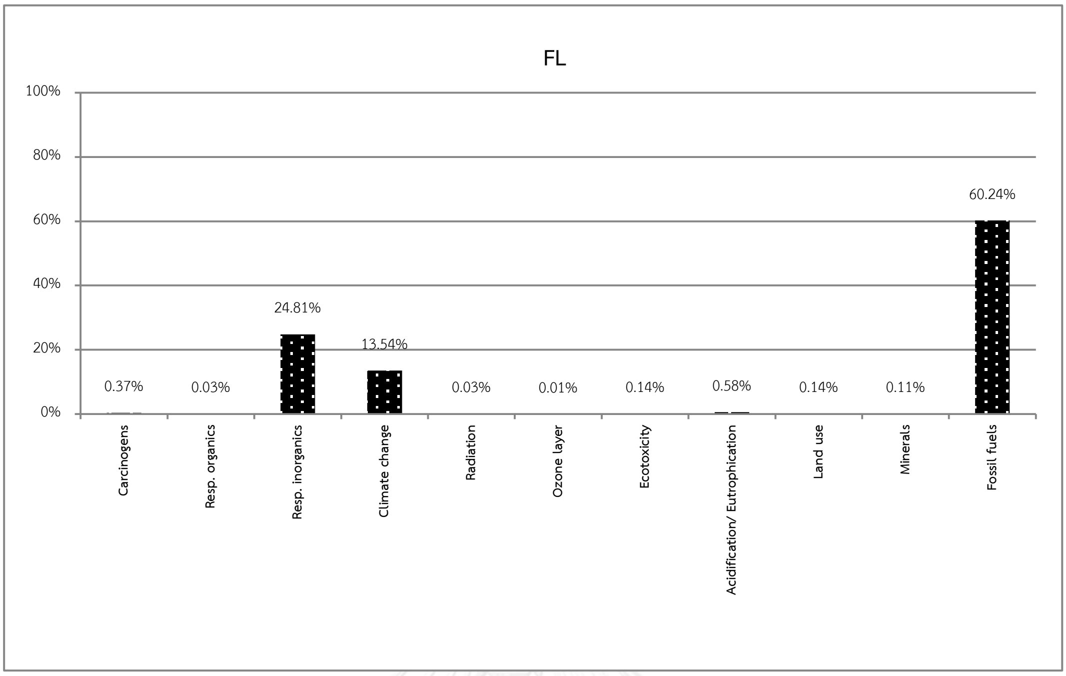

Figure 31 the environmental impacts of LED using the Eco-Indicator 99 Method

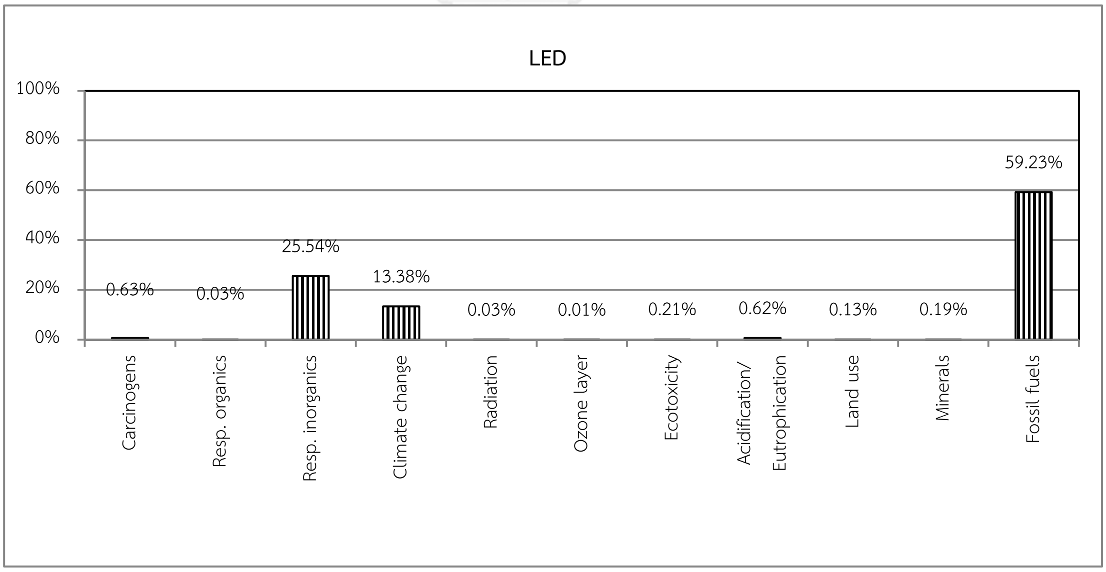

Figure 32 The environmental impacts of LED using the Eco-Indicator 99 Method

Regarding to the results using the CML 2001 method, the environmental impacts associated with the whole life cycle of LED is slightly lower than 31.62%

compared with FL. The total impact values of each category for FL were used as the equivalence value for the impact of each stage. The comparisons of difference impact categories between FL and LED are illustrated in Figure 33. Among different impact categories, the Global Warming Potential (GWP) is displays the greatest disparity from both FL and LED, with 46.46 % and 43.73 % of the total impact, respectively. The environmental impact of the FL and LED during the use stage is 97.68 % and 90.67% of the complete life cycle.

Table 36 The environmental indicator of CML 2001 Methodology

Impact category	Abbreviation	Unit	Damage Category
Ozone Depleting Potential	ODP	kg CFC11-eq	Human Health
Human Toxicity Potential	HTP	kg 1,4-DCB-eq	
Photochemical Ozone Potential	POP	kg O_3 formed	
Global Warming Potential	GWP	kg CO_2-eq	Ecosystem Quality
Acidification Potential	AP	kg SO_2-eq	
Eutrophication Potential	EP	kg PO_4-eq	
Land Use	LU	m^2a	Resource Depletion

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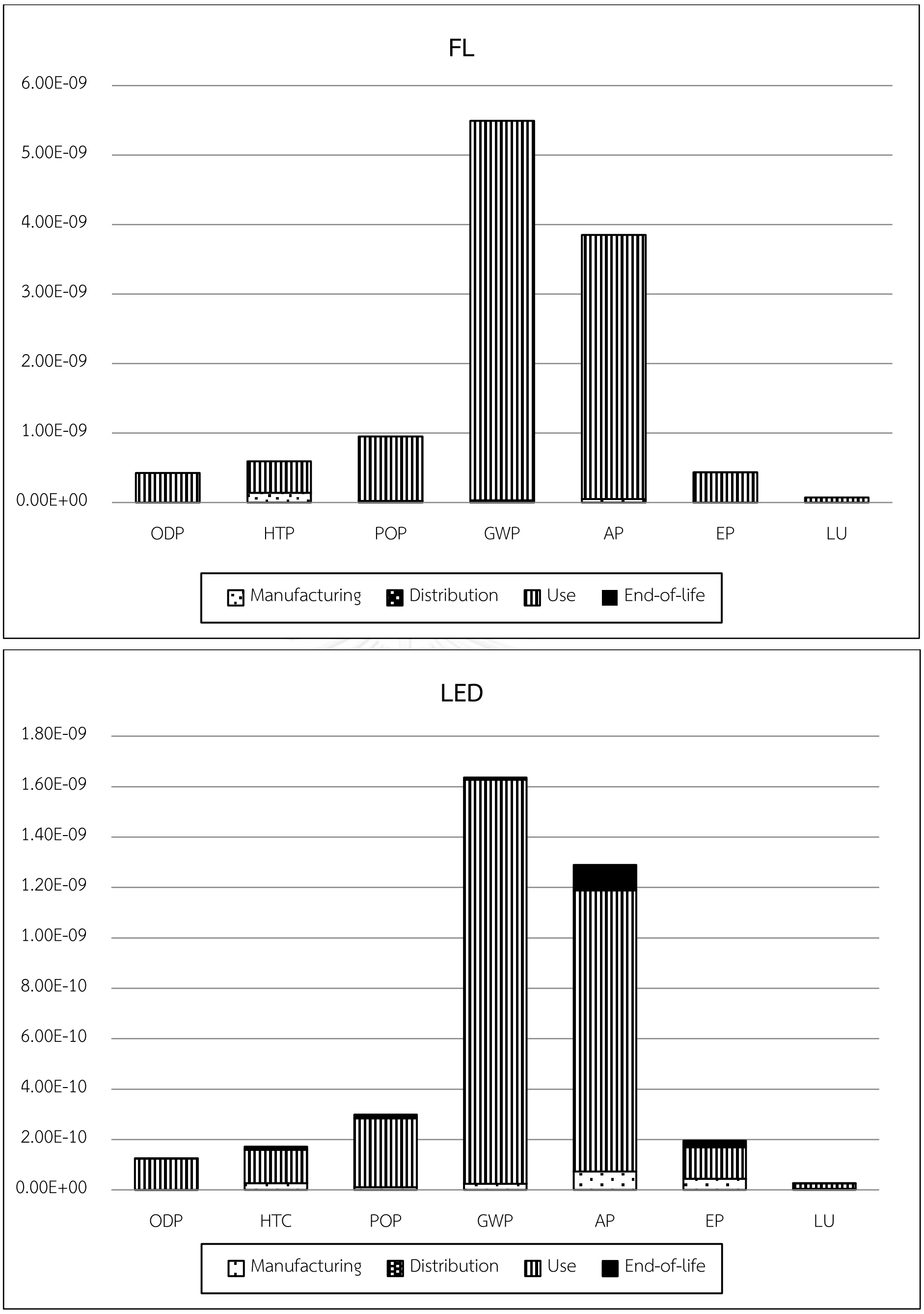

Figure 33 The environmental impact of FL and LED using CML2001 method

When compared with the studies by Principi and Fioretti (2014) and Tahkamo et al. (2014), the result indicated that the use stage of FL accounts for more than 90 % in all the categories which is analyzed based on the environmental impacts in their entire lifecycle of FL.

In addition to understanding the stage of the life cycle as the major contributors to the overall environmental impacts of each lamp analyzed, it is also important to compare the lamps themselves in order to determine which one has the smallest overall impact. The Table below presents the environmental impacts associating with human health, ecosystem quality and resource depletion for each type of the lamp. Within each impact indicator, their total impacts presented are comparable between the FL and LED because the lighting operation has been normalized to the same functional unit represented by 40,000 hours of the light output.

(1) The Human health endpoint category

The human health impact was calculated by CML2001 method were integrated from relevant three midpoint environmental impacts including ozone depleting potential (ODP), human toxicity potential (HTP) and photochemical ozone potential (POP). Overall, the results are described below.

Table 37 Human Health-Related Environmental Impacts of the Lamps

Lamp Type	Human Health		
	ODP	HTP	POP
FL	2.84E-04	6.62E+01	1.73E-01
LED	1.46E-04	3.21E+01	5.44E-02

The photochemical ozone potential (POP) displayed as the highest midpoint which leads to the human health endpoint burdens about 48.40% in FL (9.52E-10) and 50.25% in LED (2.99E-10) of overall human health impact category. Chemical reaction of sunlight, nitrogen oxides, and volatile organic compounds in the atmosphere leads to photochemical smog and the air pollution emissions. When focusing on the contribution of substances as shown in the inventory item, POP from the volatile organic compound (VOCs) is the most severe with the LED.

For human toxicity potential, the lighting lamp that has the highest impact based on the functional unit of light output is the FL. The LED offers a 1.14% reduction of the impact over FL. The main factor regarding this impact is that the FL and LED contain lead and cadmium.

For ozone depletion potential, this impact contributes about 21.56% (4.24E-10) in FL and 20.84% (2.84E-04) in LED of total human health categories, respectively.

(2) The Ecosystem Quality and resource depletion endpoint category

The following Table demonstrates the environmental impacts associated with ecosystem quality and resource reduction endpoint for each of the lamp types that normalized for 40,000 hours of light output.

In this study, the ecosystem quality was estimated by showing the potentially disappeared fraction. In this case, the damage of ecosystem diversity is shown in the unit of “PDF” regarding to Eco-indicator 99 method assumption. This result only shows the midpoint-impact indicator which causes either the environmental burdens or benefits to the ecosystem endpoint impacts.

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Table 38 Ecosystem Quality and Resource Depletion endpoint-Related Environmental Impacts of the Lamps

Lamp Type	Ecosystem Quality			Resource Depletion
	GWP (kg Co_2-eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	LU (m^2a)
FL	1.40E+03	2.49E+00	4.18E-01	2.20E+00
LED	4.13E+02	8.65E-01	9.78E-02	8.02E-01

For global warming potential (GWP), the FL has larger CO_2-equivalent emissions, with over one ton of emissions associating with the functional unit of 40,000 hours of light. The LED lamp represents about 70.50% reduction over the FL for equivalent lighting output.

For acidification potential (AP), the tendency is similar to the FL that it causes the greater impact, with 1.7 kilograms of sulfur dioxide equivalent emissions for 40,000 hours of light while the LED presents a reduction of 65.30% over the FL.

Eutrophication potential (EP) is a measure of the impact in terms of kilograms of phosphate equivalents that could cause algae blooms in waterways which lead to oxygen depletion and ecosystem damage. The FL emits approximately 0.418 kilograms of phosphate equivalents emissions for 40,000 hours of light.

Land use (LU) is the environmental impact that has been widely assessed in recent years. It concerns the products and/or benefits obtained from use of the land as well as the land management actions (activities) carried out by humans to produce those products and benefits.

Of the lamps considered, the FL has the larger impact, with a value of 2.74 times higher than that of the LED. The LED lamps can reduce the LUC further still, to only 0.802 square meters per lamp.

4.3.2 Environmental Impact in different EOL approaches

Environmental impact assessments of EOL scenarios were done by Eco-indicator 99 method. This study calculates and evaluates overall impact from EOL treatment for the lighting equipment by landfilling and recycling following the assumptions.

Overall, the study reported the endpoint effect score based on the three environmental impacts including human health, ecosystem quality and resource depletion. Then, those three impacts would be aggregated via weighting calculation into one single score (non-metric unit) which is helpful to comparison between different managing approach.

(1) Landfilling and recycling scheme

The characterized single score consists of three main endpoint categories. Overall, the EOL FL by landfilling generated total environmental impact about 3.79E-02 pt. of single score point, whereas the recycling approach could reduce about 3.39E+00 pt. as shown in negative environmental impact values. Two approaches gave a great reduction of the total environmental impact approximately by 3.43E+00 pt. The benefit of recycling compare to landfilling is about 90.44 fold of single score.

Table 39 The environmental impact of FL landfilling and recycling approach

Damage category	FL landfilling (pt.)	FL recycling (pt.)
Human Health	3.09E-02	-2.61E+00
Ecosystems Quality	5.56E-04	-3.48E-02
Resources depletion	6.44E-03	-7.44E-01
Total	3.79E-02	-3.39E+00

In case of LED as shown in Table 40, three main endpoints were weighted into one environmental single score. The disposal of LED by landfilling generated less environmental impact which contributes about 3.02E-03pt. In the opposite of the recycling scheme, it has the impacts about -8.92E-01pt. The different impact score between two approaches is 8.95E-01pt. Recycling would be better than landfilling about 296.36 fold of single score.

Table 40 The environmental impact of LED landfilling and recycling approach

Damage category	LED landfilling (pt.)	LED recycling (pt.)
Human Health	2.48E-03	-1.44E+00
Ecosystems Quality	2.81E-05	-9.49E-03
Resources depletion	5.14E-04	-3.36E-01
Total	3.02E-03	-8.92E-01

This result is also similar to the study by Quanyin et al. (2015). Their study compared environmental impacts between landfilling and recycling schemes. The result supports this study due to the fact that the recycling of FL has enormous number of environmental benefit by 2.85E-01 pt.

(2) Evaluating the potential benefit from recycling FL and LED per unit

From the calculation of the benefit from recycling of precious substance from the lighting equipment per unit, it was found that the environmental impact of the quantity of precious substance from recycling one FL decreases to be -1.46E+00 pt. as shown in Table 41.

The most benefits come from aluminum scrap recycling which can reduce 94.4% (-1.38E+00 pt.) in the FL and the magnetic ballast. When consider the sort of impact contribution, the whole recycling scheme can totally reduce about 77.40% from the human health impact, 21.99% from the resources depletion and 1.03% from ecosystems quality, respectively.

On the other hand, the LED recycling also distributes the profits to resources sustainability by recycling the aluminum from the heatsink and polycarbonate from tube cover of LED lamp set. These can largely subtract by 77.00% (-1.32E-01 pt.)

from the aluminum and 22.75% (-3.89E-02 pt.) from the polycarbonate of total impact in LED lamp, respectively as shown in Table 42.

Table 41 The environmental impact of disposal by recycling for FL per unit.

FL components	Total (pt.)	Human Health (pt.)	Ecosystems Quality (pt.)	Resources Depletion (pt.)
(1) FL lamp	-2.72E-01	-2.11E-01	-2.70E-03	-5.83E-02
Glass	8.10E-03	3.60E-03	5.72E-04	3.93E-03
Aluminum	-1.80E-01	-2.14E-01	-3.27E-03	-6.22E-02
(2) The magnetic ballast	-1.19E+00	-9.17E-01	-1.23E-02	-2.63E-01
Steel	5.03E-03	3.31E-04	1.69E-03	3.02E-03
Aluminum	-1.20E+00	-9.18E-01	-1.40E-02	-2.66E-01
Total	-1.46E+00	-1.13E+00	-1.50E-02	-3.21E-01

Table 42 The environmental impact of disposal by recycling for LED per unit

LED components	Total (pt.)	Human Health (pt.)	Ecosystems Quality (pt.)	Resources Depletion (pt.)
(1) LED lamp	-1.71E-01	-1.05E-01	-1.83E-03	-6.45E-02
Polycarbonate	-3.89E-02	-3.49E-03	-2.78E-04	-3.51E-02
Aluminum	-1.32E-01	-1.01E-01	-1.55E-03	-2.94E-02
Steel	1.02E-06	6.72E-08	3.43E-07	6.13E-07
(2) The driver	1.68E-05	1.11E-06	5.64E-06	1.01E-05
Steel	1.68E-05	1.11E-06	5.64E-06	1.01E-05

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LED components	Total (pt.)	Human Health (pt.)	Ecosystems Quality (pt.)	Resources Depletion (pt.)
Total	-1.71E-01	-1.05E-01	-1.82E-03	-6.45E-02

This result also similar to the study by Quanyin et.al (2015). They suggested that net environmental benefits can be obtained in the EOL stage of FLs with professional treatment. The majority, approximately 83 %, comes from the reuse of cullet from glass tubes, 16.8 % came from aluminum, and 0.02 % from mercury.

Another study by Hendrickson et al. (2010), possible ways of decreasing the environmental impact should be recovered and recycled to eliminate aluminum from the heatsink of LED. In addition, the aluminum recycling is a high benefit option and they can reduce energy savings in recycling scrap aluminum over producing virgin aluminum. Thus, materials recovery of the heat sink can reduce both of the cost and environmental impact of the product.

4.3.3 The End-of-life scenario analysis: projection of the potential environmental impact

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The single score was applied for analyzing the possibility of future projections. The way of projection occurred based on three scenarios which varies in the recycling and landfilling collection rate including: scenario 1 (100% secure landfilling), scenario 2 (90% secure landfilling, 10% Recycling) and scenario 3 (70% secure landfilling, 30% Recycling). Overall, the comparison between scenarios was done for each of equipment and the results were described below.

(1) The end-of-life of FL Scenario

The FL results showed that scenario 1 has the highest environmental impact, while scenario 2 and scenario 3 show negative environmental single score which both are implemented through recycling scheme (Figure 34). The baseline scenario or scenario 1 (100 % secure landfilling) was compared to other alternative scenarios. As the results, scenario 2 single score contributes environmental benefit higher than that of the scenario 1 about 2.88E-01 pt. As well as scenario 3, this also consequently contributes higher level of environmental advanrtage than the scenario 1 about 8.65E-01 pt.

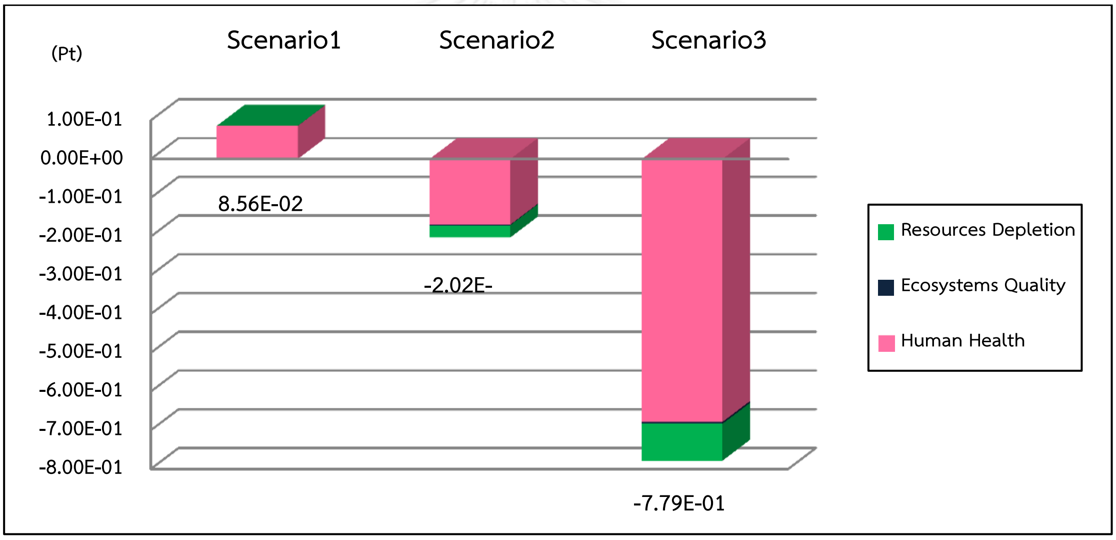

Figure 34 The projection of end-of-life of FL impact

As shown on Figure 35, the disposal of FL by landfilling generates the respiratory impact about 8.56E-02 pt. of single score point, whereas the recycling approach can reduce that impact as shown in negative environmental impact value. For scenario 2 and scenario 3, increasing the recycling rate would decrease the respiratory impact from landfilling about -2.88E-01 pt. and -8.64E-01 pt., respectively.

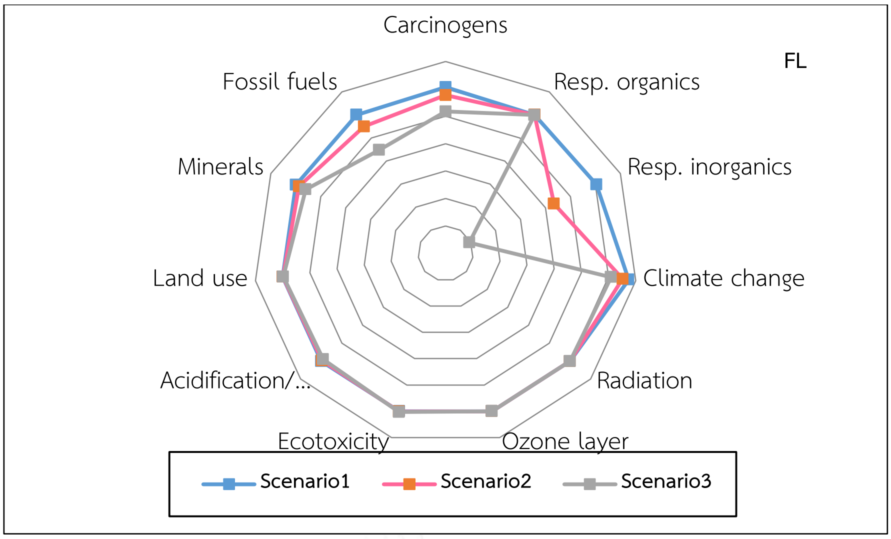

Figure 35 The environmental impact of end-of-life of FL impact

(2) The end-of-life of LED scenario

The projection of end-of-life of LED impact among three different scenarios is showed in Figure 36. It illustrated that scenario 3 creates the highest benefits for environmental potentials when compared with 100% landfilling (baseline scenario). Scenario 3 can reduce the environmental impact compared to the baseline scenario by -5.14E-02 pt. Meanwhile, scenario 2 also reduced around 1.61E-02 pt compared with the scenario 1 approach.

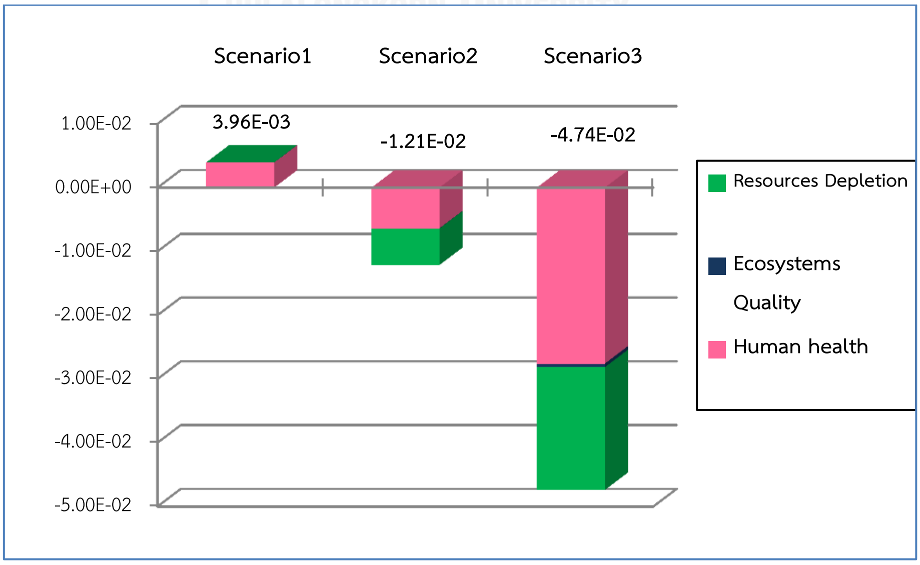

Figure 36 The projection of end-of-life of LED impact

As shown in Figure 37, the LED EOL treatment by landfilling generates the respiratory impact about 1.80E-04 pt. of single score point, whereas the recycling approach can reduce the impact about 0.0071 pt. For scenario 2 and scenario 3, increasing the recycling rate would decrease the impact with landfilling about -7.28E-03 pt. and -2.33E-02 pt., respectively.

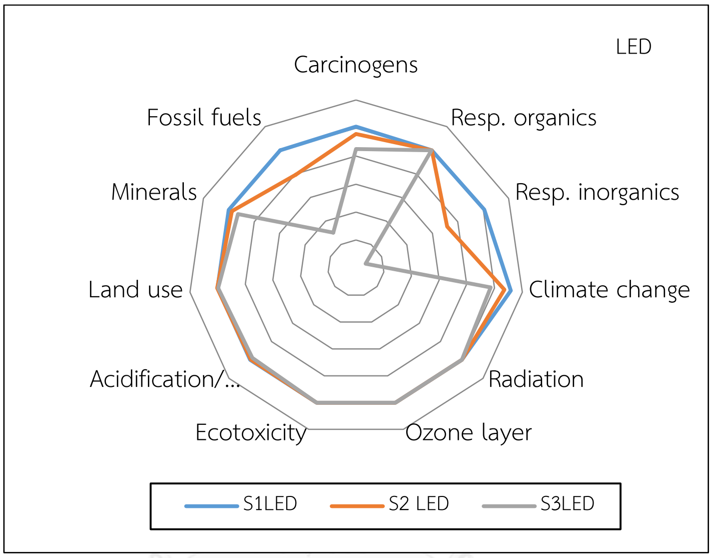

Figure 37 The environmental impact of end-of-life of LED impact

In the previous study, Apisitpuvakul et al. (2008), there is an explanation for the result of this study. When considering to the recycling scenario, the environmental impacts are reduced when recycling rate is increased.

4.3.4 The sensitivity analysis

This part was done to evaluate the degree of data uncertainty. In a sensitivity analysis the influence of the life time of the lighting equipment on the overall results was investigated. This is due to the fact that the real lifetimes of FL and LED depend much from the actual use — e.g. the more often this type of lamp is turned on and off during a day, the shorter is its total lifetimes (US-DoE, 2009). Hence, the influence of a lower life times (5 to 11% less than the value of operating lifetime. The results of this sensitivity analysis are shown in Figure 38.

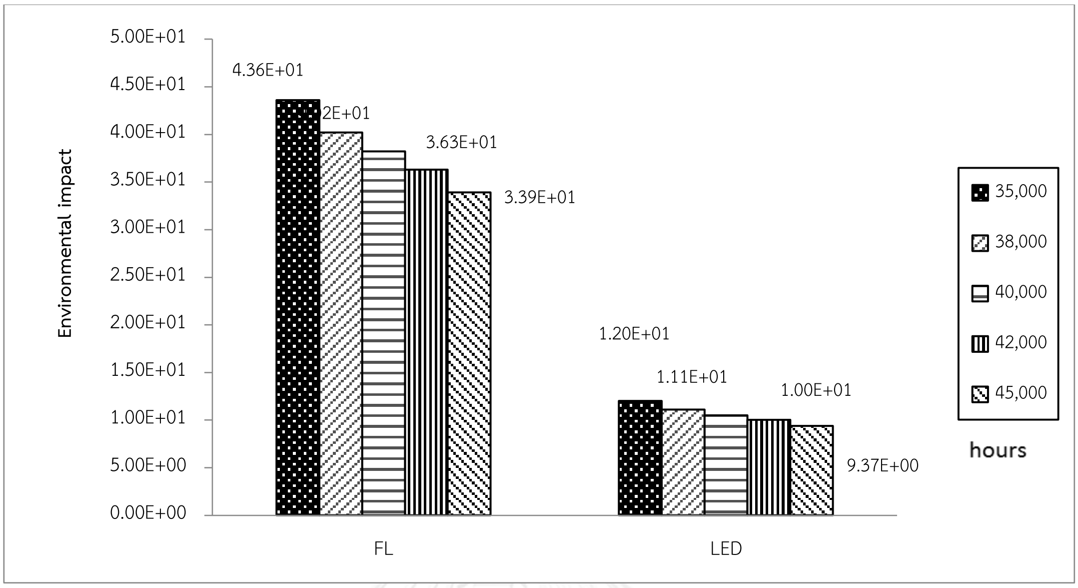

Figure 38 Influence of a change in the lifetime of the FL on the overall impact

Figure 38 shows clearly that the varying in the lifetimes (from 35,000 to 45,000 h) have an influence on the overall impact attribute to lighting equipment. The bar graph described as function of environmental burdens versus its product lifetime; the product lifetime increases with a reduction in the environmental impacts.

By increasing of 5 % and 11 % or its product lifetime from 40,000 hours to 42,000 hour) and from 40,000 to 45,000 hours, respectively in FL. The result shows that the environmental impacts decrease by 3% and 12%, respectively.

4.4 EOL Lighting equipment management Scheme

To recommend for improving EOL Lighting equipment management scheme in Thailand, the result LCA and the relevant existing data were analyzed. Accordingly, the lighting equipment management was suggested in the Table 43.

Table 43 The Lighting equipment management Scheme

Data Analysis	Measurement	
1. The company sector		
The manufacturing stage	-The magnetic ballast and the driver are the mainly component which has the greatest impacts on the respiratory inorganic in FL and LED, respiratory. -The steel of the magnetic ballast and the PCB of the driver have the highest environmental impact.	**Enhance and support the manufacturer to decrease emission from the product.** - Reduce the size of the steel and the PCB for the magnetic ballast and the driver manufacturing through eco-design concept. - Encourage the producer to reduce the hazardous substance in the PCB. - Reduce waste production by extending the lifespan of the product.
	-Glass production is the process that causes the highest respiratory inorganic impact and fossil impact of the total FL manufacturing process. - Light emitting diode production is the process that causes highest respiratory inorganic impact of the total LED manufacturing	- Control the process by purposing the green industry or reduce emissions.

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Data Analysis	Measurement	
	process	
2.Government or administrative sector		
The end-of-life stage	-Recycling would be better than landfilling	Release facilitating application to prolong lifespan capacity in Thailand including:: -The appropriate technology based on the sustainability concept should be done in order to increase technical and service support. - The national framework such as laws and regulations are needed to set for the proper recycling scheme.
	-The social, environmental and economic context is not taken into account suitability for establishing to stimulate the overall upstream and downstream of FL and LED waste management in Thailand.	**Establish the event to induce consciousness of people in waste management** -Induce people awareness by giving the necessary information including: toxic elements and valuable material available in equipment -Reduce, Reuse , recycling strategy concept (3Rs) for waste management - Advantage of Proper end-of-life management resource recovery - Disadvantages of landfilling of toxic substance, backyard recycling and other social problem.

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Data Analysis	Measurement	
		The national framework such as laws and regulations are needed to set for the proper recycling scheme - The FL and LED waste status and other Updating situation - Online Database and open-source software suitable for reused FL and LED waste - Schedule, NEWS and other updating activities - Lessons preparing for academic learning **Establish regulation and support tools for inducing people to concern in E-waste management** -Promote and support the Thai WEE policy proposal by government fund and producer compliance scheme -Develop the international law to support the collecting of waste -Establish the tax-reduction policy as monetary incentive - Establish the collection center funding program - Force the improper scrap collecting and recycling waste to pay higher tax to support the E-waste management - Evaluate the environmental potential

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Data Analysis	Measurement	
		impacts around collection site, transportation and other related area as well as the occupation health into appropriate standard
For management	-Policies are important for management of FL and LED waste	- Adjust taxation systems and tax rates for licensed operators. - Provide the recycling business financial securities so as to enable the business for commercial loan. - Create a model of control for regulating operations and entrepreneurs recycling businesses (e.g., licensing registered ones).

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CHAPTER V

CONCLUSION

This chapter summarizes all results of this study. This research applied the market supply method to quantify the generation of EOL lighting equipment in Thailand and the life cycle assessment to evaluate the environmental impacts both of the whole lifecycle and at the end-of-life stage of lighting equipment management. Furthermore, the research recommends the lighting equipment management scheme to better improvement for Thailand's FL and LED waste management.

5.1 EOL lighting equipment estimation in Thailand

The result from market supply method revealed the EOL lighting equipment generation, retrieved from total sales data of the FLs and LEDs, could be used to predict the waste disposal year for FLs and LEDs from 2015 to 2030.

The quantity of EOL FL continuously decreased in 2011 at approximately 60.15 million units to 27.23 million units in 2025.

The EOL LED will still sharply increase in 2021 (365.62 million units) and decrease in 2024. Then, the quantity of EOL LED will slightly increase in 2025 (214.12 million units), 2027 (233.82 million units) and still increase in 2030 (250.1 million units). The finding is based on the expectation that the government will promote the fluorescent replacement with LEDs as one of energy saving measures of the country

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5.2 Life cycle analysis approach

This study evaluated and compared the environmental impacts of two types of lighting equipment —FL with the magnetic ballast and LED with the driver.

The scopes of Business-to-Consumer (B2C) included the manufacturing process, transportation and distribution; consumer use, recycling, and final disposal. The 36WT8 FL and 18WT8 LED was chosen as the representative.

5.2.1 A comparison of environmental impacts between FL and LED

The comparison among the environmental impacts of the complete life cycle in the selected FL and LED with equivalent lifetimes shows that the overall impacts with using the LED is significantly reduced by 70%. The use stage has the largest impact accounting for 98.94% in FL and 96.46% in LED. The second most significant phase in the assessment is the manufacturing, which contributes about 0.99% in FL and 3.53% in LED. While the end-of-life accounts for 0.04% and 0.01% in FL and LED, respectively.

For the manufacturing stage, the main components including the magnetic ballast (or driver) of FL and LED were analyzed. The result shows that the magnetic ballast and aluminum base for end cap causes significant environmental impacts in FL which account for 50.29% and 45.60%, respectively.

The distribution stage, the FL and LED distribution has high amount of fossil fuel, respiratory inorganic and climate change accounting for 53.52%, 16.14% and 10.50%, respectively. The main substances causing the fossil fuels impact in the distribution stage are oil in diesel using for the truck.

The use phase mainly consumes the electric energy where the source of the dataset was selected from EGAT. The use of FL and LED contributes to fossil fuel, respiratory inorganic and climate change accounting for 60.70%, 24.51% and 13.60%, respectively.

For EOL treatment technology, due to the recycling of aluminum, steel, and cullet, the EOL of FL yields remarkably environmental benefits. The recycling approach can reduce environmental impacts to be 3.39E+00 pt. While polycarbonate, steel and aluminum in LED can be recycled. This creates more benefit for environment about 8.92E-01 pt.

When considering and relative impacts in the 11 categories by Eco-indicator 99 methodology. The largest proportion is fossil fuel, about 60.24 % of the total impact for the entire life cycle of FL, followed by respiratory inorganic, climate change and acidification/ eutrophication with proportions of about 24.81%, 13.54% and 0.58%, respectively. These are similar for the LED; the proportions for the three categories are 59.23%, 25.54%, 13.38% where 0.63% is the carcinogen impact.

The results using the CML 2001 methodology, the environmental impacts caused from the entire life cycle of LED is slightly lower than 31.62% compared with FL. Comparisons of the seven impact categories between FL and LED such as Ozone Depleting Potential (ODP), Human Toxicity Potential (HTP), Photochemical Ozone Potential (POP), Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP) and Land Use (LU), respectively. The Global Warming Potential (GWP) is the category in which FL and LED displays the greatest disparity, with 46.46 % and 43.73 % of the total impact, respectively. The environmental impact of the FL and LED during the use stage is 97.68 % and 90.67% of the complete life cycle.

5.2.2 Environmental Impact in different EOL approaches

Environmental impact assessments of EOL scenarios were done by Eco-indicator 99 method. This study calculates and evaluates overall impact from EOL treatment for the lighting equipment by landfilling and recycling.

(1) Landfilling and recycling scheme

Overall, the EOL FL by landfilling generated total environmental impact about 3.79E-02 pt. of single score point, whereas the recycling approach can reduce about 3.39E+00 pt. Two approaches greatly reduced the total environmental impact approximately by 3.43E+00 pt. The recycling is better than landfilling about 90.44 fold of single score.

In case of LED, the disposal of LED by landfilling generated small environmental impact which contributes about 3.02E-03pt. In the opposite of the recycling scheme, it has the impacts about -8.92E-01pt. The different impact score between two approaches is 8.95E-01pt. Recycling would be better than landfilling about 296.36 fold of single score.

(2) Evaluating the potential benefit from recycling FL and LED per unit

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From the calculation of the benefit from recycling of precious substance from the lighting equipment per unit, it was found that the environmental impact of the quantity of precious substance from recycling one FL decreases to be -1.46E+00 pt.

The most benefits come from aluminum scrap recycling which can reduce 1.80E-01 pt. in FL lamp and -1.20E+00 pt. in the magnetic ballast. When focus on the root of impact contribution, the entire recycling scheme can totally reduce about 77.40% from the human health impact, 21.99% from the resources depletion and 1.03% from ecosystems quality, respectively.

On the other hand, the LED recycling also distributes the profits to resources sustainability by recycling the aluminum from the heatsink and polycarbonate from tube cover of LED lamp set. These can largely subtract by 77.00% from the aluminum and 22.75% from the polycarbonate of total impact in LED lamp, respectively.

5.2.3 The End-of-life scenario analysis: projection of the potential environmental impact

The single score was applied for analyzing possible future projections. The way of projection occurred based on three scenarios which varies in the recycling and landfilling collection rate including: scenario 1 (100% secure landfilling), scenario 2 (90% secure landfilling, 10% Recycling) and scenario 3 (70% secure landfilling, 30% Recycling). Overall, the comparison between scenarios was done for each of equipment and the results were described below.

(1) The end-of-life of FL Scenario

The baseline scenario or scenario 1 (100 % secure landfilling) was compared to other alternative scenarios. As the results, scenario 2 single score contributes environmental benefit higher than that of the scenario 1 about 2.88E-01 pt. As well as scenario 3, this also consequently contributes higher level of environmental advanrtage than the scenario 1 about 8.65E-01 pt.

(2) The end-of-life of LED scenario

Evaluation of LED scenario, scenario 3 creates the highest benefits for environmental potentials when compared with 100% landfilling (baseline scenario). Scenario 3 can reduce the environmental impact compared to the baseline scenario by -5.14E-02 pt. Meanwhile, scenario 2 also reduced around 1.61E-02 pt compared to the scenario 1 approach.

5.3 Lighting equipment management scheme

The Lighting equipment management schemes have been proposed for the company sector and the government sector as follow.

5.3.1 The management scheme for the company sector how to improve from the result of LCA in the manufacturing stage

(1) Enhance and support the manufacturer to decrease emission from the product by reducing the size of the steel and the PCB for the magnetic ballast and the driver manufacturing through eco-design concept including encourage the producer to reduce the hazardous substance in the PCB.

(2) Control the process by purposing the green industry or reduce emissions.

5.3.2 The management scheme for the government sector that emphasizes to improve from the result of LCA in the End-of-life stage and the relevant existing data such as law and regulation, technology and education.

(1) Release facilitating application to prolong lifespan capacity in Thailand including:

- Technical and service support by finding the appropriate technology to Thailand based on sustainability concept.

(2) Establish the event to induce consciousness of people in waste management

(3) The national framework such as laws and regulations are needed to set for the proper recycling scheme.

According to the Thai WEEE, in which the major two schemes including the Government- fund model and the producer compliance scheme, the most practical way to manage WEEE is step-wise hybrid model.

Despite of the prediction from this study, the increasing market share of LEDs will also end up with high waste generation. LED can be considered as a non-hazardous waste which can be disposed normally with other non-hazardous waste. Given the potential of recycling LED and the hazardous composition in FL, lighting equipment should be included as one of priority products in the draft Thai WEEE management law.

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APPENDIX

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Appendix A

Eco Indicator99 Methodology

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A) The Eco Indicator 99 methodology

A.1 General Information

Eco-indicator 99 methodology is a quantitative LCA method meant to identify the most important environmental impacts of a product or to compare one existing product with another or a current product with new development options. The Eco-Indicator 99 method is a simpler LCA; it uses a weighting method to transform the LCA results into a single score called the eco-indicator (measured in mPt-milliPoint). The absolute value of the points is not very relevant as the main purpose is to compare relative differences between products or components. The scale is chosen in such a way that the value of 1 Point (Pt) is representative for one thousand of the yearly environmental load of one average European inhabitant5 (Ministry of Housing, 2000)

Eco-indicator 99 methodology is reviewed and improved from Eco-indicator 95 therefore; it had a number of clear limitations:

- The definition of environment was restricted to the effect of emissions to air and water on Human Health and Ecosystem Quality.
- The damage categories Human Health and Ecosystem Quality were not very well defined.
- The valuation between Human Health and Ecosystem Quality was not very explicitly done.
- Some of the newly developed characterization sets were limited in scope.
- Fate analysis was not included

A.2 Environmental Impact description

From this definition it follows that there are basically three damage categories:

Human Health, Ecosystem Quality, Resources Depletion

“Human Health” contains the idea that all human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities or premature deaths.

“Ecosystem Quality” contains the idea that non-human species should not suffer from disruptive changes of their populations and geographical distribution,

“Resources Depletion” contains the idea that the nature’s supply of non-living goods, which are essential to the human society, should be available also for future generations.

Table A-1 Detail of impact category related to the substances

Damage	Impact category	Substances
Human Health ; DALYs (Disability Adjusted life Years)	Carcinogens	Arsenic, Cadmium, Nickel
	Respiratory organics	Methane, Benzene, Xylene
	Respiratory inorganics	CO, So_x,NH_3
	Climate change	CO_2, Methane, CFCs
	Radiation	Nuclear Energy Production
	Ozone layer	CFCs, HFCs
Ecosystem Quality; PDF	Eco toxicity	Heavy Metals, Benzene

Damage	Impact category	Substances
(Potentially Disappeared Fraction)	Acidification/ eutrophication	NO_x, So_x,NH_3
	Land use	Grassland, Woods
Resource Depletion; MJ surplus Energy	Minerals	Copper, Nickel, Zinc
	Fossil fuels	Crude oil, coals

Source: Goedkopp et al. (2009)

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Appendix B

Impact assessment

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Table B-1: the environmental impacts of FL using the Eco-Indicator 99 Method

Impact category	Unit	Manufacturing	Distribution	Use	End-of-life	Total
Carcinogens	Pt	3.43E-02	3.07E-04	3.23E-01	6.91E-05	3.58E-01
Resp. organics	Pt	7.30E-04	1.37E-05	3.23E-02	3.03E-05	3.31E-02
Resp. inorganics	Pt	5.15E-01	9.99E-03	2.36E+01	1.60E-02	2.41E+01
Climate change	Pt	6.99E-02	2.97E-03	1.31E+01	1.48E-02	1.32E+01
Radiation	Pt	-2.39E-05	0.00E+00	2.79E-02	6.09E-06	2.79E-02
Ozone layer	Pt	1.49E-05	4.99E-10	1.16E-02	2.61E-07	1.16E-02
Ecotoxicity	Pt	7.19E-02	1.84E-05	6.70E-02	2.08E-04	1.39E-01
Acidification/ Eutrophication	Pt	8.77E-03	8.40E-04	5.54E-01	3.48E-04	5.64E-01
Land use	Pt	2.90E-03	0.00E+00	1.33E-01	0.00E+00	1.36E-01
Minerals	Pt	1.01E-01	0.00E+00	1.32E-03	3.72E-06	1.03E-01
Fossil fuels	Pt	1.58E-01	1.47E-02	5.84E+01	6.43E-03	5.86E+01
Total	Pt	9.63E-01	2.89E-02	9.63E+01	3.79E-02	9.73E+01

Table B-2: the environmental impacts of LED using the Eco-Indicator 99 Method

Impact category	Unit	Manufacturing	Distribution	Use	End-of-life	Total
Carcinogens	Pt	8.82E-02	6.43E-06	9.49E-02	5.51E-06	1.83E-01
Resp. organics	Pt	3.58E-04	2.87E-07	9.49E-03	2.42E-06	9.85E-03
Resp. inorganics	Pt	5.53E-01	2.09E-04	6.93E+00	1.28E-03	7.48E+00

Impact category	Unit	Manufacturing	Distribution	Use	End-of-life	Total
Climate change	Pt	7.83E-02	6.22E-05	3.84E+00	1.18E-03	3.92E+00
Radiation	Pt	3.98E-04	0.00E+00	8.20E-03	4.86E-07	8.59E-03
Ozone layer	Pt	2.47E-05	1.05E-11	3.41E-03	2.08E-08	3.43E-03
Ecotoxicity	Pt	4.18E-02	3.85E-07	1.97E-02	1.66E-05	6.15E-02
Acidification/ Eutrophication	Pt	2.00E-02	1.76E-05	1.63E-01	2.78E-05	1.83E-01
Land use	Pt	-1.51E-03	0.00E+00	3.91E-02	0.00E+00	3.76E-02
Minerals	Pt	5.40E-02	0.00E+00	3.88E-04	2.97E-07	5.44E-02
Fossil fuels	Pt	1.98E-01	3.09E-04	1.72E+01	5.13E-04	1.74E+01
Total	Pt	1.03E+00	6.05E-04	2.83E+01	3.02E-03	2.93E+01

Table B-3: the environmental impacts of the component of FL

Impact category	Unit	ballast	Glass tube	Aluminium	Phosphor	Copper	Filament	Cement	Zinc	Mercury	Argon
Carcinogens	Pt	6.73E-03	1.71E-04	3.58E-02	7.32E-06	5.37E-03	1.75E-04	2.80E-06	1.66E-05	1.25E-06	8.05E-11
Resp. organics	Pt	3.38E-04	8.43E-07	1.07E-04	6.16E-07	1.01E-06	7.81E-08	2.16E-07	3.55E-09	1.47E-09	3.48E-12
Resp. inorganics	Pt	2.07E-01	9.22E-04	1.92E-01	3.63E-03	8.02E-03	4.54E-05	1.85E-04	2.28E-06	6.28E-07	3.61E-09
Climate change	Pt	2.60E-02	3.28E-04	2.81E-02	2.86E-04	8.40E-05	9.80E-06	1.05E-04	7.17E-07	1.78E-07	1.64E-09
Radiation	Pt	2.28E-05	3.89E-06	9.75E-06	1.15E-06	3.56E-07	2.82E-08	1.42E-07	3.32E-10	4.99E-09	1.75E-11
Ozone layer	Pt	6.26E-06	2.58E-08	3.38E-06	1.25E-06	1.50E-08	1.55E-09	7.43E-09	1.17E-10	6.04E-11	3.54E-13
Ecotoxicity	Pt	3.52E-02	1.04E-05	1.52E-03	3.60E-06	3.47E-03	7.60E-05	3.12E-06	1.01E-05	1.84E-04	1.95E-11
Acidification/ Eutrophication	Pt	2.83E-03	7.08E-05	3.99E-03	3.63E-06	2.09E-04	1.44E-05	1.08E-05	2.31E-07	6.91E-08	1.39E-10
Land use	Pt	1.24E-03	1.43E-06	8.52E-04	8.54E-05	4.28E-05	2.01E-07	6.98E-07	3.69E-08	8.69E-10	3.89E-11
Minerals	Pt	4.64E-02	4.48E-05	1.63E-02	3.11E-07	3.71E-03	3.43E-05	3.37E-07	5.08E-06	1.11E-04	1.44E-12
Fossil fuels	Pt	4.83E-02	1.86E-03	6.05E-02	9.03E-04	1.75E-04	2.54E-05	1.15E-04	1.95E-06	8.49E-08	5.85E-09
Total	Pt	3.74E-01	3.42E-03	3.39E-01	4.92E-03	2.11E-02	3.81E-04	4.23E-04	3.70E-05	2.97E-04	1.14E-08

Table B-4: the environmental impacts the component of the magnetic ballast

Impact category	Unit	Total	Steel	Nylon	Polyester resin	paint	Aluminium	Paper	Copper
Total	Pt	3.74E-01	3.39E-01	9.38E-03	5.02E-03	1.01E-03	9.31E-03	1.79E-04	8.86E-03
Carcinogens	Pt	6.73E-03	5.59E-03	4.44E-05	6.39E-05	1.22E-05	9.83E-04	4.54E-06	2.18E-05
Resp. organics	Pt	3.38E-04	3.22E-04	4.56E-06	4.61E-06	1.04E-06	2.93E-06	7.05E-08	2.31E-06
Resp. inorganics	Pt	2.07E-01	1.96E-01	2.05E-03	8.12E-04	2.66E-04	5.27E-03	6.06E-05	2.52E-03
Climate change	Pt	2.60E-02	2.23E-02	1.14E-03	6.43E-04	6.52E-05	7.70E-04	1.05E-05	7.84E-04
Radiation	Pt	2.28E-05	1.71E-05	5.52E-09	-3.64E-07	-1.63E-07	2.67E-07	4.78E-08	5.51E-06
Ozone layer	Pt	6.26E-06	4.99E-06	3.41E-10	4.47E-07	6.34E-08	9.27E-08	2.77E-09	4.72E-07
Ecotoxicity	Pt	3.52E-02	3.50E-02	2.69E-05	5.69E-05	1.51E-05	4.18E-05	1.86E-06	1.61E-05
Acidification/ Eutrophication	Pt	2.83E-03	2.44E-03	1.14E-04	3.57E-05	6.16E-06	1.09E-04	2.04E-06	1.10E-04
Land use	Pt	1.24E-03	7.96E-04	2.35E-07	1.25E-06	3.56E-04	2.34E-05	5.91E-05	0.00E+00
Minerals	Pt	4.64E-02	4.26E-02	9.01E-07	1.09E-07	7.75E-06	4.46E-04	2.41E-08	3.35E-03
Fossil fuels	Pt	4.83E-02	3.39E-02	6.00E-03	3.41E-03	2.80E-04	1.66E-03	4.01E-05	2.04E-03

Table B-5: the environmental impacts of the component of LED

Impact category	Unit	Tube cover	Heatink	End cap	LED Array	Driver
Carcinogens	Pt	2.84E-03	1.69E-03	3.02E-04	3.21E-01	3.53E+01
Resp. organics	Pt	2.25E-04	5.04E-06	2.74E-06	1.20E-03	2.66E+00
Resp. inorganics	Pt	1.59E-01	9.08E-03	2.52E-03	1.52E+00	8.88E-03
Climate change	Pt	5.37E-02	1.33E-03	5.87E-04	2.57E-01	2.24E+01
Radiation	Pt	2.97E-07	4.61E-07	0.00E+00	1.52E-03	1.95E+00
Ozone layer	Pt	1.94E-08	1.60E-07	1.74E-07	8.80E-05	1.11E-02
Ecotoxicity	Pt	6.88E-04	7.20E-05	6.27E-06	1.53E-01	7.78E-04
Acidification/ Eutrophication	Pt	4.47E-03	1.88E-04	9.87E-05	6.04E-02	1.27E+00
Land use	Pt	1.51E-05	4.03E-05	0.00E+00	-2.09E-02	7.49E-01
Minerals	Pt	2.71E-06	7.68E-04	0.00E+00	1.68E-01	2.06E-01
Fossil fuels	Pt	2.41E-01	2.86E-03	5.76E-03	5.90E-01	1.89E+00
Total	Pt	4.62E-01	1.60E-02	9.28E-03	3.05E+00	4.10E+00

Table B-6: the environmental impacts the component of the driver

Impact category	Unit	Steel	Copper	Nylon	Transformer,	Capacitor	PWB	Total
Total	Pt	3.99E-04	4.22E-02	8.03E-03	5.09E-04	2.59E-01	3.50E+01	3.53E+01
Carcinogens	Pt	6.56E-06	1.10E-03	3.80E-05	3.64E-06	-3.15E-02	2.69E+00	2.66E+00
Resp. organics	Pt	3.67E-07	4.92E-06	3.90E-06	2.35E-07	1.61E-05	8.86E-03	8.88E-03
Resp. inorganics	Pt	2.37E-04	1.72E-02	1.76E-03	1.79E-04	3.08E-01	2.21E+01	2.24E+01
Climate change	Pt	2.61E-05	4.69E-04	9.77E-04	5.69E-05	4.76E-04	1.95E+00	1.95E+00
Radiation	Pt	8.37E-09	1.98E-06	4.72E-09	1.98E-08	1.15E-05	1.11E-02	1.11E-02
Ozone layer	Pt	4.91E-09	8.57E-08	2.92E-10	1.88E-08	7.44E-07	7.77E-04	7.78E-04
Ecotoxicity	Pt	4.02E-05	1.16E-03	2.31E-05	8.41E-07	-2.06E-02	1.29E+00	1.27E+00
Acidification/ Eutro	Pt	2.83E-06	3.12E-04	9.73E-05	5.50E-06	8.51E-03	7.40E-01	7.49E-01
Land use	Pt	9.93E-07	2.19E-04	2.01E-07	1.16E-06	-2.94E-04	2.06E-01	2.06E-01
Minerals	Pt	4.91E-05	2.07E-02	7.70E-07	3.11E-08	-1.16E-02	1.88E+00	1.89E+00
Fossil fuels	Pt	3.64E-05	9.42E-04	5.13E-03	2.61E-04	6.06E-03	4.08E+00	4.10E+00

Table B-7: the environmental impacts in the use stage

Impact category	Use			
	FL	%	LED	%
Carcinogens	3.23E-01	0.34%	9.49E-02	0.34%
Resp. organics	3.23E-02	0.03%	9.49E-03	0.03%
Resp. inorganics	2.36E+01	24.51%	6.93E+00	24.51%
Climate change	1.31E+01	13.60%	3.84E+00	13.59%
Radiation	2.79E-02	0.03%	8.20E-03	0.03%
Ozone layer	1.16E-02	0.01%	3.41E-03	0.01%
Ecotoxicity	6.70E-02	0.07%	1.97E-02	0.07%
Acidification/ Eutrophication	5.54E-01	0.58%	1.63E-01	0.58%
Land use	1.33E-01	0.14%	3.91E-02	0.14%
Minerals	1.32E-03	0.00%	3.88E-04	0.00%
Fossil fuels	5.84E+01	60.64%	1.72E+01	60.70%
Total	9.63E+01	100.00%	2.83E+01	100.00%

Table B-8 : Comparison the environmental impacts of EOL FL

Impact category	Unit	Scenario1	Scenario2	Scenario3
Total	Pt	4.28E-02	-1.01E-01	-3.89E-01
Carcinogens	Pt	3.07E-03	-1.18E-02	-4.14E-02
Resp. organics	Pt	1.22E-04	6.24E-05	-5.58E-05
Resp. inorganics	Pt	2.25E-03	-8.26E-02	-2.52E-01
Climate change	Pt	3.70E-02	2.62E-02	4.61E-03
Radiation	Pt	2.32E-07	2.67E-05	7.97E-05
Ozone layer	Pt	8.44E-08	-9.71E-07	-3.08E-06
Ecotoxicity	Pt	8.87E-05	5.39E-04	1.44E-03
Acidification/ Eutrophication	Pt	9.17E-05	-1.63E-03	-5.07E-03
Land use	Pt	2.82E-06	-3.52E-04	-1.06E-03
Minerals	Pt	1.37E-05	-6.45E-03	-1.94E-02
Fossil fuels	Pt	1.61E-04	-2.52E-02	-7.60E-02

Table B-9: Comparison the environmental impacts of EOL FL

Impact category	S1LED	S2 LED	S3LED
Total	3.41E-03	-1.21E-02	-4.74E-02
Carcinogens	2.45E-04	-1.07E-03	-3.76E-03
Resp. organics	9.70E-06	2.03E-06	-1.63E-05
Resp. inorganics	1.80E-04	-7.10E-03	-2.31E-02
Climate change	2.95E-03	1.80E-03	-7.10E-04
Radiation	1.85E-08	3.40E-06	7.82E-06
Ozone layer	6.73E-09	-5.34E-08	-2.90E-07
Ecotoxicity	7.07E-06	3.76E-05	4.39E-05
Acidification/ Eutrophication	7.32E-06	-1.44E-04	-5.17E-04
Land use	2.25E-07	7.34E-05	-8.81E-05
Minerals	1.09E-06	-5.83E-04	-1.80E-03
Fossil fuels	1.28E-05	-5.16E-03	-1.75E-02

Appendix C

Questionnaire form

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แบบสอบถาม

โครงการประเมินวัฏจักรชีวิตของหลอดไฟ:

เปรียบเทียบระหว่างหลอดฟลูออเรสเซนต์และหลอดไดโอดเปล่งแสงในประเทศไทย

ศูนย์ความเป็นเลิศด้านการจัดการสารและของเสียอันตราย จุฬาลงกรณ์มหาวิทยาลัยดำเนินโครงการประเมินวัฏจักรชีวิตของหลอดไฟ: เปรียบเทียบระหว่างหลอดฟลูออเรสเซนต์และหลอดไดโอดเปล่งแสง (แอลอีดีในประเทศไทย ในการนี้จึงใคร่ขอความอนุเคราะห์จากท่านในการกรอกข้อมูลแบบสอบถามเพื่อเป็นข้อมูลเบื้องต้นสำหรับการทำวิจัยหากข้อมูลใดที่ท่านไม่มีหรือไม่สามารถตอบแบบสอบถามได้ขอให้ใส่ข้อความ "ไม่มีข้อมูล" หรือ "N/A" ในการนี้ทางคณะผู้วิจัยขอขอบพระคุณเป็นอย่างยิ่งสำหรับผู้ที่เกี่ยวข้องทุกๆท่านที่ได้ให้ความร่วมมือในการกรอกแบบสอบถามฉบับนี้ซึ่งข้อมูลทั้งหมดนั้นจะถือว่าเป็นความลับโดยจะนำมาใช้เพื่อเป็นประโยชน์ต่อโครงการฯเท่านั้นและหากมีข้อสงสัยในแบบสอบถามกรุณาติดต่อ น.ส.วราภรณ์ ถาวรวงษ์ นักศึกษาปริญญาโท โทรศัพท์ 099-6750252 หรือที่ Email: letterok@hotmail.com

วัน/เดือน/ปีที่ให้ข้อมูล________/________/________

ส่วนที่ 1 ข้อมูลทั่วไป

บริษัท____

ที่อยู่เลขที่________หมู่_____ซอย__________ถนน______________ตำบล/แขวง___________

อำเภอ/แขวง________จังหวัด___________รหัสไปรษณีย์___________

ชื่อผู้กรอกแบบสอบถาม______________________________ตำแหน่งในบริษัท_____________

เบอร์โทรศัพท์_______________โทรสาร__________ E-mail address___________________

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ส่วนที่ 2 ข้อมูลทางธุรกิจ

คำชี้แจง กรุณาทำเครื่องหมาย (✓) ในช่องสี่เหลี่ยมของแต่ละหัวข้อ หรือกรอกข้อมูลลงในช่องว่างที่จัดเตรียมไว้ให้

1. บริษัทเริ่มดำเนินการเมื่อปี พ.ศ......................................
2. ส่วนแบ่งการตลาดของบริษัทในประเทศ ณ ปัจจุบัน

☐ น้อยกว่า 1% ☐ 1 – 10% ☐ 11 – 20% ☐ 21 – 30%

☐ 31 – 40% ☐ 41 – 50% ☐ มากกว่า 50%

3. อายุการใช้งานเฉลี่ยของหลอดไฟในปัจจุบัน

3.1) หลอดฟลูออเรสเซนต์แบบชนิดตรง........................ชั่วโมง/หลอด

แบบชนิดวงกลม.......................ชั่วโมง/หลอด แบบชนิดคอมแพกต์...................ชั่วโมง/หลอด

3.2) หลอดแอลอีดีแบบชนิดตรง........................ชั่วโมง/หลอด

หลอดแอลอีดี BLUB....................................ชั่วโมง/หลอด (ใช้แทนหลอดตะเกียบ)

4. โปรดกรุณาระบุข้อมูลต่อไปนี้ (ข้อมูลทุกประเภทที่ท่านตอบ และชื่อบริษัทของท่าน จะถือเป็นความลับที่สุด และใช้ในการวิเคราะห์ของงานวิจัยเท่านั้น

รายละเอียด	**ปี พ.ศ.**				
	2554	**2555**	**2556**	**2557**	**2558**
1..ปริมาณการผลิต (หลอด)					
1.1 หลอดฟลูออเรสเซนต์					
1.2 หลอดแอลอีดี					
2.ปริมาณจำหน่ายในประเทศ (หลอด)					
2.1 หลอดฟลูออเรสเซนต์					
2.2 หลอดแอลอีดี					

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5. การคาดการณ์หรืออัตราการเติบโตของหลอดไฟแต่ละประเภทในอนาคต

5.1) อัตราการเติบโตหลอดฟลูออเรสเซนต์ ร้อยละ...

5.2) อัตราการเติบโตหลอดแอลอีดี ร้อยละ..

ขอบพระคุณอย่างสูงที่กรุณาสละเวลาอันมีค่าของท่านเพื่อตอบแบบสอบถามนี้

ศูนย์ความเป็นเลิศด้านการจัดการสารและของเสียอันตราย จุฬาลงกรณ์มหาวิทยาลัย

VITA

Ms. Waraporn Thavornvong was born in July, 7 1981. Her academic background are written below;

- Bachelor of science (Environmental health science), Mahidol University

- Participated presentation in the the 6th International Conference on Sustainable Energy and Environment or “SEE 2016” , November 28-30 2016 at The Dusit thani Hotel Bangkok, Thailand, topic "Life Cycle Assessment of Fluorescent lamp and Light Emitting Diode lamp"

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